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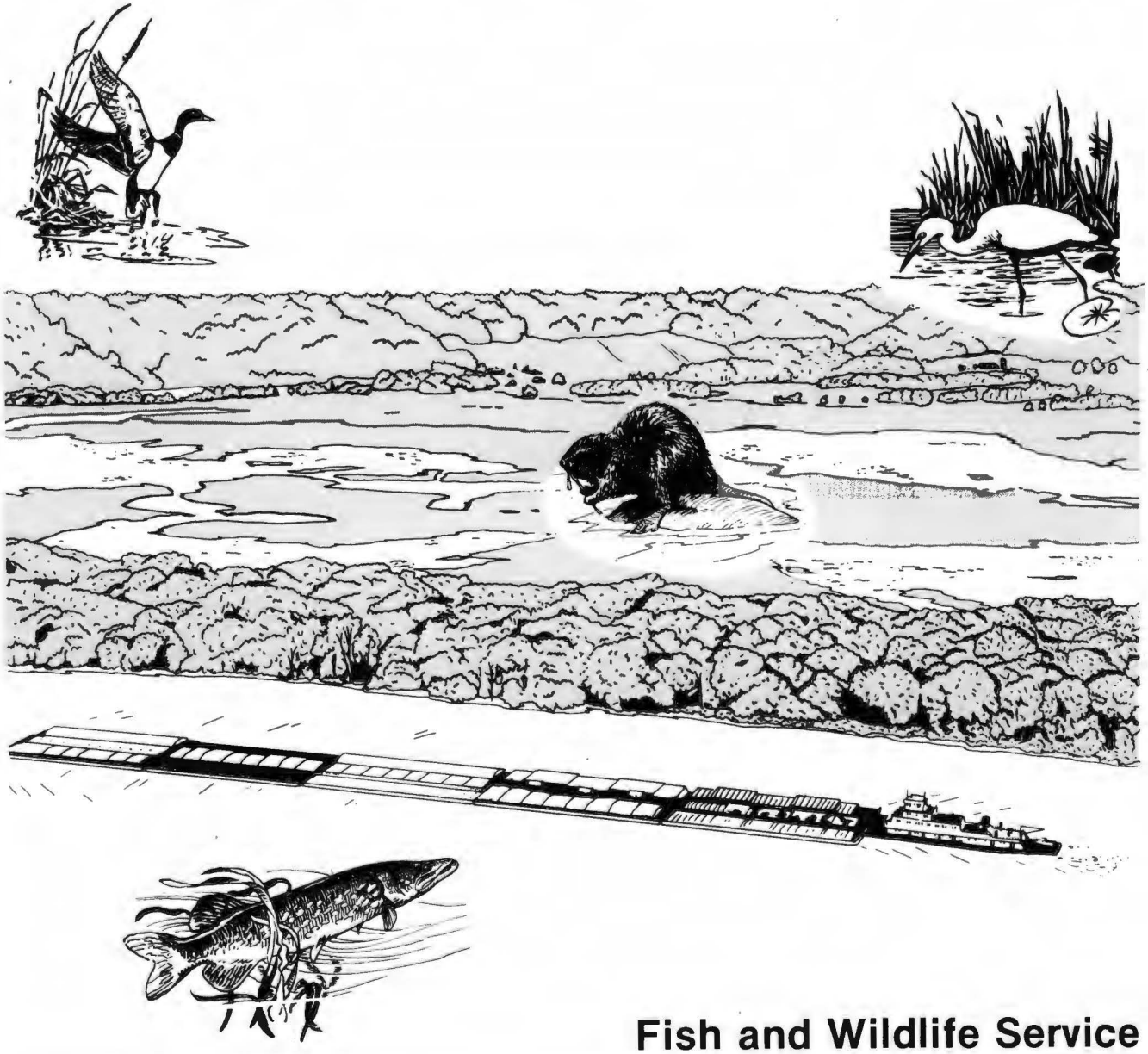
Mitigation and Enhancement Techniques for the Upper Mississippi River System and Other Large River Systems



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MITIGATION AND ENHANCEMENT TECHNIQUES FOR THE UPPER MISSISSIPPI RIVER SYSTEM AND OTHER LARGE RIVER SYSTEMS

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PREFACE

Large river systems are valuable national resources that provide numerous benefits to travel, shipping, recreation, and fish and wildlife. However, efforts to expand one of the uses frequently come in direct conflict with one or more of the others. The Upper Mississippi River System (UMRS) provides all of these benefits, and is heavily used. Development of a navigation system with numerous locks and dams has provided a rapid, efficient route for commerce to and from the Gulf of Mexico. In recent years, pressures have grown for increased navigation and for further development of UMRS for industrial uses. Managers of fish and wildlife resources and environmentalists have become alarmed about the potential adverse effects that such development may have on the ecosystem.

This guide attempts to bring together all scientific data that are available on techniques that have been or can be used to offset or reduce the impacts of development and maintenance of UMRS or other large river systems. Decision makers are thus provided an objective description of options now at their disposal when they attempt to weigh the merits or defects associated with a particular action.

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TABLE OF CONTENTS

		Page
Preface		iii
Acknowledgments		v
Table of Contents		vii
List of Tables		xv
List of Figures		xviii
Abstract		xxiii
Part I.	Introduction to mitigation philosophy, regulations, and techniques	1
Part II.	Background of the Comprehensive Master Plan for the Management of the Upper Mississippi River System	5
Part III.	Methodology for assessing the impacts of man's activities on fish and wildlife resources	8
Part IV.	Summary of the effects of navigation, and of the construction, operation, and maintenance of a navigation channel on the Upper Mississippi River System	13
Chapter 1.	Construction, operation, and maintenance of a navigation channel on the Upper Mississippi River System	14
1.1.	Clearing and snagging	15
1.2.	Channel enlargement, dredging, and disposal of dredged material	17
1.2.1.	Physical effects	19
1.2.2.	Chemical effects	20
1.2.3.	Biological effects	20
1.3.	Locks and dams	21
1.3.1.	Physical effects	22
1.3.2.	Chemical effects	24
1.3.3.	Biological effects	25
1.4.	River training structures	26
1.4.1.	Physical effects	28
1.4.2.	Chemical effects	30
1.4.3.	Biological effects	31
1.5.	Bank stabilization	33
1.6.	Flood protection levees	35
1.7.	Water level regulation	37
Chapter 2.	Adverse effects related to boat traffic	40
2.1.	Physical and chemical effects of boat traffic	40
2.1.1.	Effects of boat waves	40
2.1.2.	Drawdown effects	42
2.1.3.	Effects related to pressure and velocity changes	42
2.2.	Biological effects of boat traffic	46
2.3.	Pollution caused by boat traffic	48
2.4.	Winter navigation	50

Part V. Bank stabilization techniques 52
Chapter 3. Processes of erosion 54
3.1. Currents 54
3.2. Wave action 57
3.3. Slope failure 64
3.3.1. Piping 66
3.3.2. Flow slides 66
3.3.3. Sloughing 67
3.4. Summary of preventive measures against erosion 67
Chapter 4. Riprap revetments 71
4.1. Situation to be mitigated or enhanced . . . 71
4.2. Description of techniques 72
4.3. Impacts on the environment 79
4.4. Costs 81
4.5. Evaluation for use on UMRS 82
Chapter 5. Other revetments and bulkheads 84
5.1. Situation to be mitigated or enhanced . . . 84
5.2. Description of techniques 84
5.2.1. Cellular concrete grids 85
5.2.2. Articulated concrete mattresses 87
5.2.3. Enviroblox 88
5.2.4. Polypods 91
5.2.5. Gabions 93
5.2.6. Sand- or concrete-filled synthetic revetments 99
5.2.7. Used-tire revetments 102
5.2.8. Bulkheads 105
5.2.9. Miscellaneous revetments 106
5.3. Impacts on the environment 107
5.4. Costs 109
5.5. Evaluation for use on UMRS 112
Chapter 6. River training structures 114
6.1. Situation to be mitigated or enhanced . . . 114
6.1.1. Groins 114
6.1.2. Wind dams and dikes 115
6.2. Description of techniques 116
6.2.1. Stone wing dams 116
6.2.2. Timber pile dikes 118
6.2.3. Jacks 120
6.2.4. Fences 122
6.2.5. Tree retards 124
6.2.6. Timber cribs 124
6.2.7. Sand-filled synthetic bags 124
6.2.8. Miscellaneous river training structures 127
6.3. Impacts on the environment 127
6.4. Costs 132
6.5. Evaluation for use on UMRS 133

Chapter 7. Introduction to fixed and floating breakwater structures 135
Chapter 8. Fixed breakwater structures 139
8.1. Situation to be mitigated or enhanced . . . 139
8.2. Description of techniques 139
8.2.1. Rock breakwaters 139
8.2.2. Concrete breakwaters 141
8.2.3. Steel breakwaters 141
8.2.4. Sand-filled synthetic sandbags 142
8.2.5. Miscellaneous fixed breakwaters 142
8.3. Impacts on the environment 143
8.4. Costs 144
8.5. Evaluation for use on UMRS 144
Chapter 9. Floating breakwater structures 146
9.1. Situation to be mitigated or enhanced . . . 146
9.2. Description of techniques 146
9.2.1. Single prism breakwaters 146
9.2.2. Raft breakwaters 147
9.2.3. Catamaran breakwaters 148
9.2.4. A-frame breakwaters 149
9.2.5. Flexible breakwaters 151
9.2.5.1. Hovering breakwaters . . 151
9.2.5.2. Floating tire breakwaters 153
9.2.6. Tethered float breakwaters 158
9.2.7. Miscellaneous floating breakwaters 159
9.3. Impacts on the environment 161
9.4. Costs 164
9.5. Evaluation for use on UMRS 165
Chapter 10. Introduction to measures for reducing soil instability or hydrostatic pressures 167
Chapter 11. Vegetation 169
11.1. Situation to be mitigated or enhanced . . . 169
11.2. Description of techniques 170
11.3. Impacts on the environment 177
11.4. Costs 178
11.5. Evaluation for use on UMRS 182
Chapter 12. Chemical soil stabilizers 184
12.1. Situation to be mitigated or enhanced . . . 184
12.2. Description of techniques 184
12.3. Impacts on the environment 186
12.4. Costs 186
12.5. Evaluation for use on UMRS 186
Chapter 13. Erosion-control mattings 188
13.1. Situation to be mitigated or enhanced . . . 188
13.2. Description of techniques 188
13.3. Impacts on the environment 190
13.4. Costs 190

13.5. Evaluation for use on UMRS 191
Chapter 14. Filter fabrics 192
14.1. Situation to be mitigated or enhanced . . . 192
14.2. Description of techniques 192
14.3. Impacts on the environment 194
14.4. Costs 195
14.5. Evaluation for use on UMRS 195
Chapter 15. Hydraulic wells or drains 196
15.1. Situation to be mitigated or enhanced . . . 196
15.2. Description of techniques 196
15.3. Impacts on the environment 197
15.4. Costs 197
15.5. Evaluation for use on UMRS 197
Chapter 16. Miscellaneous soil stabilizers or hydrostatic pressure relief devices 198
Chapter 17. Island creation 200
17.1. Situation to be mitigated or enhanced . . . 200
17.2. Description of techniques 200
17.3. Impacts on the environment 202
17.4. Costs 203
17.5. Evaluation for use on UMRS 204
Chapter 18. Berm creation and beach enrichment 206
18.1. Situation to be mitigated or enhanced . . . 206
18.2. Description of techniques 206
18.3. Impacts on the environment 209
18.4. Costs 211
18.5. Evaluation for use on UMRS 212
Chapter 19. Water level control 213
19.1. Situation to be mitigated or enhanced . . . 213
19.2. Description of technique 213
19.3. Impacts on the environment 215
19.4. Costs 215
19.5. Evaluation for use on UMRS 216
Chapter 20. Regulation of boat traffic 217
20.1. Situation to be mitigated or enhanced . . . 217
20.2. Description of techniques 218
20.3. Impacts on the environment 221
20.4. Costs 222
20.5. Evaluation for use on UMRS 222
Part VI. Dredging and disposal of dredged material 224
Chapter 21. Dredges, dredging methods, and disposal of dredged material 225
21.1. Situation to be mitigated or enhanced . . . 225
21.2. Description of techniques 226
21.2.1. Dredges and dredging methods . . . 226
21.2.2. Disposal of dredged material . . . 227
21.3. Impacts on the environment 229
21.4. Costs 230
21.5. Evaluation for use on UMRS 231

Part VII. Fishery management techniques 233
Chapter 22. Fish attractors 234
22.1. Situation to be mitigated or enhanced . . . 234
22.2. Description of techniques 235
22.3. Impacts on the environment 240
22.4. Costs 241
22.5. Evaluation for use on UMRS 242
Chapter 23. Spawning structures 244
23.1. Situation to be mitigated or enhanced . . . 244
23.2. Description of techniques 244
23.3. Impacts on the environment 247
23.4. Costs 248
23.5. Evaluation for use on UMRS 249
Chapter 24. Nursery ponds, coves, and marshes 250
24.1. Situation to be mitigated or enhanced . . . 250
24.2. Description of techniques 250
24.2.1. Nursery ponds 251
24.2.2. Nursery coves 251
24.2.3. Nursery marshes 253
24.3. Impacts on the environment 253
24.4. Costs 254
24.5. Evaluation for use on UMRS 255
Chapter 25. Fish screens and barriers 256
25.1. Situation to be mitigated or enhanced . . . 256
25.2. Description of techniques 257
25.2.1. Fish screens 257
25.2.2. Fish barriers 265
25.3. Impacts on the environment 267
25.4. Costs 267
25.5. Evaluation for use on UMRS 268
Chapter 26. Fish passage 269
26.1. Situation to be mitigated or enhanced . . . 269
26.2. Description of techniques 270
26.2.1. Fishways 270
26.2.2. Fish locks and lifts 273
26.2.3. Modified or improved culverts . . . 275
26.3. Impacts on the environment 277
26.4. Costs 277
26.5. Evaluation for use on UMRS 278
Chapter 27. Water control structures 280
27.1. Situation to be mitigated or enhanced . . . 280
27.2. Description of techniques 282
27.2.1. Skimming weirs and penstocks 282
27.2.2. Energy dissipators 282
27.2.3. Reregulating dams 284
27.2.4. Side channel modification structures 284
27.3. Impacts on the environment 285
27.4. Costs 286
27.5. Evaluation for use on UMRS 287

Chapter 28. Management of water levels and flows 288
28.1. Situation to be mitigated or enhanced . . . 288
28.2. Description of techniques 290
28.2.1. Management of water levels 290
28.2.2. Management of water flows 292
28.3. Impacts on the environment 295
28.4. Costs 296
28.5. Evaluation for use on UMRS 297
Chapter 29. Wing dam modification 299
29.1. Situation to be mitigated or enhanced . . . 299
29.2. Description of techniques 300
29.3. Impacts on the environment 304
29.4. Costs 310
29.5. Evaluation for use on UMRS 310
Chapter 30. Side channel modification 312
30.1. Situation to be mitigated or enhanced . . . 312
30.2. Description of techniques 313
30.3. Impacts on the environment 315
30.4. Costs 315
30.5. Evaluation for use on UMRS 317
Chapter 31. Aeration techniques 318
31.1. Situation to be mitigated or enhanced . . . 318
31.2. Description of techniques 319
31.2.1. Destratification 319
31.2.2. Hypolimnetic aeration and oxygenation 324
31.2.3. Supplemental instream aeration . . 329
31.3. Impacts on the environment 331
31.4. Costs 334
31.5. Evaluation for use on UMRS 337
Chapter 32. Control of nuisance aquatic plants 340
32.1. Situation to be mitigated or enhanced . . . 340
32.2. Description of techniques 342
32.2.1. Chemical control 342
32.2.2. Biological control 347
32.2.3. Mechanical control 348
32.2.4. Habitat manipulation 349
32.2.5. Integrated pest management 352
32.3. Impacts on the environment 353
32.3.1. Chemical control 353
32.3.2. Biological control 354
32.3.3. Mechanical control 354
32.3.4. Habitat manipulation 355
32.4. Costs 357
32.5. Evaluation for use on UMRS 358
Chapter 33. Manipulation of fish populations 363
33.1. Situation to be mitigated or enhanced . . . 363
33.2. Description of techniques 365
33.2.1. Fishing regulations 365
33.2.2. Mechanical control 366
33.2.3. Drawdowns 367

33.2.4. Chemical control 368
33.2.5. Integrated pest management 372
33.2.6. Stocking 373
33.3. Impacts on the environment 374
33.4. Costs 376
33.5. Evaluation for use on UMRS 377
Part VIII. Wildlife management techniques 378
Chapter 34. Artificial nest structures 379
34.1. Situation to be mitigated or enhanced . . . 379
34.2. Description of techniques 379
34.2.1. Nest boxes 379
34.2.2. Nest baskets 382
34.2.3. Platforms 383
34.3. Impacts on the environment 386
34.4. Costs 387
34.5. Evaluation for use on UMRS 388
Chapter 35. Island creation or development 390
35.1. Situation to be mitigated or enhanced . . . 390
35.2. Description of techniques 390
35.2.1. Dredged material islands 390
35.2.2. Waterfowl nesting islands 395
35.3. Impact on the environment 397
35.4. Costs 398
35.5. Evaluation for use on UMRS 399
Chapter 36. Marsh creation or development 401
36.1. Situation to be mitigated or enhanced . . . 401
36.2. Description of techniques 401
36.2.1. Potholes 401
36.2.2. Level ditching 405
36.2.3. Impoundments 407
36.2.4. Marsh creation with dredged material 408
36.3. Impacts on the environment 412
36.4. Costs 414
36.5. Evaluation for use on UMRS 417
Chapter 37. Greentree reservoirs and mast management 418
37.1. Situation to be mitigated or enhanced . . . 418
37.2. Description of techniques 419
37.3. Impacts on the environment 423
37.4. Costs 424
37.5. Evaluation for use on UMRS 425
Chapter 38. Vegetation control 426
38.1. Situation to be mitigated or enhanced . . . 426
38.2. Description of techniques 426
38.2.1. Chemical control 427
38.2.2. Mechanical control 436
38.2.3. Biological control 438
38.2.4. Water level fluctuation 439
38.2.5. Burning 440
38.3. Impacts on the environment 443
38.3.1. Chemical control 443

38.3.2. Mechanical control 444
38.3.3. Biological control 444
38.3.4. Water level fluctuation 445
38.3.5. Burning 445
38.4. Costs 446
38.5. Evaluation for use on UMRS 447
Chapter 39. Water level control 450
39.1. Situation to be mitigated or enhanced . . . 450
39.2. Description of techniques 450
39.2.1. Dikes and levees 450
39.2.2. Spillways and water level control structures 455
39.2.3. Drawdowns 464
39.3. Impacts on the environment 468
39.4. Costs 471
39.5. Evaluation for use on UMRS 473
Chapter 40. Revegetation 475
40.1. Situation to be mitigated or enhanced . . . 475
40.2. Description of techniques 475
40.2.1. Selection of plant species 476
40.2.2. Site preparation 479
40.2.3. Planting of stock or propagules 481
40.3. Impacts on the environment 489
40.4. Costs 491
40.5. Evaluation for use on UMRS 493
Part IX. Summary 495
Part X. References 522
Part XI. Glossary 655
Part XII. Common and scientific names 678
Part XIII. Subject index 690

LIST OF TABLES

TABLE		PAGE
1	Maximum height (feet) of waves generated by vessels of different types moving through water 35-40 ft deep at a constant speed of 10 knots	62
2	Construction costs (per linear foot) for tire mattress protection structures (revet mattress with eight modulars) at Rogers City, Michigan, summer 1976	111
3	Costs (1977) of some methods of site preparation	179
4	Cost analysis (1977) of revegetation treatments for erosion control	180
5	A comparison of costs (dollars per acre) of inundation zone seeding techniques	181
6	Costs of moving dredged material	231
7	Construction costs for artificial reefs in Smith Mountain Lake, Virginia	242
8	Cost of walleye fry stocking compared with amortized cost of new improved spawning shoal, based on observed production of walleye fry on improved shoal, Lake Osakis, Minnesota	249
9	Man-days of labor required for building barrier nets at Lake Tyler East and Lake Jacksonville, Texas, 1975	255
10	Summary of lake volumes and pumping data for destratification of four eastern Ohio lakes	322
11	Cost comparisons of three proposed hypolimnetic aeration and oxygenation systems for San Vicente Reservoir, California	337
12	Costs (thousands of dollars, in 1978) of mechanical surface and diffusion aeration systems	338
13	Manufacturers and selected specifications of weed harvesting equipment	350
14	Selected references on the influence of drawdowns on aquatic plant species	351
15	Typical harvesting budget calculation sheet for mechanical control of aquatic vegetation	359

Tables (cont.)

16 Budget for rehabilitation of Marion Millpond, Wisconsin 360

17 Summary of manpower, basic equipment, and costs for nutrient inactivation by chemical precipitation 361

18 Guidelines for operation of disposal areas 393

19 Construction equipment needed for habitat development 394

20 Dimensions of potholes blasted with ammonium nitrate 404

21 Volume and costs of experimental potholes blasted with charges of ammonium nitrate and fuel oil (ANFO) . . 415

22 Relation of cost and surface area of 84 potholes, based on size of charge of ammonium nitrate and fuel oil (ANFO) 415

23 Dimensions and construction costs of level ditches constructed on State-owned areas in Wisconsin 416

24 Probable effects of water resource developments on lowlands and on wood duck habitat 418

25 Costs of various cattail control methods in Utah in the mid-1960's 447

26 Controlled burning costs for areas of various sizes on the Mead Wildlife Area, Wisconsin, April 1961 and 1962 448

27 Average dimensions and costs of dikes on Wisconsin wildlife areas 472

28 Size and costs of "tin whistle" spillway structures used on Wisconsin wildlife areas 472

29 Comparison of advantages and disadvantages of propagules obtained from different sources (nursery or natural stand) or of different types (seeds, tubers, rootstocks, cuttings, sprigs, seedlings, or transplants) 483

30 Some suppliers of aquatic and marsh plants in 1973 . . . 484

Tables (cont.)

31 Estimated labor required for various steps in vegetation establishment 492

32 Costs (not including seed) for wetland farming operations in Wisconsin 493

LIST OF FIGURES

FIGURE		PAGE
1	The Upper Mississippi River navigation system includes all or parts of the Upper Mississippi, Illinois, Minnesota, St. Croix, Black, and Kaskaskia rivers. Encircled numbers show location of locks and dams 1-27	6
2	Variation of velocity and sediment load with depth below water surface	57
3	Significant wave height as a function of wind velocity and effective fetch	59
4	Wave energy (H_m^2) as a function of distance from the sailing line and vessel speed (Froude number) for a cruiser model moving through shallow water (prototype depth = 5.5 ft)	61
5	Angle of repose of riprap in terms of mean size and shape of stone	74
6	Recommended side slopes of trapezoidal channels in terms of riprap angle of repose	74
7	Enviroblox on a test site in a major barge canal in comparison to an eroding riprapped revetment. Vegetation is shown established on the Enviroblox . .	89
8	Polypods, precast concrete shapes for use in protecting shores and banks	92
9	Quadripods protecting the toe and cap of a stone breakwater	93
10	Rock-filled gabion revetment construction. Filter fabric or graded granular filter may be required between the foundation and gabions	94
11	Counterfort detail for gabion placement	96
12	Terraced tube revetment. The filter fabric was sewn to the tubes at the point indicated	100
13	Tire mattress at Rogers City, Michigan, with offshore modules vented	104

Figures (cont.)

14	Timber or concrete crib bulkhead. Stones may be placed in the crib to provide habitat for aquatic organisms	106
15	Stone wing dam, showing construction details	117
16	Timber pile dike configurations including a single row of timber piles with a wire fence (upper panel), a double row of timber piles filled with rocks surrounded by a wood fence (center panel), and a cluster of timber piles (lower panel)	119
17	Jacks, showing diagrams for a typical tetrahedron (left panel) and a Kellner jack (right panel)	120
18	Typical section and installation of fences	123
19	Tree retards protect the bank by slowing the current and accumulating debris. The submerged branches provide cover for fish	125
20	Typical section and installation of timber cribs . . .	126
21	Diagram of a rock breakwater	140
22	Diagram of a Harris floating breakwater shown with the mooring arrangement and wave rider buoys	148
23	Diagram of a "Seabreaker" floating breakwater	149
24	Typical catamaran breakwater design with the basic plan (upper panel) and cross section (lower panel) . .	150
25	Prototype of an A-frame breakwater structure	151
26	Floating tire breakwater with side view of bundle of 18 tires in the water (upper panel), top view of same bundle as it is constructed on land (center panel), and top view of the same bundle ready for attachment to other bundles (lower panel)	154
27	Shore protection mat of used tires and connecting bridle	155
28	Cross-sectional view of a tethered float breakwater	159

Figures (cont.)

29	Drawings of an offset breakwater structure showing top view (upper panel), front view (lower left), and side view (lower right). All dimensions are in inches	161
30	Cross sections of airfoil or hydrofoil breakwater units. The h/c (height-to-chord or thickness) is 0.2 in the upper panel and 0.1 in the lower panel	162
31	Example of possible placement for wave-control islands in Weaver Bottoms, UMR	205
32	Schematic section (upper panel) and plan view (lower panel) of a perched beach, constructed of sand-filled bags	208
33	Schematic section of a Beach Prism installation which has just started to accrete sand	209
34	Diagram of a Wisconsin log crib for use as a fish attractor	237
35	Temporary nursery cove barrier used on Lake Tyler East and Lake Jacksonville, Texas, 1975	252
36	Schematic of a Mark VII horizontal traveling screen	261
37	Functional components of the louver diverter, which is designed to guide fish to a bypass system	266
38	The Hell's Gate paired vertical slot fish baffle	272
39	Schematic plan of a typical Borland fish lock	274
40	Cross section of spillway with deflector or flip-lip	283
41	A vortex tube sediment trap illustrating the ejection of sediment through the flow in the tube	285
42	Graph and synopsis of a typical water level manipulation plan for a warmwater reservoir	293
43	Information flow for the habitat analysis approach in which the Physical Habitat Simulation System (PHABSIM) is used	295
44	Regions of reduced flow velocity between stone dikes	299

Figures (cont.)

45	King's vanes with curved wing (upper panel) and reverse wing (lower panel)	303
46	Enclosed pool dike, a modification of a wing dam on the Missouri River	307
47	Chute dike, a modification of a wing dam on the Missouri River	308
48	L-head dike, a modification of a wing dam on the Missouri River	308
49	Decision-making process and criteria designed by the Side Channel Work Group to facilitate recommendations for opening side channels	314
50	Design of pump, pontoon, and motor used for destratification of four small lakes in eastern Ohio	321
51	Destratification system installed at El Capitan Reservoir, California	323
52	Hypolimnetic aerator design used in Mirror Lake, Wisconsin	326
53	U-tube hypolimnion aeration	327
54	Outlet structure on Twin Valley Lake, Wisconsin . . .	330
55	Side stream oxygenation system developed by Hoskings et al. (1977) that maintained 4 ppm dissolved oxygen in the Houston Ship Channel	332
56	The decision-making process for consideration of artificial aeration as a lake restoration technique	335
57	Processing methods for aquatic vegetation	356
58	Diagrams representing theoretical fish populations (underfished, planned cropping, and overfished) superimposed on segmented triangles representing the first six year classes of fish populations reduced (spaced) on a 50% mortality rate	367
59	"Beaver Pipe," a device used to control water levels in beaver ponds	409

Figures (cont.)

60 Different types of marsh containment and protection structures 411

61 Typical levees used for water retention: homogenous fill embankment (upper panel), clay core embankment (center panel), and diaphragm embankment (lower panel) 452

62 Straight drop spillway water control structure in which stoplogs and sheet piling were used 456

63 Profile of an ogee spillway 457

64 Combination of an overflow tube and gated tube in a dike for water level control 459

65 Modified drop inlet spillway in which a half-section of pipe riser with stoplogs was used 460

66 Tin whistle spillway with a vertical riser tube that is connected to a horizontal intake and discharge tube. Stoplogs in the vertical tube forces water from the impoundment to rise and spill over the stoplogs 461

67 Sketches of typical freshwater marshes near lakes or ponds (upper panel) and rivers (lower panel) in eastern and interior United States, showing plant associations that usually occur in these marshes . . . 488

Mitigation and Enhancement Techniques for the Upper Mississippi River System and Other Large River Systems

by

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ABSTRACT

Extensive information is provided on techniques that can reduce or eliminate the negative impact of man's activities (particularly those related to navigation) on large river systems, with special reference to the Upper Mississippi River. These techniques should help resource managers who are concerned with such river systems to establish sound environmental programs.

Discussions of each technique or group of techniques include (1) situation to be mitigated or enhanced; (2) description of technique; (3) impacts on the environment; (4) costs; and (5) evaluation for use on the Upper Mississippi River System. The techniques are divided into four primary categories: Bank Stabilization Techniques, Dredging and Disposal of Dredged Material, Fishery Management Techniques, and Wildlife Management Techniques. Because techniques have been grouped by function, rather than by structure, some structures are discussed in several contexts. For example, gabions are discussed for use in revetments, river training structures, and breakwaters.

The measures covered under Bank Stabilization Techniques include the use of riprap revetments, other revetments, bulkheads, river training structures, breakwater structures, chemical soil stabilizers, erosion-control mattings, and filter fabrics; the planting of vegetation; the creation of islands; the creation of berms or enrichment of beaches; and the control of water level and boat traffic. The discussions of Dredging and the Disposal of Dredged Material consider dredges, dredging methods, and disposal of dredged material. The following subjects are considered under Fishery Management Techniques: fish attractors; spawning structures; nursery ponds, coves, and marshes; fish

screens and barriers; fish passage; water control structures; management of water levels and flows; wing dam modification; side channel modification; aeration techniques; control of nuisance aquatic plants; and manipulation of fish populations. Wildlife Management Techniques include treatments of artificial nest structures, island creation or development, marsh creation or development, greentree reservoirs and mast management, vegetation control, water level control, and revegetation.

PART I. INTRODUCTION TO MITIGATION PHILOSOPHY, REGULATIONS, AND TECHNIQUES

Concern over the environmental impacts of man's activities began to grow in the 1950's and increased tremendously in the 1970's. During this period much federal legislation was enacted to protect the environment, the major piece being the National Environmental Policy Act (NEPA) of 1969 (Library of Congress 1977). For the first time all United States Federal agencies were mandated by law to protect environmental quality in all of their activities and programs. Furthermore, all Federal agencies were to develop environmental assessment procedures that could be used, along with economic and technical considerations, in any program or activity. All agencies were required by NEPA to avoid, or to minimize by restoration or enhancement, any adverse impacts their actions might have on environmental quality. NEPA directed that, to the fullest extent possible, impact analyses and mitigation recommendations by the U.S. Fish and Wildlife Service (FWS) be incorporated into any draft environmental impact statements (Library of Congress 1977).

The Fish and Wildlife Coordination Act of 1958 (Library of Congress 1977) authorized FWS to investigate "all proposed Federal undertakings and non-Federal actions proposed under Federal permit or license which would impound, divert, deepen, or otherwise control or modify a stream or other body of water and to make mitigation and enhancement recommendations to the involved Federal agency" (emphasis added; FWS 1980d). The Secretary of the Interior was directed to make recommendations "as specific as is practicable with respect to features recommended for wildlife conservation and development, lands to be utilized or acquired for such purposes, the results expected, and shall describe the damage to wildlife attributable to the project and the measures proposed for mitigating or compensating for these damages" (Library of Congress 1977). In addition, all Federal agencies must give full consideration to wildlife in all projects. Wildlife and wildlife resources are defined as birds, fishes, mammals, and all other classes of wild animals and all types of aquatic and terrestrial vegetation on which wildlife is dependent. A special section was written into the Act addressing the maintenance of adequate water levels in the Upper Mississippi River (UMR). The Act requires that the U.S. Army Corps of Engineers "give full consideration and recognition to the needs of fish and other wildlife resources and their habitat dependent on such waters, without increasing additional liability to the Government, and, to the maximum extent possible without causing damage to levee and drainage districts, adjacent railroads and highways, farm lands, and dam structures, shall generally operate and maintain pool levels as though navigation was carried on throughout the year" (Library of Congress 1977).

To develop the mitigation recommendations and impact analysis required in the Fish and Wildlife Coordination Act, FWS needed an internal document that stated its policies. The mitigation policy of FWS began to evolve in the early 1970's with a position paper related to losses of fish and wildlife habitat as a result of federal water resource developments and activities

affecting navigable waters and wetlands. This paper was general, and did not provide enough guidance for making decisions. As a result of issuance of Executive Orders on the Protection of Wetlands and Floodplain Management (U.S. President Executive Order 1977a, 1977b) and the expanding development of energy resources, the need to develop an overall policy to mitigate impacts of projects involving fish and wildlife became more critical. Consequently, FWS developed a formal mitigation policy, which addresses (1) the levels of and priorities for mitigation, (2) the techniques for impact analysis, and (3) selection among mitigation tools. Although the policy addresses impacts to fish and wildlife, habitat, and its uses, the primary purpose of the policy focuses on recommendations related to losses in habitat value. The policy adopted the definition of mitigation developed by the President's Council on Environmental Quality in the NEPA regulations, which included the following measures (Jahn 1979; FWS 1981a):

1. Avoiding the impact altogether by not taking a certain action or parts of an action.

2. Minimizing impacts by limiting the degree or magnitude of the action and its implementation.

3. Rectifying the impacts by repairing, rehabilitating, or restoring the affected environment.

4. Reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action.

5. Compensating for the impact by replacing or providing substitute resources or environments.

This policy allows Federal agencies to anticipate recommendations by FWS and to plan for measures to mitigate impacts or enhance natural resources in the area of the proposed action (FWS 1981a).

In this guide we have used the definitions, principles, and regulations of the Fish and Wildlife Coordination Act and the U.S. Fish and Wildlife Service Mitigation Policy in identifying techniques and measures for enhancing environmental resources and mitigating the impact of navigation and related activities on the fish and wildlife resources of the Upper Mississippi River System (UMRS) and other large river systems. These techniques can then be used by resource managers to reduce the impacts of present and future operation and maintenance of a navigation channel, of industrial and urban development, and of natural processes--especially sedimentation.

Mitigation, as it relates to this guide, is defined to include the first four kinds of measures. Compensatory actions or techniques are excluded. The provision for substitute resources is a mitigation technique in the sense that a certain area can be improved or reclaimed. Certainly, land could be acquired in compensation for other land on large river systems, but the

emphasis in this document is on management or mitigation techniques that can be applied directly to an existing environmental resource. An ad hoc panel of the Upper Mississippi River Conservation Committee (UMRCC) recognized this actuality for UMRS in the following statement:

> "Many of the mitigation/enhancement techniques described in the handbook, particularly management techniques, necessitate the purchase of lands adjacent to the UMRS. The lands with greatest potential for management to enhance fish and wildlife are the levee and drainage districts. These areas were historically floodplain lands which are currently farmed. The levees and water control make this possible. While many economic benefits are realized, levee and drainage districts also result in detriments to the environment (loss of flood storage capacity, loss of fish and wildlife habitat, increased sedimentation from agricultural runoff, toxicity from pesticides and herbicides in agricultural runoff). Lands could be purchased and returned to fish and wildlife purposes as a mitigative measure.
>
> "Land acquisition by itself is not an appropriate mitigation measure unless it can be shown that in private ownership, that land would be lost forever as a fish or wildlife habitat. More appropriately, funds should also be provided to manage the land to raise its value beyond that which normally would have existed without the project."

For certain areas within UMRS, acquisition is the only remaining method of preserving environmental resources. D. Urich (personal communication) described one such area: "Land acquisition is extremely important on the open river and Illinois and Kaskaskia Rivers where little habitat remains to mitigate/enhance. Agricultural levee construction, often federally subsidized, along these rivers, coupled with drainage and clearing, have reduced terrestrial habitat to narrow bands riverward of the levees. On the 170 mile stretch of the open river from Cairo to St. Louis, only 23 side channels are left. Land acquisition followed by levee construction to reduce siltation and dredging to recreate new side channels is about the only way to enhance/mitigate where little fish and wildlife habitat exists."

Enhancement refers to the improvement of a situation that is already operational; it does not include the rehabilitation or reconstruction of something that was destroyed or damaged. There could be instances, however, where a measure would be mitigating in one location and enhancing in another.

The mitigation and enhancement techniques identified in this document are considered to be those that have or can be implemented on UMRS. We have tried to indicate which techniques are most useful, least expensive, easiest to implement, and least likely to cause environmental impacts.

The techniques involve four primary categories: (1) Bank Stabilization Techniques, (2) Dredging and Disposal of Dredged Material, (3) Fishery Management Techniques, and (4) Wildlife Management Techniques. Certain techniques, such as water level control, have applicability to more than one category. When this situation arises, the measure is thoroughly discussed in one section and only briefly in others. Techniques have also been grouped by function, rather than by structure; thus, some structures are discussed in several contexts. For examples, gabions or synthetic sandbags are discussed for use as revetments, river training structures, and breakwaters.

Discussions of each technique or groups of techniques include (1) situation to be mitigated or enhanced, (2) description of technique, (3) impacts on the environment, (4) costs, and (5) evaluation for use on UMRS. Many uncommon or unique terms are used to discuss the many devices, forces, and factors involved in hydrology. Readers are advised to consult the Glossary (Part XI) for definitions of unfamiliar terms.

PART II. BACKGROUND OF THE COMPREHENSIVE MASTER PLAN FOR THE MANAGEMENT OF THE UPPER MISSISSIPPI RIVER SYSTEM

Man has always had a great interest in large rivers, especially in their use as transportation routes for himself and his goods. The UMRS is no exception (Fig. 1). This system is an economic asset of great national importance because it not only provides an efficient means of transportation, but also sustains a sizable share of the nation's wildlife and fishery resources. These interests sometimes come into conflict with each other, and this conflict stimulated the formation of the Great River Environmental Action Teams (GREAT) I, II, and III.

The Water Resources Development Act of 1976 (P.L. 94-587, 90 Stat. 2917) authorized the development, investigation, and study of a river system management plan by the GREAT teams that would incorporate total river resource requirements--navigation, effects of increased barge traffic, fish and wildlife, recreation, watershed management, dredging requirements, channel maintenance, and water quality (U.S. Congress 1976). GREAT I, established in 1974, studied the Upper Mississippi River (UMR) from Minneapolis-St. Paul, Minnesota, to Guttenberg, Iowa; GREAT II, organized in 1976, studied the stretch from Guttenberg to Saverton, Missouri; and GREAT III, established in 1977, was made responsible for the reach from Saverton to Cairo, Illinois. The Upper Mississippi River Basin Commission (UMRBC) was directed by the U.S. Congress (P.L. 95-502, October 21, 1978) to conduct and use studies to develop a management plan for UMRS (UMRBC 1981). GREAT studies were included in this mandate. The final report by GREAT I had, as its keystone element, a channel maintenance plan that detailed improved methods for disposal of dredged material (GREAT I 1980a). The GREAT II study plan centered on dredging guidelines, interagency monitoring of dredged sites, and procedures for selection of placement sites as outlined in its Channel Maintenance Handbook (GREAT II 1980b). GREAT III identified problems and discussed procedures and requirements for further study.

The directive to prepare a Comprehensive Master Plan for the Management of the Upper Mississippi River System received its impetus from the controversy surrounding the proposed construction of a replacement for Lock and Dam 26 at Alton, Illinois. The debate centered on the premise that a second lock would increase the capacity of UMRS for waterway traffic, and that this increased traffic would adversely affect the natural resources of UMRS. The technical studies recommended for generating the data needed to develop management plans for UMRS were divided into four sections: environmental studies, navigation and transportation, disposal of dredged material, and computer inventory and analysis. Work on each section was to be conducted by a specific work team.

One of the study objectives was the identification of enhancement and

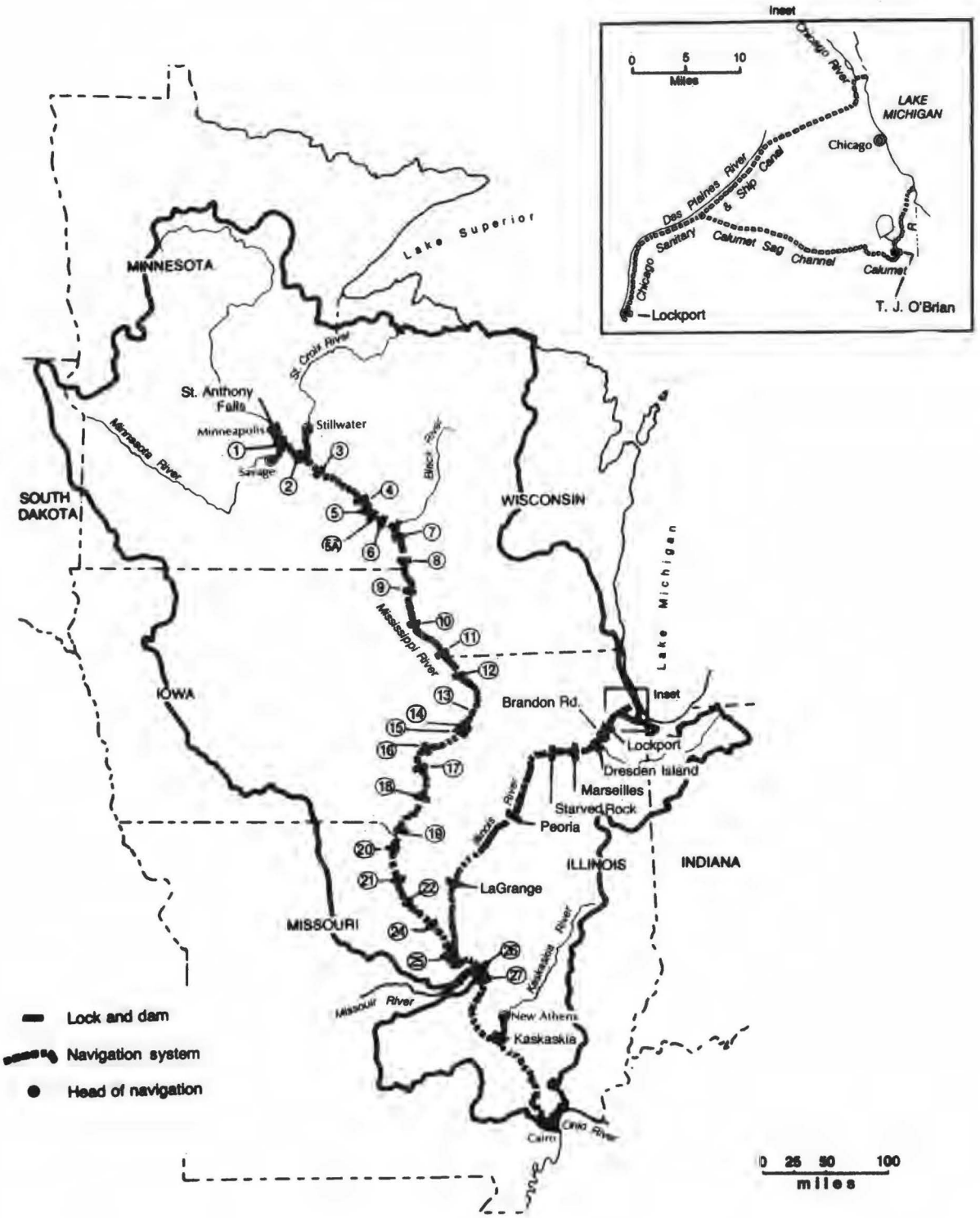

Fig. 1. The Upper Mississippi River navigation system includes all or parts of the Upper Mississippi, Illinois, Minnesota, St. Croix, Black, and Kaskaskia rivers. Encircled numbers show location of locks and dams 1-27 (UMRBC 1982).

mitigation techniques. The Environmental Subteam (later the Environmental Work Team) of UMRBC determined that a study to identify enhancement and mitigation measures was important because present and future operation and maintenance of the 9-ft channel, industrial and urban development, and other increasing demands on UMR ecosystems would ultimately result in losses of desirable fish and wildlife habitat, recreation, and cultural resources. In addition, natural processes (mainly sedimentation) accelerated by urban and rural development, would cause losses of habitat. Careful planning can minimize many of these impacts; however, significant losses of desirable resources could still continue. To overcome these situations, resource managers need to identify and use mitigation and environmental enhancement techniques to restore or replace lost habitats. The objectives of the study were to (1) identify measures that could be used for mitigation, restoration, protection, management, and enhancement of environmental resources; (2) determine the adverse and beneficial impacts of each measure identified with respect to the environment, national and regional economics, and the social character of the region; (3) determine which of the measures identified could be immediately implemented; and (4) determine costs and studies for the measures identified that would require demonstration projects to evaluate adverse and beneficial impacts.

The present document represents fulfillment of those objectives. The study included a review of more than 3000 references, which helped identify techniques currently in use, and others that are potentially useful, in mitigating the adverse effects of navigation--including both operational and maintenance aspects, and related activities of man on UMRS. Some of the measures that require further study should have demonstration projects designed to test their feasibility.

In this guide we identify numerous beneficial and adverse impacts, address the application of techniques needed to mitigate negative effects or improve specific conditions, evaluate the cost of applying different techniques, and assess the applicability of these techniques to UMRS (UMRBC 1981).

PART III. METHODOLOGY FOR ASSESSING THE IMPACTS OF MAN'S ACTIVITIES ON FISH AND WILDLIFE RESOURCES

It is not enough simply to identify the impacts of man's activities on environmental resources and to suggest mitigation techniques. Methodology must be available to quantitatively measure or assess the effects of these activities on fish and wildlife. The traditional method of assessing the value of fish and wildlife was based on the concept of "man-days of use." Under this system, any perceived damages to environmental resources were considered to have been mitigated if the number of hunting and fishing days were the same before and after a project was completed. This approach did not consider the quality or the amount of resource available (Schamberger 1979). FWS has responded to the need for impact assessment methodology by developing a habitat evaluation approach (FWS 1980b), rather than using other methods of assessment. This method, called Habitat Evaluation Procedures (HEP), standardized the means of quantifying fish and wildlife values.

The FWS has been refining the HEP method since 1974. The latest revision (FWS 1980c) should aid in evaluating the status of individual species as well as habitat types. Guidance in the selection of species to be assessed has also been improved. The latest revision can be used throughout the planning process rather than in the mitigation process alone. Guidelines in determining relative values of unlike habitats are provided for in the planning and mitigation process. Criteria in the form of habitat suitability index models have been developed to provide information on the habitat requirements of selected fish and wildlife species. The models are based on suitability indices indicating preferences. Indices have been formulated for variables found to affect the life cycle and survival of each species (McMahon and Terrell 1982; Allen 1982; FWS 1980c, 1980d). Other documents, in the form of handbooks, that can be used in conjunction with HEP include an evaluation of reservoir habitat by Aggus and Morais (1979), of aquatic habitat by Raleigh and Terrell (1978) and of terrestrial habitats by Baskett et al. (1980).

A description of the HEP method and its application was provided by Schamberger (1979):

> "The HEP methodology was designed to provide an objective and quantitative estimate of the 'value' of fish and wildlife resources. Habitat quality and quantity are integrated in a single index value called Habitat Units, based on measurable criteria in the habitat known to be important in providing the life requisites of the fish and wildlife species of interest. Measurements for a specific sample site or area are compared against ideal conditions for species found in the habitat being evaluated. The Procedures provide both a description of baseline conditions and a comparative display of any number of potential future conditions. Future-with-project conditions can be compared with each other and against baseline conditions or future-without-project conditions for

the target years desired. The difference between with-project and without-project index values demonstrates the magnitude of the impact. The HEP provide the type of display useful to planners and decision makers when evaluating environmental/economic tradeoffs."

HEP is based on the assumption that (1) habitat for selected wildlife species can be described by a Habitat Suitability Index, and (2) the Habitat Suitability Index number is linearly related to carrying capacity. However, HEP methodology does have limitations (FWS 1980b):

1. HEP presents a relatively static view of the ecosystem and thus forces long-term averaging of analyses. In some respects this is a positive feature, but it is also limiting because no assurance is given that wildlife populations will exist at the potential level predicted by habitat analyses.

2. HEP may not include all of the environmental or behavioral variables that limit wildlife populations below the habitat potential, including socioeconomic or political constraints imposed by man.

3. HEP does not provide guidance for reliable predictions of future land use projections.

4. HEP is applicable only for the species evaluated and does not directly relate that species with other ecosystem components. HEP conceptually addresses only the issues of populations of certain species and habitat; biological integrity and environmental values are not as well covered.

These limitations are not peculiar to HEP, but apply to many habitat-based assessment methodologies and other resource planning procedures as well.

The various steps required in HEP are as follows: (1) determination must be made whether the procedures are applicable to a particular study; (2) if they are applicable, the study limits need to be defined, including delineation of the study area, determination of cover types, and selection of species to be evaluated; (3) baseline conditions must be described in terms of Habitat Units, (4) future habitat conditions must be projected in terms of Habitat Units, and (5) compensation plans must be developed, if appropriate (FWS 1980c). The FWS has been using this methodology to evaluate many water resource development projects of the U.S. Army Corps of Engineers, Soil Conservation Service, and Bureau of Reclamation (formerly the Water and Power Resources Service).

When HEP assessments do not fully cover the important biological characteristics of an area, FWS uses supplemental data, other methodologies, or professional judgments to make mitigation recommendations.

In situations where instream flows are important in determining habitat value, resource managers may consider using Instream Flow Incremental Methodology to develop mitigation recommendations. The FWS has developed this methodology "to quantify the impact on fish habitat resulting from incremental modifications in stream flow" (FWS 1979a). The Cooperative Instream Flow Service Group (IFG), Fort Collins, Colorado, developed this system. Information gathered illustrates how changes in stream flows affect physical aspects of fish habitats. The information is then developed into an index of surface area of usable habitat for each section of river or stream studied. The index allows comparison with optimal habitat of the same surface area and helps predict how suitable a stream or river habitat would be for certain species of fish and their various life stages. Calculations are made on the area of stream required to provide good fish habitat, and this area is compared with the total surface area. The comparison creates the "weighted usable area" index. Using computer manipulations, one can calculate the weighted usable area for each of several stream flows.

The IFG Incremental Methodology is based on the following assumptions (FWS 1979a):

1. The physical variables of depth, velocity, and temperature, as associated with the substrate, are assumed to be the most important fish habitat variables when one is considering changes in stream flow regimes.

2. The structure of the stream channel will not be altered by changes in flow regimes.

3. The probability that fish will choose to live in any particular hydraulic dimension (such as depth or velocity) is independent of the probability that they will choose to live in any other dimension.

4. A selected segment of river may be modeled by using a representative sample reach of that river.

5. There is a direct relation between calculated suitability of habitat and the use of the habitat by selected fish.

The IFG Incremental Methodology, as a result of this approach, can provide solutions to problems that could not be solved with other inflow methodologies. It allows for predictions of the impact that a given change in flow will have on the fish habitat, various fish species, and each life stage for any month of the year. Minimum flow concepts used previously did not predict how a reduction of 50 cfs would affect fish; IFG Incremental Methodology can supply an answer. This methodology allows fishery biologists and hydraulic engineers to analyze fishery data in conjunction with stream simulation models.

The IFG Incremental Methodology is not designed to provide solutions to several types of problems (FWS 1979a):

1. It does not address reservoir, lake, or estuarine problems. It is specifically intended for use in streams and rivers.

2. It is not designed to generate a "minimum flow" recommendation. However, it quantifies and predicts impacts associated with various flows, thereby permitting the decision-maker to choose among alternatives.

3. It does not predict the number or weight of fish that will be produced in a stream under given conditions. It does predict and quantify changes in the suitability of a specific habitat for various species and life stages under differing flow conditions.

4. To date, only physical aspects of a stream have been treated by the IFG Incremental Methodology. The methodology does not consider chemical or water quality variables.

Because benthic invertebrates are important in the food chain of fishes, Herricks and Furnish (1980) considered extending the IFG concept of incremental methodology to benthic invertebrates by evaluating the data and literature available. Although data are available, they must be evaluated from a number of perspectives before they can be used to develop relations between habitats and organisms.

No single methodology is likely to be adequate for evaluating instream flow needs for all species of fish; however, the basic approach should be the same. Methodologies should eventually become standardized for groups of species with similar biological and physical needs. Such standardization would provide more credibility to the establishment of maintenance flow criteria (White 1976).

The IFG Incremental Methodology has been standardized to some extent by a computer simulation model called the Physical Habitat Simulation System (PHABSIM). This system can portray the variation of physical habitat as a function of flow and the variation of physical habitat over time, and can be combined with water quality and temperature information to provide a total habitat analysis (Milhous and Grenney 1980). A manual has been developed to deal with the analysis of the physical habitat as it relates to flow (Milhous et al. 1981).

The FWS developed methods to assess the impacts of multiple, rather than single, land or water projects within an entire river basin. Porter et al. (1979) described one such approach in which a combination of techniques were

used on the Yampa River basin in northwest Colorado. A Geographic Information System was used to manipulate map detail by computer rather than by manual methods. Locations of projects were overlaid on composited wildlife maps to determine possible conflicts. Methods were developed that could quantify and compare relative impacts of projects on wildlife and that could predict changes in fish habitat as a result of various projects. Porter et al. (1979) stated that the combination of these methods provided FWS with the capability to (1) "address incremental and cumulative impacts on fish and wildlife of multiple development actions in basin-wide settings," and (2) "evaluate alternative development scenarios from the standpoint of impacts on fish and wildlife." The authors recognized that these methods required further development, refinement, and analysis of cost effectiveness.

Other habitat evaluation systems have been developed, but are not widely accepted or institutionalized (FWS 1981b; Yorke 1978; Galloway 1978). The major methodologies in use by FWS at the present time are HEP and IFG Incremental Methodology (FWS 1981a).

PART IV. SUMMARY OF THE EFFECTS OF NAVIGATION, AND OF THE CONSTRUCTION, OPERATION, AND MAINTENANCE OF A NAVIGATION CHANNEL ON THE UPPER MISSISSIPPI RIVER SYSTEM

A summary of the effects of navigation and the construction, operation, and maintenance of a navigation channel on UMRS is required to enable an understanding of the need for the various mitigation and enhancement measures identified in this guide. Even though discussions of each technique describe the "situation to be mitigated or enhanced" and "impacts on the environment," an overview of the total impact on UMRS is needed.

The various methods used to construct and maintain an adequate navigation channel on UMRS have resulted in both adverse and beneficial impacts on the physical, chemical, and biological features of the area. Topics addressed in this Part include clearing and snagging; channel enlargement, dredging, and disposal of dredged material; locks and dams; river training structures; bank stabilization; flood protection levees; water level regulation; and adverse effects related to boat traffic.

Channelization is also examined in a general and total approach, to provide comprehensiveness. According to Parrish et al. (1978) "channelization in its various forms (1) increases turbidity; (2) destroys natural substrate habitat; (3) creates wide, shallow, unnatural flows; (4) causes excessive illumination, water temperatures, and pH levels; and (5) creates topographical difficulties for upstream migration." General effects of channelization as they relate to UMRS are discussed in the environmental impact statements on the 9-ft channel and the study reports by GREAT I and GREAT II.

The following works concern the general effects of channelization: Arner et al. (1976), Barclay (1980), Benke et al. (1979), Benson and Weithman (1980), Bragg and Tatschi (1977), Bulkley (1975), Bulkley et al. (1976), Carey (1966), Corning et al. (1975), Degenhardt (1973), Edwards (1977), Fredrickson (1979), Griswold et al. (1978), Headrick (1976), Huish and Pardue (1978), Hunt and Graham (1975), Keller (1976, 1978), King and Carlander (1976), Lund (1976), Maki et al. (1980), Menzel and Fierstine (1976), Morris et al. (1968), Nord and Schmulbach (1973), Norton et al. (1978), Porter (1977), Sanders (1976), Schmal and Sanders (1978), Schmulbach (1974), Simons (1979), Speir et al. (1976), Stern and Stern (1980a, 1980b), Timbol and Maciolek (1978), Winner and Simmons (1977), and Zimmer and Bachmann (1976).

CHAPTER 1. CONSTRUCTION, OPERATION, AND MAINTENANCE OF A NAVIGATION CHANNEL ON THE UPPER MISSISSIPPI RIVER SYSTEM

The development of a navigation channel on UMRS has been a continual process of construction, maintenance, and river training efforts since the early 1800's.

In 1824 Captain Henry Shreve was commissioned by Congress to remove tree snags from the main channel of the Mississippi River. This work included the removal of trees as much as 100 to 200 ft back from the bank to eliminate the source of snags. In one 3-year period, for example, the removal of 75,000 trees from the bankline resulted in banks being changed from vertical to sloping.

In 1878 the U.S. Army Corps of Engineers was authorized to create a 4.5-ft navigation channel that involved channel training devices such as wing dams and revetments. These structures tended to direct the river flow into one main channel.

Later, in 1907, the navigable depth was extended to 6 ft between St. Louis, Missouri, and St. Paul, Minnesota. This deepening was accomplished by constructing two locks at the Rock Island Rapids and by dredging, in addition to increasing the construction of river training structures.

It was not until a project of the 1930's--the construction of a 9-ft channel--that the most significant modification of the Upper Mississippi River (UMR) occurred. Beginning with authorization in 1930 and continuing until the last navigation dam was closed in 1940, the upper reaches of UMR were systematically converted from a free-flowing river to a series of 27 pools. This change, coupled with the construction of additional revetments and channel maintenance dredging, produced the most apparent changes in the biology of UMR associated with navigation (Sinning and Zimmerman 1979).

The lower reaches of UMR (St. Louis, Missouri, to Cairo, Illinois), usually called the Middle Mississippi River, experienced a different type of development after 1927 to achieve a 9-ft channel. Before that time, both stretches followed the same pattern of contraction, revetment, and dredging to maintain the navigation channel desired (Simons et al. 1981b; Lagasse 1975). In 1927, when a 9-ft channel (300 ft wide) was authorized for the Middle Mississippi River, work began on lengthening the dikes and increasing their numbers. By 1944, dikes had been built that constricted the width of the river to 2000 to 2500 ft. An 1800-ft contraction plan was adopted that required the construction of more than 800 timber pile dikes; however, a 9-ft depth could not be maintained during low-flow periods. By 1965, stone had

been added to the timber pile dikes, but a 9-ft channel still could not be maintained consistently. After 1965, emergent stone wing dams were built to contract the width to 1500 ft. By 1973, over 800 wing dams with a total length of 91 miles had been built in 195 miles of river. In addition, 122 miles of revetments were developed to control bank erosion, and mainline levees lined almost the entire Middle Mississippi River for flood protection (Lagasse 1975; Simons et al. 1981b).

There are a total of 3166 wing dams on the upper and lower reaches of UMR, of which 2438 are submergent and 728 are emergent. The Middle Mississippi River contains 91% of the emergent wing dams on UMR. The rest of UMRS has only a few wing dams. The Illinois River has 25 submerged and 7 emergent wing dams (UMRBC Environmental Work Team 1981d).

The UMRS navigation system, in addition to UMR, normally includes all or parts of the Illinois, Minnesota, St. Croix, Black, and Kaskaskia rivers (Fig. 1). The navigable portions of these rivers were described as follows by the UMRBC Environmental Work Team (1981b): "Tributaries included in the study are the Illinois Waterway in Illinois, with 327 miles of navigable water and eight locks; the Kaskaskia River in Illinois, with 24.8 miles of navigable water and one lock; the Black River in Wisconsin, with 1.4 miles of navigable water; the St. Croix River in Minnesota and Wisconsin, with 24.5 miles of navigable water; and the Minnesota River in Minnesota, with 21.8 miles of navigable water. The latter three tributaries have no locks and are maintained by dredging."

1.1. CLEARING AND SNAGGING

Clearing and snagging involves the removal of vegetation, rocks, and other debris from channels and riverbanks to drain floodplains for agriculture, to protect people from floods, or to create and maintain a navigable channel. The primary reason for clearing and snagging in the 1800's on the UMR was to make the river suitable for navigation (Rasmussen 1979).

Yorke (1978) described the impacts of clearing and snagging on certain physical and chemical characteristics of rivers as follows:

Depth and stage: Removal of vegetation and other obstructions in channels tends to create more uniform depths. Pools formed by turbulence from water flowing around or over logs, gravel berms, or other obstructions gradually disappear. Depth of overbank flooding decreases due to improved conveyance of the main channel.

Water surface area: Removal of organic debris, gravel bars, and small islands increases water surface area. However, continued clearing eventually may train the stream to a deep, narrow channel with less surface area than the

original channel.

Channel configuration: The channel becomes more uniform. Gravel bars, scour holes, and protected pockets of slack water are eliminated. Edge habitat is reduced.

Velocity: Water velocities become more uniform. Pools decrease in cross-sectional areas and velocities increase when debris, gravel bars, or small islands are removed. Velocities decrease in the previous riffle areas as the cross-sectional area increases.

Temperature: Extensive removal of instream and streambank vegetation increases insolation and the variability of water temperatures. Selective snagging of stumps and deadheads does not affect temperature appreciably.

Suspended solids: Suspended solids at the site and downstream increase temporarily during the removal operations. Clearing vegetation from the banks could disturb the stability of the banks and result in a long-term increase in suspended solids.

Bed material: Removal of downed timber and other obstructions on the streambed may eliminate much of the instream cover and preferred substrate of aquatic organisms. Removal of vegetation on the streambanks eliminates the primary source of detritus for benthic organisms. Clearing has only a relatively minor effect on the movement of bed material unless the armor layer of the bed material is inadvertently removed. If this occurs, significant local scouring may follow. If such scouring results in the removal of extensive deposits of bed material, the increase in bedload may be substantial.

Dissolved substances: A relatively short-term increase in total dissolved solids, nutrients, and pesticides can be expected when bottom sediments are disturbed during removal operations. An excessive increase in nutrients may increase biochemical oxygen demand and cause an oxygen deficiency downstream.

Light transmissivity: A short-term decrease in light transmissivity occurs at the site and downstream during actual clearing operations. A long-term decrease in transmissivity may occur if the operations involve extensive removal of streambank vegetation. This removal results in increased bank erosion and higher sediment concentrations.

Flow variability: There is no impact on flows unless clearing involves overall deepening of the channel; the rapid drainage of adjacent lands may then significantly decrease low flows.

Under the Environmental and Water Quality Operational Studies program, the U.S. Army Engineer Waterways Experiment Station at Vicksburg, Mississippi, is identifying and assessing the environmental impacts of waterway projects such as clearing and snagging. These projects are being studied in efforts to

develop improved design and construction procedures that will reduce the environmental impacts of clearing and snagging (J. R. Niemi and F. D. Shields, Jr., personal communication).

Lubinski et al. (1981) and Marzolf (1978) found potential ecological impacts, but they did not consider the data adequate to yield quantitative predictions of the biological effects of clearing and snagging. Lubinski et al. (1981) stated that potential biological impacts depend on the operating philosophy of the performing agency. Clearing and snagging modify certain physical factors that, in turn, can have a potential biological effect. The reduction of physical habitat diversity causes a decreasing hydraulic roughness of stream channels and has several adverse results: (1) downstream movement of decomposing organic matter, (2) reduction of spawning and nursery habitat, (3) reduction in fish cover and shelter, (4) disruption of fish territoriality and orientation, and (5) reduction in plankton production because of the reduction of quiet-water areas. The removal of canopy increases light, elevates stream temperatures, encourages growth of benthic algae and macrophytes, and decreases organic matter input from terrestrial vegetation.

The associated change in stream substrate can produce changes in the production and kinds of benthic algae and macrophytes and in the distribution and species composition of benthic macroinvertebrates. The removal of vegetation results in (1) reduced habitat for macroinvertebrates, (2) reduced habitat for the accumulation and decomposition of organic matter, which results in less food for macroinvertebrates, (3) reduced diversity and amount of fish food, (4) reduced fish cover and spawning habitat, and (5) disruption in fish territoriality and orientation (Marzolf 1978).

Although most of the information and analyses in this section on the impacts of clearing and snagging were incorporated from Lubinski et al. (1981), Marzolf (1978), and Yorke (1978), the following references contain pertinent information that augments this summary: Funk and Robinson (1974), Hansen (1971), Hickman (1975), Lund (1976), and Strauser and Long (1976).

1.2. CHANNEL ENLARGEMENT, DREDGING, AND DISPOSAL OF DREDGED MATERIAL

Channels are often enlarged to increase their capacity to convey water or provide drainage. Instream mining and maintenance dredging for navigation result in enlarged channels.

Yorke (1978) described the impacts of channel enlargement and dredging on certain physical and chemical characteristics of rivers as follows:

Depth and stage: Channel enlargement eliminates the diversity of water depths

associated with natural meandering channels. Pools and riffles are replaced by uniformly deep or uniformly shallow reaches of channels. Enlarged channels carry a greater percentage of flow during floods, and thus reduce the depth and duration of floodplain overflow. If the channels are deepened, flows are lowered during dry periods, thereby promoting the drainage of adjacent wetlands.

Water surface area: Deepening creates nearly uniform surface areas throughout the year. The shallow-water zone near the banks, which is exposed during dry periods and inundated during wet periods, is reduced in area. Widening increases surface area and variability of the water surface area. Disposal areas resulting from excavations to restrict the channel reduce the amount of the floodplain area that is subjected to periodic flooding.

Channel configuration: Enlargement creates uniform conditions. Pools, riffles, undercut banks, and other diverse habitats are usually eliminated.

Water velocity: Mean water velocities are reduced because the cross-sectional area is increased. Velocities become more uniform throughout the cross section because areas of high and low velocity are eliminated.

Temperature: Widening increases water temperature and the range of temperature because of the greater water surface area, reduced velocity, and elimination of shade by removal of streambank vegetation. These actions increase the effect on insolation. Deepening has little effect on temperature if streambank vegetation is not disturbed. However, the disposal of excavated or dredged material in the adjacent floodplains will increase water temperature because streamside vegetation is usually removed or destroyed by construction equipment or suffocated by the deposits.

Suspended solids: During the construction phase of channel enlargement, the concentration and discharge of suspended solids at the site and downstream are temporarily increased. The result is an increase in the rate of sediment deposition in the channel or floodplain, or both, at downstream sites. Sediment discharge decreases after construction, but may persist at higher than normal levels for a number of years as the stream channels adjust to new flow regimes. Certain reaches of deepened channels may become sinks and aggrade rapidly with fine sand and silt.

Bed material: Both widening and deepening disrupt the equilibrium of the stream channel, disturb the bed material, and create a period of constantly changing bed conditions. Deepening removes the armor layer of the streambed and increases the movement of bed material until large particles restabilize the surface. Channel widening may increase bedload as additional fine bed material becomes available for transport, or it may decrease the bedload and cause deposition because the increased cross-sectional area severely reduces the competence of the channel for transporting bed material. Removal of organic material from the bed reduces food sources and the diversity of substrates available to benthic organisms. Removal of streamside vegetation during construction may substantially reduce the source of detritus that is added to the system

annually.

Dissolved substances: Construction increases the total dissolved solids eroded from newly exposed soils. Nutrients, pesticides, heavy metals, and other substances that were bound to bottom sediments may be released to the system. The disturbance of organic bed material and the release of nutrients may increase the biochemical oxygen demand and cause oxygen deficiencies downstream. Enlargement, particularly deepening, may promote an increase in agricultural drainage and concomitant increases in salts, nutrients, and pesticides during surface runoff. Increased channel capacity reduces overflow and use of the floodplain for assimilation of organic nutrients and wastes.

Light transmissivity: Construction activities reduce light transmissivity at the site and at downstream locations because of increased sediment loads. This condition may persist for many years as streambanks adjust to new flow regimes. A more efficient channel and ancillary drains increase runoff, and the accompanying silt and clay load reduces light transmissivity.

Flow variability: The range in water discharge increases. Peak flows are higher and low flows are lower. Improved conveyance causes floodwaters to move quickly through enlarged channels and concentrate at some point downstream. This faster runoff results in higher peak discharges and shortened periods of flooding. Deepening a channel increases drainage from adjacent floodplains, which in turn increases the rate of groundwater discharge and decreases the amount of water available to sustain the base flow during dry periods. The deepened channel also may penetrate through an impermeable or semipermeable layer beneath the stream bed and dewater the channel as a result of water being lost to the groundwater.

Under their Environmental and Water Quality Operational Studies program, the U.S. Army Engineer Waterways Experiment Station at Vicksburg, Mississippi, is identifying and assessing the environmental impacts of waterway projects such as channel enlargement. These projects are being studied in efforts to develop improved design and construction procedures that will reduce the environmental impacts of channel enlargement (J. R. Niemi and F. D. Shields, Jr., personal communication).

Morton (1977) reviewed the physical, chemical, and biological effects of dredging and disposal in estuaries. Lubinski et al. (1981) discussed the impacts of dredging and dredged spoil disposal on the physical, chemical, and biological aspects of UMRS.

1.2.1. Physical Effects

Three of the most important physical effects of dredging and disposal of dredged material are filling of backwaters and main channel border areas,

changes in bottom topography, which result in changed circulation patterns (e.g., channel currents, induced shoaling, reduced flushing rates), and filling in of a dredged channel from the erosion of a disposal site and redistribution of the sediments. A lesser effect of dredging and disposal is increased turbidity, but it is temporary and considered to be relatively unimportant.

1.2.2. Chemical Effects

A critical chemical effect of dredging and dredged material disposal is the release of contaminants from polluted dredged materials. Such releases can result in bioaccumulation, direct toxicity to aquatic organisms, or reduced dissolved oxygen levels (Morton 1977). On the other hand, adverse effects from contaminants are highly site-specific. Lubinski et al. (1981) evaluated five dredging operations that did not result in significant increases in contaminants.

1.2.3. Biological Effects

Lubinski et al. (1981) reported that dredging and disposal of dredged material create impacts on the aquatic biota through (1) habitat destruction, (2) physical damage and burial of benthic organisms, (3) increased exposure to toxic contaminants, and (4) dissolved oxygen stress caused by additional oxygen demand created by resuspended sediments and by the lowering of photosynthetic rates that results from increased turbidity. GREAT I and II determined that the most destructive impacts on UMR are habitat destruction from disposal of dredged material and the movement of dredged materials into backwater areas, or blocking flow into them. As a result, flow rates and dissolved oxygen in backwater areas have often been reduced and sedimentation has been increased (Lubinski et al. 1981).

Most of the information and analyses in this section on the impacts of channel enlargement, dredging, and disposal of dredged material were incorporated from Lubinski et al. (1981), Morton (1977), and Yorke (1978). The following references also contain pertinent information that augments this summary: Allen and Hardy (1980), Buchanan (1976), Farnworth et al. (1979), Gammon (1970), GREAT I (1980a, 1980b, 1980f, 1980g, 1980h, 1980i, 1980j), GREAT II (1980a, 1980b, 1980c, 1980f, 1980h), Held (1978), Herbich (1979), Johnson (1976a), Lagasse (1975), Lohnes et al. (1979), McNutt et al. (1976), O'Connor et al. (1977), Saucier et al. (1978), Shuba et al. (1978), Solomon et al. (1974), U.S. Army Engineer Waterways Experiment Station (1976), and Wright (1978).

There are additional references on contaminants in dredged material and

sediment: Anderson (1978), Blom et al. (1976), Brannon (1978), Brannon et al. (1978), Burks and Engler (1978), Chen et al. (1976), Fields (1976), Marking et al. (1981), Nathans and Bechtel (1977), Neff et al. (1978), Nicholas and Thomas (1978), Peddicord et al. (1980), Peddicord and McFarland (1978), Peterson and Randolph (1977, 1979, 1980), Schnoor et al. (1980), and Sparks and Smith (1979).

1.3. LOCKS AND DAMS

Locks and dams are low head structures on major rivers that are operated to maintain constant water depths for navigation (Yorke 1978). Locks and dams were constructed in the 1930's on UMR from the head of navigation at Minneapolis-St. Paul, Minnesota, to St. Louis, Missouri, and have been in operation since 1940.

Yorke (1978) described the impacts of locks and dams on certain physical and chemical characteristics of rivers as follows:

Depth and stage: The construction and operation of these navigation structures increases and stabilizes water depths in the channel because the dams are operated to maintain fairly constant pool elevations. Flood stages are increased slightly because of constriction of the channel by the tie-back levees and locks. Aggradation of the channel near the head of each pool decreases water depths and degradation immediately below each dam increases water depths.

Water surface area: The pools created by locks and dams increase water surface area over that of the natural channel. The variation in surface area decreases because nearly constant pool elevations are maintained for navigation. Overbank areas subject to flooding are increased unless levees are used to contain the pools during flood stages.

Channel configuration: Regulation of flows through the structures creates uniform channel configurations. Continuous pools eliminate riffle habitat. Inundation of the floodplain in the lower reach of each pool increases the shallow-water zone and the total edge habitat.

Velocity: Water velocities are lower for all stages and all points on the affected reach of river, except in the immediate vicinity of the locks and dams. The impact is greatest at low flow, when there is little water surface gradient in the pools. At higher stages, the backwater effect of the structures is drowned out and water surface gradient and velocity are only slightly less than they were without the structures. High-flow velocities in the immediate vicinity of the structures are higher than normal because the structures constrict the channel.

Temperature: Water temperature probably increases because of an increase in surface area and clearing of overstory vegetation in the permanent pool

area. Thermal stratification usually does not occur because the pools are generally shallow and through-flow is sufficient to maintain adequate mixing.

Suspended solids: Construction of locks and dams and clearing of vegetation in the pool areas causes a temporary increase in discharge of suspended solids. This increase may cause sedimentation problems at downstream points. Pools formed by these navigational structures eventually retard sediment movement. Much of the sand normally transported through the system settles out in the main channel, backwater channels, and sloughs. Most of the silt and clay passes through the pools.

Bed material: The decrease in the energy gradient and associated water velocity as a result of the navigational structures causes a decrease in the movement of bed material in the river. The coarse material settles out at the head of each pool, leaving only the fine sand to move as bedload. The fine bed material throughout most of the river reach is relatively unstable and a poor substrate for aquatic organisms.

Dissolved substances: Construction of locks and dams on a river causes a temporary increase in total dissolved solids because of erosion at the construction site. Lower dissolved oxygen levels may be a long-term result because of reduced aeration in the navigation pools.

Light transmissivity: There probably is a significant decrease in light transmissivity during construction of locks and dams. Long-term effects are minor. Less light penetrates to the channel bed because depths are increased, but this loss is probably compensated for by an increase in the shallow-water zone in the floodplain area inundated by the navigational pool.

Flow variability: The structures have little effect on flow variability because the storage capacity of most navigational pools is small. Peak discharges may be reduced and attenuated slightly. Low flows may be reduced because of evaporation from the greater water surface area of the pools.

Simons et al. (1981b) investigated the effects of the locks and dams on the physical aspects of UMR, and Lubinski et al. (1981) reviewed the physical, chemical, and biological impacts of the locks and dams on UMR.

1.3.1. Physical Effects

Simons et al. (1981b) made the following points in their analysis of the physical response of UMR to the construction of the locks and dams:

1. The construction of the locks and dams during the late 1930's resulted in an immediate widening of the river due to inundation

of a portion of the floodplain.

2. The long-term effect of the locks and dams has been to increase the river width immediately upstream from a lock and dam and to slightly narrow the river immediately downstream. In the period between 1930 and 1973, the riverbed degraded below the locks and dams, since much of the sediment that would have normally been delivered was being trapped or dredged in upstream pools.

3. After construction of locks and dams, the main channel surface area decreased in the upper subreaches of the study pools, but increased in the lower subreaches.

4. In response to lock and dam construction, the number of islands in the main channel initially increased between 1929 and 1938, although the total island area decreased. This response was mainly due to inundations of the lower areas of large islands and floodplains. Between 1938 and 1973, however, the number of islands generally decreased and total island area increased as a result of sedimentation and coalescence of small adjacent islands.

5. The riverbed areas of the upper subreaches of the pools decreased between 1929 and 1972 because of encroachment of floodplains. However, riverbed areas of the lower subreaches increased because parts of the floodplain and islands were submerged.

6. After construction of the lock and dam systems, the non-main channel areas in the lower subreaches of each pool greatly increased due to inundation of marshlands. However, after more than 40 years of operation of the 9-ft navigation channel, the water areas outside the main channel are slowly being filled. The surface area is decreasing and the bottom is aggrading. The U.S. Soil Conservation Service pointed out that, since construction of the lock and dam system, periodic floods no longer sweep accumulations of sediment downriver. The natural processes of river change are no longer subject to the destructive forces of floods. The result is a rapid loss of water areas due to sediment inflow, deposition, and accumulation.

7. In each pool, the riverbed elevation in the main channel degraded immediately downstream from the lock and dam because sediment was trapped in the upstream pool. However, the riverbed aggraded above and near the primary control points because operation of the lock and dam system reduced the sediment transport ability of flow in the lower subreaches. Aggrading portions of the river are the reaches that have required extensive dredging to maintain channel depth.

8. Annual minimum stages are lower now than in the past at locations immediately below locks and dams and are higher at locations immediately above them.

9. The locks and dams create a slight backwater effect during floods.

10. The river position has remained basically unchanged.

11. Discharges were not significantly changed.

12. The velocity of the water decreased at low flow and remained unchanged at high flow.

Lubinski et al. (1981) also reviewed physical effects of the locks and dams on UMR and arrived at the following conclusions:

1. A major effect of pool construction was a decrease in current velocities.

2. Such decreases in velocities usually result in a lower concentration of suspended solids in the main channel and increased sedimentation rates in off-channel areas. These generalizations, however, do not hold in all reaches or habitats of UMRS or at all flow rates. Turbidity has also increased in many reaches of UMRS.

3. As a result of lock and dam construction, sediments were accumulating at an average rate of 1 in. per year in selected areas between Pools 3 and 10 of UMR. Most of the sediment deposition occurs where the current is slowest, such as in the downstream portion of the pool and backwater areas.

4. Long-term effects of pool construction have resulted in an increase in island development upstream from locks and dams, in addition to the silting of backwater lakes and marshes.

5. The temperature regime of a stream can be greatly altered by impoundment. However, no comparative pre- and post-impoundment data related to water temperatures in UMRS appear to be available.

1.3.2. Chemical Effects

The construction of locks and dams on UMRS seemingly has had no measurable effect on dissolved oxygen. Because of lack of data, no assessment could be made of the impact on river nutrient quality (Lubinski et al. 1981). General information on the impacts of locks and dams on chemical and physical

characteristics of rivers was given by Yorke (1978).

1.3.3. Biological Effects

Lubinski et al. (1981) arrived at the following conclusions regarding the effects of locks and dams on the biota of UMRS:

1. In general, lentic species were selected for, and lotic species were selected against. Many lentic species may be eliminated.

2. Because the locks and dams broadened the river, increased its surface area, corrugated it, and supplied nutrient to it, more fish inhabit UMR below Lake Pepin, Minnesota, than lived there before the arrival of the white man.

3. The degree to which locks and dams affect fish migration patterns depends on the timing, magnitude, and duration of floods that enable fish to circumvent these barriers.

4. The life cycles and distribution of some mussels with host-specific glochidia have probably been changed, largely because the migratory patterns of their fish hosts have been altered.

5. Changes in aquatic plants, waterfowl, and mammals that were related to pool construction have been noted. In particular, inundation probably reduced the low-flow drying periods of marshes that earlier helped "rejuvenate" marsh soils. Many established submergent plant associations were replaced with pondweeds after inundation and some reed stands in Pools 5 and 8 disappeared because of their need for occasional dry periods. Many acres of bottomland timber have been converted to marsh after inundation. In general, aquatic furbearing animals increased in UMRS after inundation, but dryland furbearers decreased. In addition, waterfowl increased remarkably, but upland game birds decreased.

Although most of the information and analyses in this section on the impacts of locks and dams were incorporated from Lubinski et al. (1981), Simons et al. (1981b) and Yorke (1978), the following references contain pertinent information that augments this summary: Bellrose et al. (1976, 1979), Brunet (1977), Chen and Simons (1979), Claflin (1973a, 1973b), Eckblad et al. (1977), Eddy and Underhill (1974), Fremling et al. (1973), Fuller (1978, 1980a, 1980b), GREAT I (1980d), GREAT II (1980g, 1980i, 1980k), Green (1960), Hubley (1963), Madden (1974), McHenry and Ritchie (1976, 1977, 1978), McHenry et al. (1976, 1978a, 1978b, 1980), Nakato et al. (1979), Solomon et al. (1975), Sparks (1975b, 1978), Sparks et al. (1979), U.S. Army Corps of Engineers, North Central Division (1978), U.S. Army Corps of Engineers, St.

Louis District (1979), and U.S. Army Corps of Engineers, St. Paul District (1974).

The following references concern the general effects of impoundment: Avakyan (1975), Baxter and Glaude (1980), Benson (1980), Butts and Evans (1978, 1979), Ciliberti (1980), Cooper and Hubbell (1967), Dunst (1969), Gill (1979), Hammad (1972), Kimsey (1957), Kittrell (1959), Lagler (1969), Lindstrom (1973), Morris et al. (1968), Petts (1980a, 1980b), Purcell (1939), Ragan (1972), SCOPE Working Group on Man-made Lakes (1972), Spence and Hyn (1971a, 1971b), Walburg (1976), Whitley and Campbell (1973-1974), and Wright (1968, 1978).

1.4. RIVER TRAINING STRUCTURES

River training structures (wing dikes, trail dikes, closing dams, stone wing dams, wing deflectors, spur dikes, groins, and bank protectors) have been built in a variety of configurations and materials. Generally, most are wing dams or dikes that are built perpendicular to the flow or angled slightly downstream to increase water flow and scouring in the navigation channel. Another common structure is a closing dam that blocks a side channel and diverts flow from backwater areas into the main channel (Turner 1969). Use of river training structures constricts the river and supplants the natural river meandering process. Training structures have been constructed with rock, timber, concrete, and metal.

Yorke (1978) described the effects of perpendicular river training structures on selected physical and chemical characteristics of rivers as follows:

Depth and stage: Perpendicular river training structures constrict and deepen channels by concentrating flow in the center of the channel. Channel areas between the ends of the structures and the banks gradually become shallower as sediments accumulate in the slack water area behind the structures. River stages are lower during low flows because the center channel is degraded and higher during floods because the structures and accumulated sediments reduce conveyance capacity of the channel.

Water surface area: Constriction of channels by perpendicular river training structures and sediment deposition behind the structures reduce water surface area during normal flows. The area inundated during floods may be greater because the conveyance capacities of the main channels are reduced by structures and more water is conveyed in the floodplain.

Channel configuration: Perpendicular river training structures initially increase the diversity of stream channels. Deep water occurs in the center channel, slack water behind the structures, scour holes at the end of structures, and shallow water in deposition areas behind the structures.

Edge habitat increases. However, sediment deposition behind the structures eventually reduces the size of the channel and creates a deep, narrow, uniform channel.

Velocity: Velocities increase in the center of the channel, and little or no velocity remains behind the structures. Slack water areas eventually fill with sediment, resulting in uniform velocities throughout the reach affected by the structures.

Temperature: Perpendicular river training structures have little effect on water temperature. Temperatures may increase if extensive streambank clearing is required for equipment access.

Suspended solids: A local increase in suspended solids at the site occurs during construction. The increase probably remains undetectable downstream. Slack water immediately downstream from the structures induces deposition of fine suspended sediments and, in turn, probably reduces the total discharge of suspended solids and sedimentation at downstream points.

Bed material: The purpose of perpendicular river training structures is to constrict flow and to develop a self-scouring channel. Bedload increases in the constricted channel area. Continuous sediment deposition occurs in the channel area buffered by wing dikes. As a result, the bed material is in a constant state of change and provides poor substrate for aquatic organisms. However, rocks or timbers that form the structures provide substrate for aquatic organisms.

Dissolved substances: Perpendicular river training structures generally cause channel degradation that results in lower stages during low flow periods. The lower stages can cause an increase in drainage from adjacent agricultural land, thereby increasing the movement of nutrients and pesticides into the waterway. A greater inflow of nutrients during low flow periods increases the biochemical oxygen demand and can cause a dissolved oxygen deficit. Conversely, an increase in overbank flooding because of a decrease in channel conveyance capacity increases the use of nutrients by floodplain vegetation and decreases the total nutrient load entering downstream lakes or estuaries.

Light transmissivity: A slight decrease in light transmissivity often occurs at the site and immediately downstream during construction. Deeper and faster water in the central channel may also increase the amount of suspended material and reduce light transmissivity. Light transmissivity may increase behind the structures if sediment laden currents are precluded from these areas and as sediments are deposited in slack waters.

Flow variability: The extensive use of perpendicular river training structures along reaches of streams or rivers significantly affects downstream flows. A reduction in channel conveyance increases overbank flooding and and storage of water in the floodplain. This storage, in turn, extends the duration of flooding and reduces peak discharges

downstream. Reduction of the channel may induce rapid drainage of adjacent land and a lowered water table. As a result, less ground water will be available to sustain base flows during dry periods. The net result is lower peak flows, higher median flows, and lower low flows downstream from the controlled section of river.

Under its Environmental and Water Quality Operational Studies program, the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, is identifying and assessing environmental impacts of waterway projects such as river training structures, with the aim of improving design and construction procedures and reducing the environmental impacts of these structures (J. R. Niemi and F. D. Shields, Jr., personal communication).

Simons et al. (1981*b*) ascertained the effects of river training structures on the physical characteristics of the pooled reaches of the Upper and Middle Mississippi River. Lubinski et al. (1981) reviewed the physical, chemical, and biological impacts of stone wing dams and closing dams on the upper and lower reaches of UMR. There are 3166 wing dams on UMR, of which 2438 are submergent and 728 are emergent. The lower reaches of UMR contain 91% of the emergent dams (UMRBC Environmental Work Team 1981*d*).

1.4.1. Physical Effects

Simons et al. (1981*b*) analyzed physical responses of the upper reaches of UMR to the construction of submerged river training structures:

1. New islands and side channels were formed as a result of sedimentation in dike fields.
2. River surface area and surface width were reduced.
3. Total area and number of islands were both increased.
4. No significant changes were caused in river stage, discharges, or river deposition.
5. The riverbed was degraded at low flows.
6. Water velocity was increased at low flows and remained about the same at high flows.
7. Sediment was deposited in the floodplain and backwater areas.

The response of the Middle Mississippi River to emergent river training structures built in the 20th century, (in combination with flood protection levees) has been as follows (Simons et al. 1981*b*):

1. The position of the river in the valley has remained unchanged during the last century. In the absence of earthquakes or great floods, it should remain so.

2. The average width of the river has been halved (from about 4200 ft to 2100 ft) since the 1880's. However, the present area would not be significantly less than the original area if great floods had not occurred during the 19th century.

3. River flows have changed little. Large peak flows do not occur as frequently now as in the past. The annual minimum flow is larger now, and mean annual flow is unchanged.

4. The mean annual maximum flood stage at St. Louis, Missouri, has increased slightly during the last 100 years, whereas the annual minimum stage has decreased significantly.

5. Except for occasional stages greater than 20 ft, daily stages at St. Louis are lower now than in the past.

6. At all discharges, the depth of water in the river is greater now than before modification.

7. The change in river cross section has reduced the carrying capacity of the channel for flows that exceed the bank-full stage. Perpendicular river training structures have constricted the main channel. Stages for flood discharges are higher now than in the past.

Lubinski et al. (1981), who also reviewed the physical impacts that both stone wing dams and closing dams have had on the upper and lower reaches of UMR, made these observations:

1. The principal physical effect of stone wing dams is that of concentrating flow in the main channel. As main channel areas are narrowed by these structures, greater volumes of water are forced through smaller spaces and the potential for scouring increases. Some unpooled sections of the river are 11 ft deeper than before construction of these emergent structures. As volumes of water carried in the main channel increase, velocity in other areas decreases. Reduced flows in the main channel border areas may have beneficial effects in the form of locally decreased bank erosion, but adverse effects in increased sedimentation rates and the resultant loss of water surface area. Since 1888 one-third of the water surface area in the lower reaches of UMR where emergent wing dams were constructed has become dry land.

2. Another effect of the construction of stone wing dams has been to fix the position of the main channel in the riverbed. The

UMR could soon consist of a main channel bordered only by terrestrial habitat, rather than by the shallow lakes, marshes, and backwaters that now exist on the upper reaches of UMR.

3. Depending on their heights, configurations, and angle to the shoreline, stone wing dams result in either increased or decreased bank erosion in the vicinity of the structure on opposite shorelines.

4. Stone wing dams increase the available substrate-water surface area and increase substrate diversity in the river.

5. The physical effects of closing dams are similar to those of stone wing dams except that their impacts are greatest in backwater areas where flows have decreased and sedimentation rates have increased. Long-term decreases in backwater surface areas can result from these effects. The magnitude of impacts is directly related to the degree of flow loss, and therefore also depends on the height and length of these structures and their efficiency in blocking normal flow.

Although river training structures cause a decrease in water velocity in the backwater areas, an increase in the velocity in the main channel areas results in greater turbidity because of the increased capacity of the water to carry suspended material (Weck and Crossan 1981).

1.4.2. Chemical Effects

Lubinski et al. (1981) summarized the chemical effects of stone wing dams and closing dams on UMRS as follows:

> Although the chemical effects of stone wing dams and closing dams are similar, they are more pronounced for closing dams. Closing dams greatly reduce flow rates into side channels and backwaters and permit the aggradation of fine silt and detritus in these areas. Since the organic content of these materials is generally higher than that of coarser sediments, a considerable demand may be placed on the oxygen budget of water flowing through backwaters and side channels. Daytime oxygen production by macrophytes and algae in the areas can offset this oxygen demand. However, in shallow backwaters with few macrophytes, water turbulence can resuspend the fine sediments, increase turbidity, and limit oxygen production by photosynthesis. Nighttime respiration of aquatic organisms can reduce oxygen concentrations to critical levels unless adequate oxygenated water flows through the area.
>
> In some areas the buildup of fine sediments in backwater areas has also been accompanied by an accumulation of toxic contaminants that

are adsorbed on the sediments.

Additional information on the impacts that perpendicular river training structures have on chemical and physical characteristics of rivers was given by Yorke (1978).

1.4.3. Biological Effects

Lubinski et al. (1981) analyzed biological effects of stone wing dams and closing dams on UMRS as follows:

> Biological impacts of stone wing dams and closing dams have been both detrimental and beneficial. Detrimental effects have been long-term, and related primarily to increased sedimentation rates in main channel border and backwater areas and a resultant loss of aquatic habitat.
>
> Backwaters represent the most productive areas of UMRS. These areas produce tremendous quantities of macrophytes, plankton, and macroinvertebrates. They provide reproductive and feeding areas for valuable fish and wildlife resources. The resources produced in backwaters provide important energy that helps to drive the total biological system of UMR. Thus, any impact on biological productivity, such as sedimentation induced by stone wing dams, is a serious threat to biological resources in the entire system. Not only are standing crops of organisms within backwaters limited by sedimentation, but the reproductive potential of backwater species is reduced due to physiological stress and physical interferences with reproduction (e.g., sediment covering spawning beds or smothering organisms).
>
> The beneficial effects of stone wing dams and closing dams are associated with added substrate and benthic diversity in UMR, especially in areas where flow rates are suitable for productive and diverse benthic communities. Not all of the stone wing dams and closing dams constructed to date provide a useful substrate diversity. A study of stone wing dams and closing dams along the Iowa border revealed that nearly 33% had been covered with sediments and almost 4% had been removed.
>
> Structures that are not covered with sediment can provide a stable substrate with a high surface to volume ratio, provide important interstitial space, and serve as a catchment for detritus. Thus, these structures provide food and protection for organisms and provide high primary and secondary production. The large amount of stable surface area and occasional increased light penetration due to the low height of some stone wing dams provide ideal habitat for periphyton. The periphyton, deposited detritus, associated

bacterial communities, and surface area provide a habitat that is typically high in secondary production.

The protection and food resources provided by submerged wing dams attract a variety of species of fish, typically including smallmouth bass, crappies, northern pike, and walleyes. They also provide substantial winter cover for catfish. In addition, longnose gar, shortnose gar, gizzard shad, mooneye, common carp, silver redhorse, golden redhorse, shorthead redhorse, and smallmouth buffalo have been collected near submerged wing dams by the Wisconsin Department of Natural Resources (Fernholz 1980b).

Within the lentic backwaters created by the wing dam, the reduction in flow velocities causes suspended materials to settle out. This sedimentation can alter the stream bottom and produce a mud-bottom habitat for aquatic organisms. The population of benthic invertebrates may change from one requiring strong currents and high dissolved oxygen concentrations to one preferring or tolerant of quiescent conditions and lower dissolved oxygen. Increased stability of bottom sediments and an increase in organic content of these sediments may accompany the reduction in flow velocity (UMRBC Environmental Work Team 1981d).

An additional impact of wing dams may be a reduction or elimination of fish populations specifically adapted only to the main channel or its border habitats. Critically important to long-term survival is the presence of suitable spawning grounds. Paddlefish and most suckers, for example, typically spawn on gravel bottoms in main channels. Transformation to lenthic habitat will probably destroy these spawning grounds. Any change in benthic invertebrates, forage fish, or aquatic and marsh vegetation and algae has the potential to adversely affect fish populations. This effect can be caused by a reduction in the quality or character of fish food, which can be deleterious to species with specific food requirements (UMRBC Environmental Work Team 1981d).

Most of the information and analyses on the impacts of river training structures reported in this section were incorporated from Lubinski et al. (1981), Simons et al. (1980b), and Yorke (1978). The following references contain pertinent information that augments this summary: Allen and Nordstrom (1977), Barton et al. (1973), Burke and Robinson (1979), Burress et al. (1982); Chee (1979), Colbert et al. (1975), Colson and Wilson (1974), Degenhardt (1973), Emge (1972), Emge et al. (1974), Everts (1979), Franco and McKellar (1973), Funk and Robinson (1974), Gill (1972), Johnson et al. (1974), Kallemeyn and Novotny (1977), Lagasse (1975), Lovejoy and Kennedy (1979), Lun (1976), Mikkelsen (1977), Rasmussen (1979), Schneberger and Funk (1971), Solomon et al. (1975), Sport Fishing Institute (1971), and Swales and O'Hara (1980).

Additional general references are listed in Section 1.3 (Locks and dams) and the section "Impacts on the environment" in Chapter 6 (River training structures).

1.5. BANK STABILIZATION

Bank stabilization techniques, as defined here, include those used to reduce erosion and the impact of sedimentation. Such measures include the installation of revetments, river training structures, and breakwaters, among others. In this section, however, our discussion of bank stabilization structures includes only revetments and bulkheads that protect the bank directly. Perpendicular river training structures and closing dams were discussed earlier in this chapter.

Yorke (1978) described the effects of revetments and bulkheads on selected physical and chemical characteristics of rivers as follows:

Depth and stage: Stabilization of the banks prevents or limits the natural tendency for channels to migrate within the floodplain. Constricting the channel eliminates much of the variability in water depth that occurs as a result of scouring in pools on the outside of bends and point bar formation on the inside of bends. The channel eventually becomes narrow and uniformly deep.

Water surface area: Constraining natural channel migration creates deeper channels with less surface area. The variability in amount of surface area is also reduced.

Channel configuration: Bank stabilization produces a relatively smooth and uniform bank configuration. Undercut banks and other protective pockets or niches along banks are eliminated. Total edge is reduced.

Velocity: Bank stabilization causes the channel to narrow and deepen, resulting in more uniform and rapid velocities.

Temperature: Installation of revetments and riprap normally requires the removal of all streambank vegetation and some floodplain vegetation to provide access for heavy equipment. This removal increases insolation and the variability of water temperatures. Impacts are long-term because normal maintenance practices prevent the reestablishment of overstory vegetation.

Suspended solids: An increase in suspended solids at the site and immediately downstream occurs because of bank erosion and disturbance of bed material during construction. This increase sometimes causes temporary sedimentation problems downstream. However, bank stabilization reduces long-term, suspended-sediment discharge and sedimentation problems.

Bed material: The lateral migration of the channel is contained and, as a result, the channel may adjust by downcutting. Bedload may increase and reduce the value of bed material as suitable substrate for benthic organisms. Removal of streambank and floodplain vegetation eliminates a major source of detritus that serves as an energy source for the biological community.

Dissolved substances: Removing streambank vegetation and preparing the banks for protective materials may release organic matter to the stream system that temporarily increases the biochemical oxygen demand and sometimes causes a dissolved oxygen deficit downstream. Total dissolved solids may increase during construction, but are reduced over the long term because of the reduction of bank erosion. An increase in the discharge of nutrients and pesticides and other agrichemicals may occur during low flow periods because channel downcutting increases drainage from adjacent land.

Light transmissivity: Activities associated with installing protective materials on the banks cause a temporary decrease in light transmissivity, but the long-term impact is an increase because bank erosion and associated turbidity are reduced.

Flow variability: The impact on flow variability is minor. If channel downcutting occurs it induces a more rapid discharge of groundwater, resulting in lower flows during dry periods.

Under its Environmental and Water Quality Operational Studies program, the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, is identifying and assessing the environmental impacts of waterway projects such as bank stabilization. These projects are being studied to develop design and construction procedures that will reduce the environmental impacts of bank stabilization (J. R. Niemi and F. D. Shields, Jr., personal communication).

Lubinski et al. (1981) determined that revetments have the potential to (1) create needs for more revetments downstream and on the opposite shore, (2) reduce or eliminate the natural meandering of the main channel of streams, (3) increase current velocity, which results in degradation of the channel bed, (4) restructure shoreline habitat, (5) stabilize or completely control erosion of banks, (6) temporarily destroy existing nearshore and bank communities, (7) cause temporary resuspension of sediment, (8) provide cover for reptiles, amphibians, and small mammals, (9) provide desirable habitat for fish, (10) reduce habitat diversity if too much of the shoreline is riprapped (as in the Middle Mississippi River), and (11) eliminate habitat preferred by animals that use eroded and undercut banklines (e.g., catfishes, muskrats, and river otters).

Most of the information and analyses in this section on the impacts of bank stabilization was incorporated from Lubinski et al. (1981) and Yorke

(1978). For further information on adverse and beneficial impacts of bank stabilization measures, see the sections entitled "Impacts on the environment" in Chapters 4 to 6, 8 to 9, 11 to 15, and 17 to 20.

1.6. FLOOD PROTECTION LEVEES

Flood protection levees are earth embankments or concrete walls parallel to stream channels designed to contain flood discharges within narrow banks of the natural floodplain.

Yorke (1978) developed a generalized description of impacts that flood protection levees have on certain physical and chemical characteristics of rivers:

Depth and stage: Flood protection levees reduce the flood conveyance and storage capacity of the floodplain and increase variability of stages and water depths. Flood stages, in particular, are greater with levees in place. Containment of flood discharges in a smaller cross-sectional area may cause scouring and eventually create a deeper channel.

Water surface area: Levees contain overbank flooding and reduce the total area subject to periodic inundation. Containment of flood discharges in a smaller cross-sectional area may cause streambank erosion and widening of the channel.

Channel configuration: Containment of flood discharges in a smaller cross-sectional area may cause extensive scouring in the channel floodplain inside the levees. Cutoffs in a meandering channel may also occur, reducing total channel length, but increasing habitat diversity by creating oxbow lakes and sloughs.

Velocity: Containment of flow in a smaller cross-sectional area increases water velocities during floods, but there is no effect when the water stage is bank full or less.

Temperature: Flood protection levees placed immediately adjacent to the channel necessitate the removal of overstory vegetation and result in greater variation in water temperatures. Daytime temperatures are higher and nighttime temperatures lower. Levees set back on the floodplain do not affect water temperature.

Suspended solids: Construction of levees causes a temporary increase in concentration and discharge of suspended solids because erosion occurs at the construction site. Erosion of levees during extreme floods may increase temporary sediment discharge and cause local sedimentation problems.

Bed material: Levees have little effect on bed material. Containment of

flood discharges in a relatively narrow cross section may induce channel scouring and increase bedload, reducing the substrate value of the bed material for aquatic organisms. Levees along the streambanks eliminate overstory vegetation and a major source of detritus that provides an important energy source for the biological community.

Dissolved substances: Total dissolved solids may increase below levee projects because the areas of floodplain and vegetation available for assimilating dissolved substances usually are severely reduced. More importantly, expanded agricultural, residential, and industrial use of land protected by levees is likely to increase the amount of nutrients and pesticides and other pollutants released into the river. The problem may be particularly severe if agricultural drainage or residential and industrial discharges are released when the river is low and insufficient water is available to dilute the effluents. Pesticides and other toxic substances may adversely affect aquatic organisms directly, and a high nutrient load may affect organisms indirectly by causing oxygen deficiencies in the river.

Light transmissivity: The transport of fine sediments during levee construction temporarily decreases light transmissivity at the site and downstream. Clearing of additional land or more intensive farming of land protected by the levees increases surface runoff downstream from the levee project, and the accompanying sediment transport reduces light transmissivity.

Flow variability: Flood protection levees reduce storage capacity of the floodplain. Flood waters are transmitted downstream faster and increase flood peaks and decrease flood duration at downstream points.

Under its Environmental and Water Quality Operational Studies program, the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, is identifying and assessing the environmental impacts of waterway projects such as flood protection levees. The projects are being studied to improve design and construction procedures and reduce environmental impacts (J. R. Niemi and F. D. Shields, Jr., personal communication).

The responses of the Middle Mississippi River to flood protection levees and emergent river training structures as determined by Simons et al. (1981a) are presented in section 1.4 on "River training structures." They also noted that, although flood stages are higher now than in the past, flood protection levees prevent flood damage when the Middle Mississippi River exceeds the bank-full stage. Under natural conditions, flood damage occurred whenever the river exceeded that stage.

Although most of the information and analyses in this section on the impacts of flood protection levees were incorporated from Simons et al.

(1980b) and Yorke (1978), the following references contain pertinent information that augments this summary: Carson (1975), Dort (1980), Hansen and Muncy (1971), Linder (1976), New England River Basins Commission (1976), Pacific Northwest River Basins Commission (1969), and Simons et al. (1974).

1.7. WATER LEVEL REGULATION

Water level regulation helps maintain sufficient depth to provide for navigation at low or moderate flows. The effects due to the stabilization of low-flow water levels and to operational drawdown are of particular interest in assessing impacts on the river ecosystem (Lubinski et al. 1981).

According to Lubinski et al. (1981), the responses of UMRS to stabilization of low-flow water levels have been as summarized here:

1. Low-flow water levels in UMRS are more stable now than they were before construction of the locks and dams. This stabilization has been beneficial to populations of submerged aquatic plants in UMRS.

2. On the other hand, the stable water levels probably shortened the low-flow drying periods of some marshes. These drying periods had earlier helped to "rejuvenate" marsh soils. The lack of a drying period may now be preventing compaction of the soils of many of the shallow bottomland lakes along the Illinois River, thus sustaining the flocculent condition of their bottom sediments.

3. Substantial water level fluctuations regularly occur in the unpooled reaches of UMRS and have been known to dewater certain side channels between St. Louis, Missouri, and Cairo, Illinois.

4. The operation of the locks and dams on the Illinois River reduces dissolved oxygen concentrations.

Lubinski et al. (1981) found that operational drawdowns affect UMRS as stated here:

> Biological effects of drawdowns concern both the upstream (from a dam) effects of decreasing water levels and the downstream effects of increasing water levels. Sudden and drastic lowering of water levels often leave fish stranded in pools isolated from the main channel. Winter drawdowns lead to oxygen depletion and fish kills and have a greater deleterious effect on game fish than on non-game species. Falling water levels during the winter accompany a definite movement by common carp, northern pike, crappies, spotted suckers, and bowfins out of backwater areas. Water level

fluctuations adversely affect plant communities and muskrats in the Illinois River.

Drawdowns in impoundments cause certain zones to be periodically exposed and result in those zones becoming virtually barren. Diel flow fluctuations below dams can eliminate many invertebrate species. Areas periodically exposed below dams were lower in macroinvertebrate diversity, density, and biomass than areas not exposed to drawdown. Water level fluctuations prevented the establishment of "normal" benthic communities. Benthic organisms have been reduced by 50% in fluctuation zones on the Lower Colorado River, and submergent vegetation in these zones is non-existent.

GREAT II (1980k) noted that the biota on UMRS could be adversely or favorably affected by drawdowns or water level fluctuation in the following ways:

During critical spawning, nesting, feeding, migration, and other periods of life cycles, fish, wildlife, and flora can be drastically affected by sudden fluctuation of water levels. Natural rises in pool levels and manipulation of pool levels to maintain commercial tow passage can expose and destroy benthos and flora that are primary food sources for fish, waterfowl, and furbearers. Additional adverse impacts include island inundation during waterfowl nesting, furbearer nest exposure or inundation during critical times, flooding of vegetation, increased wave action and turbidity, exposure of erodable shorelines, and development of a littoral zone that is not constant in location and area.

Despite these potential adverse impacts, water level manipulation can be extremely beneficial if managed with consideration for fish and wildlife needs. Such management would entail comprehensive evaluation of seasonal stress periods in fish, wildlife, and aquatic vegetation. Manipulation of water levels can be used to facilitate management of fish and wildlife resources by controlling vegetational growth, providing fish access to spawning areas, isolating islands from disturbance, limiting access of predators to waterfowl nesting areas, and maximizing littoral zone productivity. The management potential to control undesirable biological productivity such as excess vegetation through water level manipulation can be highly important. The GREAT II work group recommended manipulation of water levels in Pool 16 to improve habitat.

Although most of the information and analyses in this section on the impacts of water level regulation was incorporated from Lubinski et al. (1981), the following references contain pertinent information that augments this summary: Austin et al. (1979a, 1979b), Delfino (1977), Havera et al. (1980), Helms (1969), Johnson (1971), Keeley et al. (1978), Kennedy (1979),

Kuznetsov and Fadeyev (1979), Orlova and Popova (1976), Ragan (1971), and Solomon et al. (1975).

Further information on adverse and beneficial impacts of water level regulation on the environment and natural resources is given in the discussion of Water level control (Chapters 19 and 39), Water control structures (Chapter 27), and Management of water levels and flows (Chapter 28).

CHAPTER 2. ADVERSE EFFECTS RELATED TO BOAT TRAFFIC

Boat traffic, as defined in this chapter, includes recreational boats as well as commercial barges, but the major emphasis is on commercial barge traffic. In general, commercial barge traffic affects the biological communities of UMRS by "increasing turbidity; resuspending sediments which move into the backwaters; creating changes in waves, velocity and pressure; and increasing shoreline erosion. The development of fleeting areas, terminals and other facilities are related impacts" (UMRBC Environmental Work Team 1981b).

2.1. PHYSICAL AND CHEMICAL EFFECTS OF BOAT TRAFFIC

Any impact that the movement of commercial barges has on the environment begins with physical effects (i.e., waves, currents, drawdown, and pressure and velocity changes).

2.1.1. Effects of Boat Waves

Physical impacts of waves generated by boats depend on the size and shape of the boat, boat speed and draft, water depth, location of boat in relation to shoreline, and width of the channel (Hay 1969; Bumm et al. 1973; Schulz 1978; Bhowmik 1975; Karaki and Van Hoften 1974; Johnson 1969; Camfield et al. 1980; Das and Johnson 1970). Generally, a boat traveling fast in shallow water close to the shoreline generates the highest waves (Sorenson 1973). High waves in narrow channels impact upon the shoreline with considerable energy and have a potential to cause substantial erosion. The Illinois State Water Survey (Bhowmik et al. 1981b) has collected data on the effects of waves near shore in the Illinois and Upper Mississippi rivers that resulted from 41 tow passage events. Additional data were collected for a cabin cruiser and a towboat without barges. The maximum wave heights ranged from 0.1 ft to 1.05 ft. Recreational boats travel faster than commercial vessels and generate waves that are higher but of shorter duration than those generated by tows. The observed wave heights and energies of both tows and pleasure craft are sufficient to cause bank erosion.

Lubinski et al. (1981) reported on criteria developed by Hurst and Brebner that accounted for a sizable proportion of the erosion attributable to navigation on certain sections of the St. Clair and St. Lawrence rivers. The criteria they established follow:

1. If the center of the navigation channel is 2000 ft or less from the bank, 50% or more of the bank erosion is due to navigation.

2. If the center of the navigation channel is between 2000 and 3000 ft from the bank, less than 50% of the bank erosion is due to navigation.

3. If the center of the navigation channel is more than 3000 ft from the bank, erosion is essentially due to natural causes.

According to Bhowmik et al. (1980), "vessel-generated waves have a direct effect on bank erosion and sediment suspension in the near-shore zone. The waves travel with little energy loss, but do dissipate with distance from the vessel track. Thus vessel-generated waves are more important in narrow channels or where the sailing line is close to the shore." Bhowmik and Schicht (1980), who studied bank erosion of the Illinois River, concluded that most shoreline erosion is caused by wind-induced waves and boat traffic. Barges produce three successive effects as they pass a point on shore. First there is a slight rise in the water as the bow wave passes. Then the water is drawn away from the shore. The vertical fall can be substantial, perhaps on the order of 1.5 ft. If the shore has a shallow slope, a considerable portion of the bottom may be exposed. Finally, as the stern of the towboat passes, the water rushes back in a series of waves. The water level along the shore may continue to oscillate for many minutes after the towboat has passed. All of these effects are most pronounced in narrow parts of the river channel with gently sloping shorelines. Significant bank and shoreline erosion result and the amount of sediment entering the system is increased (Sparks 1975a).

Simons et al. (1979) rated the relative magnitude of bank erosion factors: shear stress or velocity was first; pool fluctuation was second; and boat generated waves were third. The authors wrote that average boat waves generate erosive forces on river banks of the Connecticut River with a magnitude on the order of 9 to 12% of the shear stresses caused by the flowing water in an unrestricted channel system.

Erosion, and the additional sedimentation due to erosion, can adversely affect the environment and necessitate additional dredging. On the other hand, additional sediment loads may result in a wider channel with greater capacity to handle flood waters (Lubinski et al. 1981). The GREAT II (1980i) Sediment and Erosion Control Work Group attributed only 26% of the sediment in UMRS to streambank erosion. Floods, wind waves, and boat waves are the causes of this erosion. Simons et al. (1981b) estimated that 246.7 miles or 37% of UMR and 91.4 miles or 32% of the Illinois River are very susceptible to barge wash or maneuvering. If bank erosion and sediment entering side channels and backwater areas are currently causing a problem, increased navigation could aggravate the problem by increasing wave wash and rates of sediment discharge.

2.1.2. *Drawdown Effects*

A loaded barge (large size, deep draft) traveling rapidly downstream causes the greatest drawdown. Drawdown caused by loaded barges can expose shore areas for several minutes. It can also cause significant flow changes in small tributaries by changing the hydraulic gradient at their outlets. Little or no drawdown is caused by recreational craft. Drawdown causes periodic exposure of substrates and flushing action. A variety of organisms associated with substrates can be exposed or temporarily stranded. For example, floating aquatic plants, algae, and phytoplankton are washed from the edges of emergent beds into sloughs and flushed from backwater areas. It is not known how significant this effect is in UMRS, but drawdown effects may be more significant in shallow channel border areas, in side channels, and in backwater lakes and sloughs (Lubinski et al. 1981; UMRBC Environmental Work Team 1981b; Sparks 1975a).

Bhowmik et al. (1981b) collected data on drawdowns during 27 tow passages on the Illinois and Upper Mississippi rivers. The maximum drawdown, which ranged from 0.05 to 0.69 ft, depended on the velocity of the vessel, the blockage factor (ratio of cross-sectional area of river to submerged cross-sectional area of the barge), the length of the vessel, and the distance of the vessel from the sailing line.

2.1.3. *Effects Related to Pressure and Velocity Changes*

Tows cause temporary increases in flow and turbulence that, in turn, cause resuspension of sediments (Lubinski et al. 1981). The amount of material resuspended is dependent on several factors:

1. Velocity distribution downstream from the propeller (Liou and Herbich 1976).
2. Proximity of the barge bottom to the riverbed, and the particle size of bed material (Karaki and Van Hoften 1974).
3. Speed and frequency of passage of barges (Johnson 1976b).
4. Size of barges (Karaki and Van Hoften 1974).
5. Breaking region of waves produced by barges (Lubinski et al. 1981).
6. Water depth and engine horsepower (Yousef et al. 1980).

Areas with the following characteristics are usually most susceptible to towboat-induced resuspension of sediments (Simons et al. 1981b): (1) short

distance between bank and sailing line; (2) high sinuosity; (3) eroding banks; (4) shallow depth; and (5) unusually fine bottom sediments.

Results of studies of navigation on UMR (Pools 9 and 26) illustrated that barges traveling upstream can double or triple ambient velocities for 2 or 3 minutes. The studies also showed that a barge headed downstream could actually reverse the flow of the river for a short time. These changes in ambient velocities were recorded at various distances and depths away from the sailing line. In fact, 29% of the tows observed were outside the maintained navigation channel. Increases in current velocities in the backwaters that were attributable to barge traffic were generally 0.5 to 1.0 fps. This factor is associated with unnatural resuspension of sediments and creates major impacts on sediment deposition, resuspension, shore and bank erosion, and water quality in side channels and backwaters (UMRBC Environmental Work Team 1981b, 1981c, 1981d).

Sparks (1975a) observed changes in rate and direction of flow in side channels on the Illinois River after the passage of tows. Johnson (1976b) recorded temporary velocity increases of 64% and 55% at the surface and mid-depth, respectively, of a side channel on the Illinois River after the passage of a single upbound tow. Herricks and Gantzer (1980) measured velocity changes of up to 0.7 fps on the Kaskaskia River. Bhowmik et al. (1981c) measured velocity and suspended sediment in a side channel on the Illinois River. Velocity changes--both increases and decreases from velocities before tow passage--observed for 27 tow passage events ranged between 10 and 100%. Temporary velocity changes of 50 to 100% coincident with tow passage were also observed in side channels and above wing dams in Pool 9 of UMR (UMRBC Environmental Work Team 1981d).

Tow passage can cause increased velocities in off-channel areas as well as in and along the main channel. Relative increases in velocities decline as distance from the tow increases. Consequently, finer particles are transported farther than larger ones and have a tendency to settle out away from the main channel. The smaller particles accumulate along the banks, where velocities are lower. The rate of accumulation has been observed to be greater after barge passage, for both fine particles in the main channel border and sand and coarser material in the main channel. A study by Johnson (1976b) demonstrated that resuspended sediments could be transported to backwater areas (UMRBC Environmental Work Team 1981d).

Karaki and van Hoften (1974) observed that the bed material is usually finer in the Illinois River than in UMR and, as a result, more easily resuspended. The median particle diameter in the navigation channel of Pool 26 on the Illinois River is between 0.3 and 0.4 mm; the bed materials in Pool 26 of UMR have median diameters between 0.25 and 1.0 mm. In general, bed material becomes finer as one progesses downstream in the main channel of the main stem UMR (UMRBC Environmental Work Team 1981d).

The Kaskaskia River is also sensitive to navigation-induced sediment resuspension. Herricks and Gantzer (1980) found significant increases in suspended solids associated with barge passage, although relative effects were related to flow. Fine sediments moved laterally to the main channel border and settled out where accumulations of fine silt fractions were the greatest. Bhowmik et al. (1981a) and others noted that suspended concentrations following tow passage were greater in the main channel border than in the main channel itself. Coarser sediments were also moved in the main channel (UMRBC Environmental Work Team 1981d).

The resuspension of sediments causes a corresponding increase in the concentration of suspended sediments in the water column. Simons et al. (1981a) demonstrated that this concentration is the major cause of turbidity in UMRS. The turbidity plumes from tow traffic have been observed through infrared photographs by Karaki and van Hoften (1974). Field measurements of tow traffic by Johnson (1976b) also showed significant statistical increases in turbidity on the Illinois River and UMR. A study by the River Studies Center, La Crosse, Wisconsin, showed that significant increases in suspended sediments occurred at five morphologically different locations in navigation Pool 9 of UMR and that the resuspension of sediments increased mass transport of sediments in both the main channel and side channels. Mass transport was greater in side channels that are located on outside bends and that intersect the main channel at right angles. The levels of mass transport above background levels in the side channels ranged from 0.22 to 31 tons per event (UMRBC Environmental Work Team 1981d).

The recovery time--that is the amount of time required for suspended sediment concentrations or turbidity levels to return to ambient levels--varies greatly. Sparks (1975a) found that main channel turbidity in the Illinois River required as long as 2.5 h to return to ambient levels. Herricks and Gantzer (1980) found in the Kaskaskia that it took up to 30 min for suspended sediment concentrations to return to pre-passage levels. At higher flow the recovery time was the same. Bhowmik et al. (1981a) observed that in Alton Pool and Pool 25 in UMR, suspended sediment concentrations returned to ambient levels 60 to 90 min after tow passage. The River Studies Center, La Crosse, Wisconsin, found that the recovery time in Pool 9 of UMR ranged from 35 to 90 min (UMRBC Environmental Work Team 1981d).

Bhowmik et al. (1981a) observed that resuspension of sediments by tows was greater when the pre-tow-passage concentration was low, and that the increases were greater in channel border areas than in the navigation channel. Tow passages less than 90 min apart caused average periods of increased sediment concentration, although the average increase for multiple events was less than the average increase for isolated events (UMRBC Environmental Work Team 1981d).

The results of two studies indicate that passage of commercial vessels

increased the proportion of larger diameter particles resuspended in the water column. The passage of four size classes of recreational vehicles (16 to 65 ft long) at high velocities through a narrow side channel in Pool 9 of UMR containing fine bed sediments resulted in significant increases in suspended sediments. The recovery times, however, were shorter than those observed for commercial vessels. A similar study, conducted in Pool 4 of UMR, showed that the passage of commercial vessels resulted in greater increases of suspended sediments than those observed in Pool 9 of UMR. These greater increases were related to the presence of fine bed sediments and a small channel (UMRBC Environmental Work Team 1981d).

Johnson (1976b) found that the passage of several tows within the recovery time on the Illinois River had an additive effect on suspended solids concentrations and turbidity levels. Although the recovery time for transparency and suspended solids can be rapid, continuous passage of tows have maintained high levels of turbidity and suspended solids that have sometimes exceeded the maximum turbidity levels that normally occur during flood stages. As traffic levels increase, the frequency of these additive events also increases (UMRBC Environmental Work Team 1981d).

Deposition of resuspended solids is of grave concern, particularly as it relates to the backwaters of a riverine system. During tow passage on the Illinois, Bhowmik et al. (1981c) found increases in suspended sediment concentrations in the inlet and outlet to a side channel to range from 10 to 800% of concentrations present before the passage of the tow. Tow-induced deposition could be a significant portion of the total deposition rate of the pooled portions of UMRS. Simons, Li, and Associates estimated that, on the average, tows currently add from 2% to 28% to the annual amount of suspended sediment volume entering backwaters of UMRS. The percent contribution varies with the physical characteristics of specific sites (UMRBC Environmental Work Team 1981d).

Dissolved oxygen is a critical water quality characteristic that can be influenced by tow passage. Both temporary increases and decreases of dissolved oxygen have been documented. Slight increases have been attributed to the mixing action of turbulence caused by tows moving through the area or natural diel oxygen charges (Johnson 1976b). Herricks and Gantzer (1980) found that decreases in dissolved oxygen (integrated for depth) resulted after most tow passage events on the Kaskaskia River. The most severe reduction occurred in August during low flow, when surface concentrations were reduced from 9.7 ppm to 4.9 ppm. Recovery time was 60 min or less. They further reported on the water quality of the Kaskaskia River as follows:

> The effect of barge passage on water quality of the Kaskaskia River includes lowering dissolved oxygen concentrations, decreasing transparency, and increasing suspended solids. Additional impacts include turbulent mixing of the water column, which alters temperatures, chlorophyll concentrations, and primary productivity.

The effects of barge passage are most pronounced during periods of low flows and on bright, sunny days. The primary mechanism of oxygen reduction was loss to the atmosphere due to turbulent mixing. However, the data indicated that suspension of oxygen-demanding sediments and displacement of phytoplankton from the photic zone may also have had adverse effects on dissolved oxygen concentrations.

Observed decreases in dissolved oxygen can, in part, be explained by resuspended bottom sediments containing fine organic matter entering the water column to cause an increase in biochemical oxygen demand. Therefore, areas that contain higher percentages of fine organic bed materials that are susceptible to resuspension may be most susceptible to tow-induced decreases in dissolved oxygen (Herricks and Gantzer 1980).

2.2. *BIOLOGICAL EFFECTS OF BOAT TRAFFIC*

Sparks (1975a), who investigated the effects of wave wash and resuspension of sediments caused by boat traffic in the Illinois River, found that barges can cause changes in the direction and magnitude of current in side channels that interfere with spawning of fish and cause the resuspension of sediments. Resuspended sediments can move into backwater areas and cause increased sedimentation, turbidity, and biochemical oxygen demand. These changes can lead to a shift in fish populations from game fish to catfish and rough fish species, which have a higher tolerance for turbidity and low dissolved oxygen.

Wave action can have considerable impact on some of the most productive river areas, i.e., backwaters and littoral zones. These areas serve as nurseries for larval fish and produce large amounts of macroinvertebrates and plankton. Moreover, the greatest intensity and frequency of wave action caused by heavy boat traffic (commercial and pleasure boats) during the warmer months occurs during the most productive season for animals. Wave action may affect the fauna and flora in a variety of ways. Larval and small fish and benthic organisms may experience stress from excessive wave action; the shock wave may actually knock invertebrates from plants and substrates, causing physical injury and exposing them to predation. Invertebrates may be more likely to be entrained in drift along steep shorelines exposed to currents sufficient to sustain drift. Macrophytes may be uprooted by wave action, and the wave action may make it difficult for plants to remain established in a given area.

Sediment movement and resuspension may change the habitat to the extent that it is no longer optimal or even marginally acceptable by some species. Turbidity induced by wave action restricts periphyton communities and the primary production of phytoplankton. Settling of resuspended sediment fouls the gills of fish and invertebrates, smothers their eggs, and restricts

primary production areas of submerged vascular plants (Sparks 1975a).

Virtually every biological component of the river ecosystem is affected by physical and chemical changes caused by barge traffic. (UMRBC Environmental Work Team 1981c). The major impacts related to each component are summarized here.

Component	Source of Impact
Terrestrial vegetation and habitat	Bank erosion and runup.
Aquatic habitat	Total effect of the following factors: altered water velocities, directions, and levels; increased concentrations of suspended solids; high turbidity and sediment rates; and increased wave action.
Aquatic vegetation	Water quality degradation; water level changes; increased turbidity and sedimentation.
Plankton	Increased sedimentation, turbidity, and resuspended solids.
Benthos	Increased velocity and turbulence; scouring action causing dislodgment; burial by resuspended bottom sediments; species density and diversity altered; increased drawdown.
Fish	Changes in populations of food organisms; increased suspended solids and associated turbidity and sedimentation that interfere with physiological functions and behavior; reduction in spawning habitat; direct damage from barge propellers and hulls; water level fluctuations.
Birds	Accelerated degradation of aquatic habitats resulting in reduction of food sources and nesting and resting areas; accumulative effects of wave wash, sediment resuspension, bank erosion, and general degradation of water quality.
Furbearers	Water level fluctuations; loss of denning areas due to bank erosion; loss of vegetation and cover.

Lubinski et al. (1981) admitted that the magnitude of all these impacts has not been determined on the biota of UMR, but believed that barge traffic

is a significant contributor to increased turbidity and resuspension of sediments.

Lubinski et al. (1981) and Morgan et al. (1976) pointed out four potential direct biological impacts of boat traffic:

1. Significant reduction of carbon fixation as traffic increases.

2. Greater propeller entrainment of larval and juvenile fishes as traffic increases.

3. Behavioral disturbance of nesting fishes.

4. Disturbance of eggs and larvae due to shear stress from boats.

2.3. POLLUTION CAUSED BY BOAT TRAFFIC

Simons et al. (1981a), who investigated the potential for barge traffic to resuspend contaminated sediments and to affect the water quality of certain areas on UMR known to possess polluted sediments, reached the following conclusions:

1. Barge passage resuspends bottom sediments, and increases both turbidity and the concentrations of total suspended solids. These effects are most pronounced where sediments are fine-grained and easily suspended.

2. Where bottom sediments are contaminated, barge passage is likely to result in the release of certain pollutants. Fine-grained sediments display the greatest desorption tendencies. Desorption of pollutants varies widely from site to site. Pollutants most likely to be desorbed are manganese, ammonia, oil, and grease.

3. Navigation can be expected to degrade water quality in locations where sediments are contaminated by pollutants that have high desorption tendencies or by pollutants that commonly exceed water quality standards for aquatic life.

4. At locations where sediments are not polluted, barge traffic would not increase levels of toxic substances in the water column as a result of sediment resuspension. Barge traffic would have little effect in most reaches of UMRS because the bed materials in the main stem are mainly sand, which is relatively free from contamination.

5. Most heavy metals are bound to the sediment and do not readily reenter the dissolved state even during sediment disturbance.

Manganese is the most frequently desorbed heavy metal, but is one of the least toxic. Under conditions in which oxygen is present, hydrous oxides of manganese and iron inhibit release of heavy metals into the water column. In locations where the oxygen demand of the sediment is high (e.g., Hastings, Redwing, and Alma Boat Harbors, Lake Pepin, Alton, and the St. Louis area), low oxygen and pH may periodically favor the release of heavy metals. Problems would be greatest during low-flow conditions when temperatures are high and oxygen concentrations low.

6. Resuspended sediments often remove most heavy metals from the dissolved state. Iron and orthophosphate are frequently adsorbed or precipitated during sediment resuspension.

7. Resuspension of contaminated sediments may increase the quantity of pollutants ingested by certain fish species if they ingest sediment particles to which pollutants are adsorbed. Pesticides (such as dieldrin and chlordane), PCB's, mercury, and lead pose the greatest problems because they accumulate in tissues of the biota.

8. Increased barge traffic would tend to redistribute contaminated sediments because sediment resuspension increases mobility of the sediment.

9. At locations where bed sediments are fine-grained, disturbance of sediments by barge passage may decrease dissolved oxygen concentrations at the surface during low flows and at night. Barge traffic causes little change in dissolved oxygen during high flows.

Bhowmik et al. (1980), who analyzed the potential for pollution caused by traffic on UMRS, found the following impacts:

1. Water quality changes are primarily associated with the movement of sediments and with chemical processes related to sediment resuspension and aeration by propellers. Chemical effects of vessel traffic are more intense in areas where sediment is resuspended or deposited.

2. Accidents involving spills of chemicals or petroleum products present specific cases that can be studied and will have definite, potentially serious, effects on the river biosystem or on municipal water supplies near and downstream from the accident site.

3. Wastes from vessels and pollution occur wherever there is vessel traffic. Fuel and oil leakage and spills are probably the most important sources of pollution and are most significant near

marinas, docks, or fueling areas. Oil leaks from cooling systems and contaminants from outboard motor exhaust are present in proportion to the number of vessels and the amount of traffic in any given reach of the river.

4. Increased vessel traffic may increase the number of accidents. Physical effects of accidents include shoaling, flow and traffic blockage, channel obstruction, and damage to vessels and structures along or in the river. Each accident involves a combination of vessels, structures, channels, and circumstances, and the affected area is peculiar to that accident.

2.4. WINTER NAVIGATION

Lubinski et al. (1981) summarized the effects that winter or year-round navigation has had on the natural resources of UMRS. Winter navigation is now restricted to the entire Illinois River and the Mississippi River south of its confluence with the Illinois River. The potential for environmental damage is great because of the increased physiological stress on organisms during cold periods. Potential adverse physical impacts of year-round navigation include ice breakage, disturbances caused by barge noise and movement, increased wave action, disturbance of the river bottom, resuspension of sediments, and increased possibilities of oil spills, release of toxicants from sediments, and changes in water quality.

Areas with the greatest potential for damage are bends and river crossings. Drift rates increased dramatically during barge passage. In the absence of a traffic-free winter period, a failure of macroinvertebrate populations to be replenished or recolonized may lead to lower species diversity and density among fish and invertebrate populations. Other potential impacts include increased instability of sediments, scouring of productive benthic areas, increased probability of hazardous spills, adverse changes in water quality, physical damage to aquatic organisms, and behavioral changes in both terrestrial and aquatic organisms. However, few of these effects have been quantified. Environmental studies are needed to assess the impacts that year-round navigation may have on the environmental resources of a river.

Although most of the information and analyses reported in this section on impacts related to boat traffic were incorporated from Lubinski et al. (1981) and Simons et al. (1981a), the following references contain pertinent information that augments this summary: Academy of Natural Sciences of Philadelphia (1980), Ashton (1974), Ashton et al. (1973), Bhowmik et al. (1980), Bhowmik and Schicht (1979), Blaauw and van de Kaa (1978), Bouwmeester et al. (1977), Bowman (1978), Bumm et al. (1973), Camfield et al. (1980), Carstens (1980), Cawley (1978), Danys (1979), Environmental Control Technology

Corp. (1975), ERT/Ecology Consultants, Inc. (1978), Great Lakes and St. Lawrence Seaway Winter Navigation Board (1979), Harich (1972), Herricks and Gantzer (1980), Karaki and Van Hoften (1974), Koster (1971), Kolkman (1979), Link and Williamson (1976), Liou and Herbich (1976), McDonald et al. (1979), McElroy et al. (1978), Morgan et al. (1976), Mueller (1980), Ostdiek et al. (1978), Ouellet and Baird (1978), Schulz (1978), Sinning and Zimmerman (1979), Souder et al. (1979), Sparks (1975a), Sparks and Thomas (1978), Stone and McHugh (1977), Sydor and Stortz (1980), Teppen (1978), Van de Kaa (1979), Wang (1974), Winslow (1977), Yousef (1974), Yousef et al. (1980), and Zimmerman (1979).

The effects of boat traffic are further discussed in Chapter 20, on "Regulation of boat traffic."

PART V. BANK STABILIZATION TECHNIQUES

Bank stabilization is commonly used to channelize river flow for navigation. As Lindner (1969) noted, there are two fundamental reasons for employing channel stabilization measures: (1) protection of properties from erosion and from floods, and (2) provision or improvement of channels for navigation. Protection of the bank from erosion inhibits lateral migration of the channel bed, and the energy of the river is dissipated in scouring the bed and deepening the channel.

Simons et al. (1975) stated that the term "bank protection" implies that the bankline has failed or is about to fail. Bank protection may also be used as a preventive measure. The proper design of bank protection requires an understanding of how or why a bank failed. Identification of the ways in which a bank fails and of the forces that cause these failures enables one to understand why a given form of protection may be used only as upper bank protection, lower bank protection, or full bank protection, depending on the forces to be neutralized.

An understanding of the mechanical processes that influence erosion and sedimentation should be important to resource managers operating on UMR. The GREAT I Sediment and Erosion Work Group (GREAT I 1980d) "demonstrated that sediment from upland and streambank erosion poses an immediate and serious threat to the vital environmental resources of the river corridor." The following problems were identified by the work group:

1. Streambank erosion on tributaries increases dredging requirements.[1]

2. Secondary movement of dredged material adversely affects backwaters and dredging requirements.

3. Fine sediment from upland erosion adversely affects backwaters.

4. Lake Pepin is rapidly filling in as a result of sedimentation and dredging.

5. Backwaters and side channels are filling, thus impairing recreational access.

6. Increased sedimentation is increasing flood elevations.

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[1]Since the GREAT I report, Nakato (1981) found that "there is no correlation between total tributary sediment input and the amount of sediment dredged from each pool." This finding re-emphasizes the need for understanding river system dynamics.

7. Accelerated sedimentation is shortening pool life.

8. Aquatic habitat is being lost as a result of sedimentation.

CHAPTER 3. PROCESSES OF EROSION

Mitigation of erosion and sedimentation problems requires techniques to reduce erosion and sedimentation and to reduce the impact of sedimentation once erosion has occurred. One must have some knowledge of the forces that induce erosion in order to understand, somewhat, how bank stabilization measures and other methods discussed in this handbook can mitigate problems caused by river channel responses to land development, navigation structures, and water resource demands within the UMRS corridor.

Keown et al. (1977) reviewed several types of streambank erosion identified in the literature:

1. Erosion of bank particles by current action.
2. Erosion of bank particles by wave action.
3. Slip-circle failures caused by undermining of the toe.
4. Flow slides caused by liquefaction in saturated silty and sandy soils.
5. Sloughing of saturated cohesive soils (i.e., banks incapable of free drainage due to their relative impermeability and rapid drawdown).
6. Erosion of soil by seepage out of the bank at relatively low channel velocities.

This list of types of streambank erosion indicates that the causes are not only a function of physical forces that act on the bank material but are also related to the erodibility of the bank (i.e., soil type, soil moisture content). Erosion may result from the forces induced by wave and current action (erosion types 1 and 2, respectively). Slope failure (erosion types 4 to 6) is essentially caused by the failure of different bank materials to restrict subsurface flow (e.g., piping, seepage) and the development of differential hydrostatic pressures between soil particles. The undermining process identified in erosion type 3 may be caused by current action, wave action, or slope failure. The following discussion of channel bank erosion therefore considers bank recession as a result of erosion (i.e., wave and current action), slope failure, or a combination of the two (after Camfield et al. 1980).

3.1. CURRENTS

River flow affects the channel boundary by general degradation, aggradation, and local scouring. These processes may occur concurrently or independently. Their relative importance is determined by current velocities and their distribution within the main channel boundary.

The structure of currents in the stream flow is an important determinant

of the distribution, type, and extent of erosion. Circular upwellings and spiral vortices frequently occur and patterns of currents change with river stage. Turbulent features tend to become more pronounced at high flows and often recur at the same locations in the channel bed, indicating that they are related to irregularities in the channel boundary. It has not been possible to relate the distribution and amount of erosion to the flow patterns or turbulence features (Hooke 1979).

The distribution of currents may be qualitatively determined by calculating the Reynold's number, which is essentially a measure of drag. This value is the ratio of the inertial forces of river flow to the viscosity of the river water. It is directly dependent on current velocity and depth of flow. Turbulent flow is associated with very large Reynold's numbers and conversely, laminar flow is associated with the physical factors that are represented by very small Reynold's numbers (Simons et al. 1975).

Rapid variations in velocity distribution and resultant fluctuations in pressure may be an important cause of slope or revetment failures. The spatial extent of these major fluctuations may be on the order of several hundred feet (Rouse 1963). Tiffany (1963) suggested that these 'blocks' of turbulence in the Mississippi River act simultaneously over areas large enough to raise a serious question as to the ability of revetments to stay in place under the effect of differential uplift pressure. For example, monitoring of pressure variations in the Mississippi River showed that pressures may fluctuate by 0.37 psi for 10-s periods and by as much as 0.5 psi for 15- to 30-s intervals. For comparison, the submerged weight of a 3-in. concrete revetment is 0.152 psi (Tiffany 1963). Such forces are great enough, and the effective spatial area is large enough, to lift blocks of concrete 3 to 6 in. thick (Fenwick 1969).

Current velocity is an important determinant of the sediment-transport capacity of a river. However, the velocity of river flow does not completely reflect the potential forces that may impinge upon river banks. Flowing water also exerts an inertial force against the channel boundary; consequently shear stress, rather than velocity, may be used as a measure of potential erosion within a given reach of the river.

Shear stress (or tractive force) is the force exerted by the sediment-water mixture on the channel boundary (bank and bed) and it exists only when the mixture is in motion. It can be used to assess the force exerted on a bank or structure by river flow, as well as the force required to initiate movement in a sediment particle. It can therefore be used to evaluate the effectiveness of a bank stabilization structure. Simons et al. (1979) stated that this method is basically sound and has been used widely to evaluate the stability of alluvial channels.

The critical boundary shear is the minimum force required to initiate movement of a particle on the channel bed. When the shear stress exerted on the boundary exceeds the critical tractive stress for a particle, incipient motion can occur. This movement can be defined, for present purposes, as erosion of the bank or degradation of the channel bed.

Shear stress is generally evaluated by empirical techniques because of the difficulties involved in determining velocities in turbulent flow (Simons et al. 1975). Empirical equations, such as "Manning's roughness coefficient" or "Chezy's discharge coefficient," implicitly express the shear stress as a function of average flow velocity. These relations account for boundary irregularities ("roughness") and the coefficients vary with discharge. In general, the greater the boundary roughness, the lower the flow velocity and tractive force exerted by that flow. A catalog of values of Manning's n and Chezy's C was developed for engineers to estimate values through knowledge of the general nature of channel boundaries (Simons et al. 1975).

In large alluvial channels like the Mississippi River, the average shear stress can be approximated by the equation:

$$\tau_o = \gamma d S$$

where τ_o = average boundary shear stress; γ = specific weight of the sediment-water mixture (mass density of the fluid X gravity); d = average depth of flow; and S = channel slope.

Shear stress is a measure of changes in the hydraulic flow characteristics, since the average boundary shear stress is proportional to the mean velocity squared (Simons et al. 1979), and is therefore very sensitive to changes in velocity or discharge. Similarly, the boundary shear stress also varies spatially in response to the velocity distribution in a vertical column of water. Fig. 2 shows the variation of velocity and sediment load with depth below the water surface. This concept of velocity and sediment load approaches equilibrium below the water surface and has led Lane et al. (1953) and other investigators to demonstrate, in both theoretical evaluation and physical experiments in the laboratory and the field, that the maximum tractive shear stress acts on the banks of the channel at about two-thirds of the depth below the air-water interface.

The average shear stress may also maximize at bends in the river channel as a result of centrifugal force. Simons et al. (1975) noted that transverse currents superimposed on the longitudinal flow form the screwlike, helicoidal secondary circulation observed in river bends and laboratory flumes. These transverse currents, generally 15% of the mean current velocity, have been cited as the primary mechanism for scouring and deposition at bends. The increased velocity may increase the shear stress acting on the outside bank in the bend by as much as 1.5 times the shear in a straight reach. This value,

1.5 times the mean shear stress, is often used as the potential maximum shear force that must be considered in the design of bank stabilization structures.

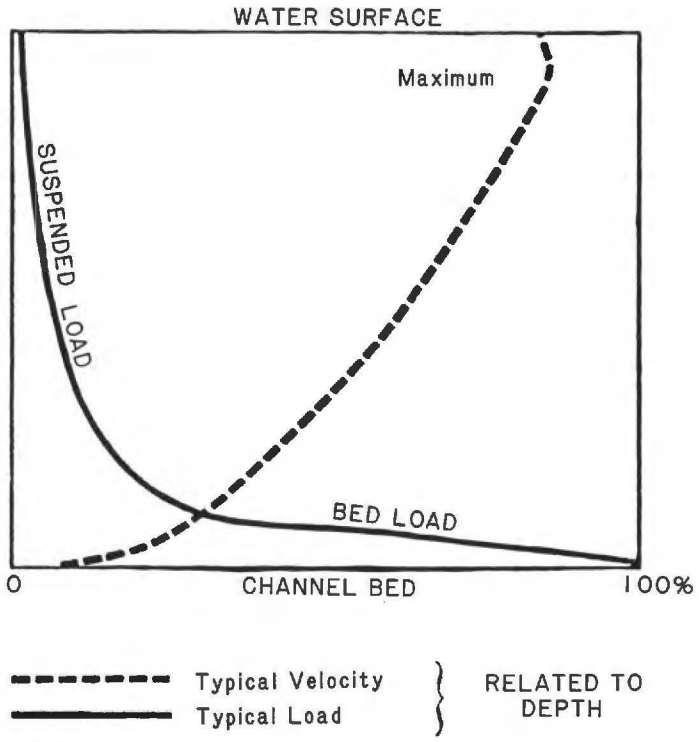


Fig. 2. Variation of velocity and sediment load with depth below water surface (Keown et al. 1977).

In general, then, any disturbance of the river flow that increases flow velocity or the total sediment load will increase the shear force acting on that reach of the boundary, other factors being constant. Therefore, to reduce the tractive force that river flow exerts on the channel bank, one can either reduce sediment loads or reduce flow velocity. Sediment loads can be reduced by stabilizing banks, improving land use practices, providing sediment traps, or constructing impoundments; flow velocity can be reduced by reducing slope (impoundment), reducing maximum flood stage, diverting current away from banks (e.g., by installing wing dams, jacks), or increasing boundary roughness (e.g., by planting aquatic vegetation).

Similarly, the impact of shear stress on the channel boundary can be mitigated by using appropriate lower bank stabilization structures.

3.2. WAVE ACTION

Waves, created by wind blowing over the surface of the water or by a boat

moving through the water, can cause soil bank erosion and subsequent increases in turbidity and sedimentation (Karaki and Van Hoften 1974; Sparks 1975a). Bhowmik (1975) wrote: "As the wave approaches upward onto a sloping beach, the lower part of the wave is retarded by the friction and pressure of the beach, while the top part continues with almost its original velocity. After breaking against the shore, waves sometimes throw water high in the air, depicting the tremendous amount of energy they contain. The breaking waves follow a downward path along the bank to the lake and may wash away the fine sands and start the failure of the bank."

Wave-induced river bank erosion may be caused by three processes (Simons et al. 1979):

1. The impact of the wave on the bank.
2. The wave runup and rundown on the bank.
3. Fluctuating water levels (induced by wave action). Such fluctuations may cause piping or differential hydrostatic pressure (piping refers to the process of dislodgment of bank particles, which results in undermining of the bank).

The force of the wave impact and wave runup on the bank is a function of the embankment slope and wave characteristics (e.g., relative steepness). Erosion due to fluctuating water levels is largely dependent on soil type, soil compaction, and soil moisture. Model studies of canal bank erosion due to wind waves showed that, with other factors held constant, the rate of erosion of an embankment compacted to 97% of the Proctor maximum dry density was about 3 times that for an embankment compacted to 99% of maximum density. If the embankment was permitted to become dry, slaking occurred upon rewetting, and resistance to erosion was greatly reduced (Carlson and Sayre 1961). This process is explained in greater detail in the section on "Slope failure" that follows.

Waves are generally classified as deep, intermediate, and shallow. Deep waves occur when the depth of water is greater than about half the wave length, and shallow waves occur when the depth is less than $1/20$ the wave length. Deep water waves have a celerity (speed of wave propagation) independent of depth, whereas the speed of propagation for shallow waves depends on depth (Karaki and Van Hoften 1974).

Wind waves and boat-generated waves are created by different forces. The significant wave height of wind waves can be shown to be a function of wind velocity, wind direction, and fetch length and width by the following equation (Bhowmik 1975):

$$gH_s/U_e^2 = 3.23 \times 10^{-2} (gF_e/U_e^2)^{0.435}$$

where H_s = significant wave height (wave height where $^1/_3$ of the wave profile

is more than this wave height), Fe = effective fetch, Ue = effective wind velocity, and g = acceleration due to gravity

Figure 3 illustrates the relation between significant wave height, wind velocity and effective fetch.

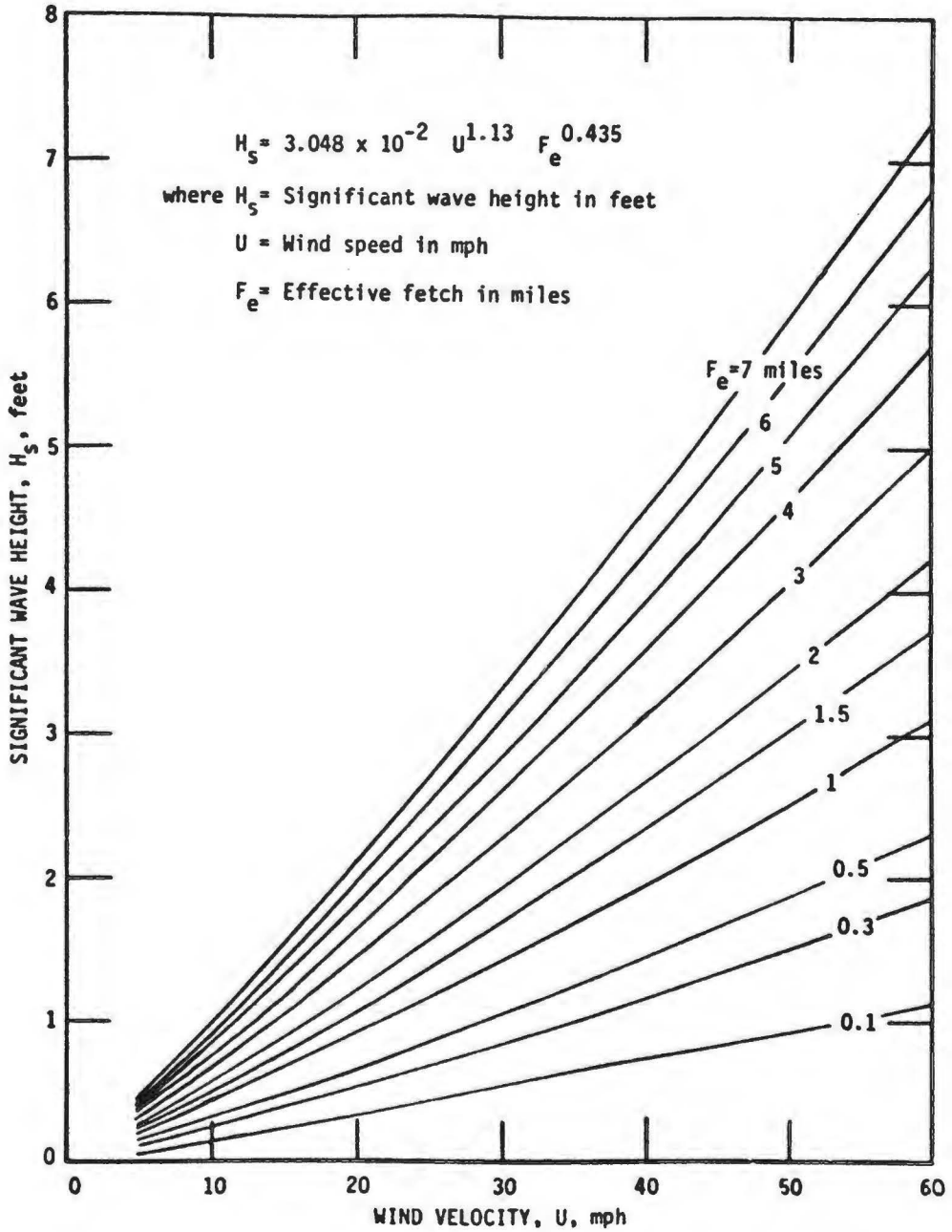


Fig. 3. Significant wave height as a function of wind velocity and effective fetch (Bhowmik 1975).

Energy dissipation due to the vertical water column (depth) has not been accounted for in Bhowmik's model. Sheng and Lick (1979) developed a semi-empirical method for estimating the significant wave height and significant wave period at a given location. The model includes consideration of the average depth over the fetch length. Modification due to bottom friction (shear stress generated at the sediment-water interface) can also be evaluated by this model.

Wind-generated waves are most pronounced in bodies of water with large areas exposed to the force of the wind, like many of the pools behind the locks and dams on UMR. Where the fetch is limited in a direction coincident with the wind direction, but stretches out in directions at an angle to the wind (up to 45° of the angle's cosine), an effective fetch length greater than the distance directly in the path of the wind may result. Sibul (1955) was the first to recognize that these angular wind components may contribute to wave propagation.

According to Bhowmik (1975) the maximum wave height (H_m) generated by a moving boat is a function of draft (d_s), speed (V) and length of boat (L), and the distance between the boat and the wave gage (x):

$$(H_m/d_s)^2 = (3.45) \times (10^{-2}) \, V^{1.174} \, (x/L)^{-0.915}$$

Although this model incorporates the distance between the vessel and the wave gage, the significance of this variable needs to be emphasized. A typical boat-generated wave consists of diverging waves propagated by the bow and transverse waves generated by displaced water behind the boat. These waves form a constant pattern and the maximum wave height occurs where these waves converge and superimpose on one another. The angle of convergence, with respect to the sailing line, increases with decreasing water depth (Johnson 1969). Hence, the decrease in wave amplitude with distance from the sailing line may not be linear, since that decrease varies with depth. This lack of linearity indicates that both distance between boat and wave gage, as well as depth of water must be accounted for in a model of the dynamics of boat-generated waves.

The point of convergence is significant from the standpoint of wave impact on the shoreline. Camfield et al. (1980) noted that, depending on the distance between the vessel and the channel bank, waves propagating from the bow may coincide with transverse waves from the stern and actually amplify the wave height at the bank.

In addition to depth, the gradual decrease of wave height with distance from the sailing line varies with vessel speed (Fig. 4) and vessel characteristics (Table 1). Wave heights generally decrease faster for waves generated by high-speed vessels than for waves generated by boats traveling at lower speeds (Fig. 4).

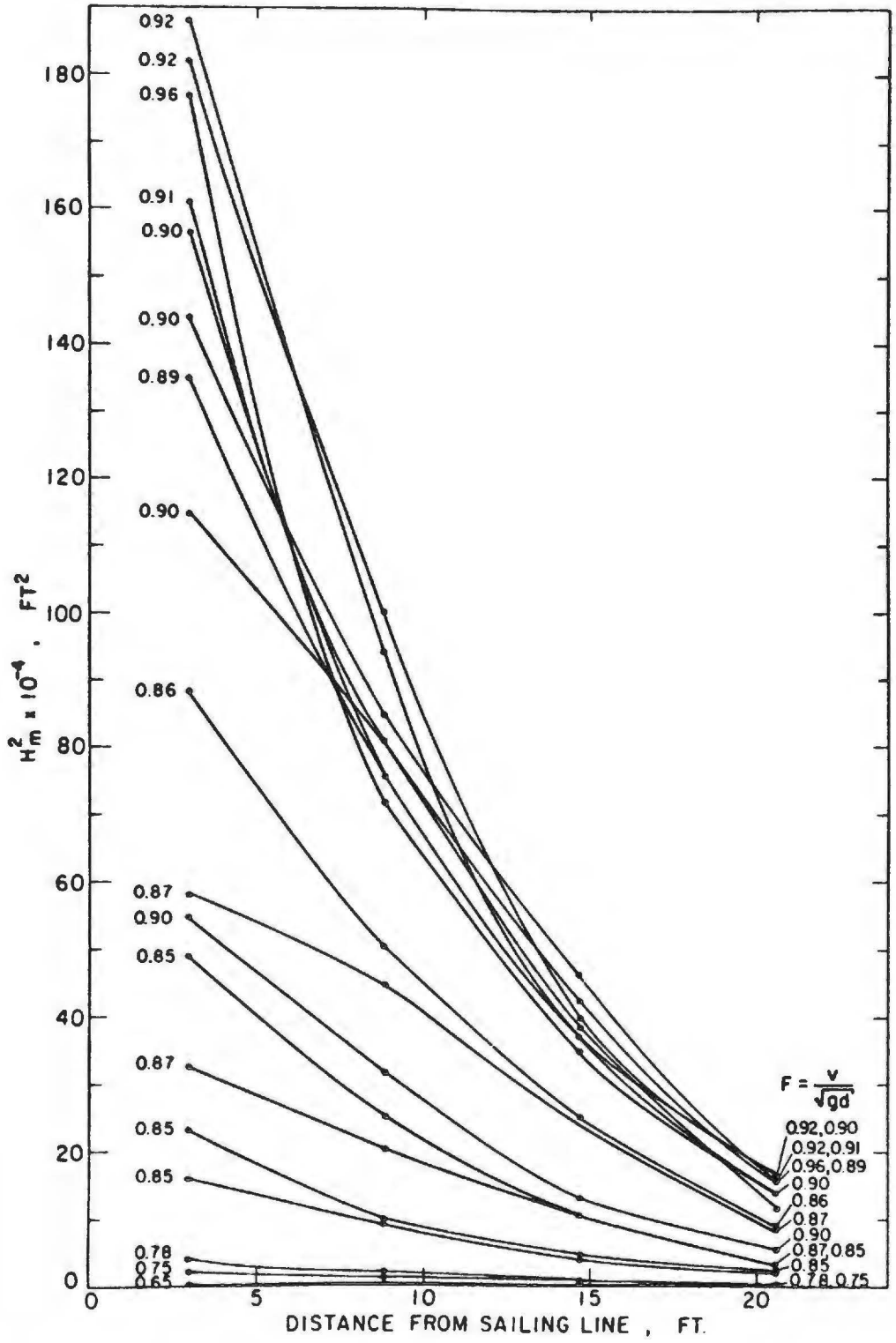


Fig. 4. Wave energy (H_m^2) as a function of distance from the sailing line and vessel speed (Froude number) for a cruiser model moving through shallow water (prototype depth = 5.5 ft) (Das and Johnson 1970).

Table 1. Maximum height (feet) of waves generated by vessels of different types moving through water 35-40 ft deep at a constant speed of 10 knots (modified from Sorenson 1973).

Vessel	Vessel dimensions and characteristics				Distance from sailing line (feet)	
	Length (feet)	Beam (feet)	Draft (feet)	Displacement (tons)	100	500
Cabin cruiser	23	8.25	1.7	3	1.1	0.8
Coast guard cutter	40	10	3.5	10	1.6	1.0
Tugboat	45	13	6	29	1.6	0.9
Fishing boat	64	12.8	3	35	1.8	0.7
Fireboat	100	28	10.5	343	1.6	1.0

Vessel speed is critical and may not be adequately emphasized in the model developed by Bhowmik (1975). According to Karaki and Van Hoften (1974), wave height is entirely dependent on boat speed; and Table 1 shows that vessels with vastly different displacements and hull forms generate waves of about the same amplitude, even when the boats are traveling at the same speed. Figure 4 shows the energy of a wave as a direct function of vessel speed as measured by the Froude number, which is the ratio of inertial forces in the system to the gravitational forces. Karaki and Van Hoften (1974) verified this concept on the Illinois and Upper Mississippi rivers, using infrared photography. A small boat traveling at 18 knots generated waves 4 ft high, where a towboat moving at 8 knots generated waves only 1.5 ft high.

The relation between wave height and vessel speed can be expressed as

$$H = C/C_o$$

where C is the speed of the boat and C_o is the velocity of the wave in shallow water defined as $\sqrt{gd}$, where g = acceleration of gravity and d = water depth (Johnson 1969). Because C_o decreases with increasing water depth, wave height must increase with decreasing water depth. Therefore, wave height may be reduced by decreasing vessel speed or increasing water depth.

The observation that small boats may generate greater waves than large vessels may be a reflection of both greater speed and the fact that small boats with small drafts dissipate their energies at or near the water surface. Waves generated by boats represent a transfer of energy from the boat to the water surface. Because wave energy is concentrated at the still-water level, one might expect that small boats traveling at the air-water interface would dissipate a relatively much larger proportion of the energy into wave height. Similarly, Hay (1969) noted that small vessels may produce waves similar in

height to those produced by larger vessels traveling at a lesser speed. Das and Johnson (1970) acknowledged that small boats can induce more serious wave conditions than a large ship.

Energy generated by larger vessels (with deeper drafts and greater horsepower) can also be dissipated in forms other than surface waves. Camfield et al. (1980) noted that effects of vessel traffic on bank erosion include the return current, the slope-supply current, and the propeller jet, in addition to the waves propagated by the bow and stern. The impact of these subsurface currents on river banks would presumably be greatest when the rudder is oriented directly toward the bank. Bumm et al. (1973), in reference to navigation in European ports, reported that the mooring of vessels along the river bank (e.g., barge fleeting areas and areas in proximity to locks) subjects the bank to the direct impact of eddies produced by the propellers. In particular, when a vessel begins to move away from the quay or turns inside the port, the propeller's backwash is thrown directly and violently against the bank because of the position of the rudder. According to these authors, this type of force is much greater than the destructive effect of bow and stern waves. Bumm et al. (1973) also stated that uplift pressures may be generated by waves and eddies resulting from the passage of vessels. These uplift pressures last for only a short time but they occur at each passage of a vessel. When the water level of a river drops momentarily because of passing vessels, a trapezoidal pressure is produced upon the lower face of a bank or revetment. These observations indicate that the erosive forces generated by large boats, such as towboats, are not restricted to wave action; therefore appropriate lower bank protection may be required to mitigate the full impact of commercial boat traffic.

The magnitude of subsurface currents generated by vessels may not be directly related to the height of the wave or the speed of the boat. Schulz (1978) found that barge speeds fluctuate from 15 to 37% during constant power due to the effects of steering, current, and the river bank and bottom. Conversely, for a given speed, vessel horsepower may be expected to fluctuate over time. With the knowledge that wave height is proportional to vessel speed, this observation implies that the waves propagated by two identical barges, traveling at the same speed (as opposed to velocity) in the same reach of the river, will be of the same height. However, horsepower generated during this same interval may have varied by as much as 37% for each vessel, indicating that the magnitude of subsurface currents generated by the vessels may have varied considerably as well.

Regardless of the forces contributing to the maximum or significant wave height, wave height is an important variable because the potential and kinetic energy of a wave system is largely a function of wave height. The energy contained per unit of wave surface is directly proportional to the square of the wave height (Bowley 1974; Karaki and Van Hoften 1974; Wiegel 1960). Similarly, wave modeling at the Hydraulic Laboratory of the Bureau of Reclamation in Denver showed that the rate of canal bank erosion was dependent

primarily on wave amplitude and the density to which the soil had been compacted (Carlson and Sayre 1961).

Hence, the erosional forces of wind- and boat-generated waves can be mitigated by reducing the conditions contributing to wave height, by increasing wave attenuation, or by reducing wave impaction on the shoreline. More specifically, the forces can be reduced in four general ways: (1) Boat traffic can be reduced by restricting speed, increasing or decreasing draft, restricting the volume or frequency of boat traffic, or maintaining some off-limit zones between boats and channel banks. (2) Fetch can be reduced by the creation of islands. (3) Wave height can be reduced by breakwaters, aquatic vegetation, or artificial reefs. (4) Wave impact can be reduced by revetments or bulkheads and by riparian vegetation.

3.3. SLOPE FAILURE

Resistance of a river bank to the erosive forces of current and wave action is closely related to the characteristics of the bank material. The material forming the banks of rivers is highly variable and can be broadly classified as noncohesive, cohesive, or stratified (Simons et al. 1979).

Noncohesive soils are composed of coarse materials, such as silts, sands, and gravels, which have no chemical or electrochemical bonding between the particles (Camfield et al. 1980). Such bank materials tend to be removed from the embankment grain by grain. The rate of particle removal, and hence the rate of bank erosion, is affected by such factors as local current velocity, turbulence fluctuations, local shear stress, seepage forces, piping, and wave forces (Simons et al. 1979). The erosive characteristics of noncohesive soils, which are controlled by gravitational forces, and the basic characteristics affecting the erosion of cohesionless particles (i.e., particle size, shape and gradation, moisture content, relative density) are fairly well understood (Keown et al. 1977).

Cohesive soils are clays consisting of fine particles of chemically active minerals that create strong chemical bonds between particles. The chemical and electrochemical properties of clays complicate the analysis of the behavior of cohesive soils (Camfield et al. 1980). The basic variables affecting the erosion of cohesive soils are soil pore-water concentration (type and amount of cations), composition of soil type, amount of clay mineral, moisture content, dry unit weight, soil pH, eroding fluid composition, eroding fluid pH, and the temperature of the eroding fluid (Keown et al. 1977). Cohesive material is more resistant to surface erosion and has a low permeability that reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. However, such banks, when undercut or saturated, are more likely to fail due to mass wasting processes such as flow sliding (Simons et al. 1979).

The stratified bank is very common on alluvial rivers and generally is the product of past transport and deposition of sediment by the river. These types of banks consist of layers of materials of various sizes, permeabilities, and cohesion. The layers of noncohesive material are subject to surface erosion, but may be partly protected by adjacent layers of cohesive material. This type of bank is also vulnerable to erosion and sliding as a consequence of subsurface flow and piping (Simons et al. 1979).

The mechanisms that trigger failure of bank materials may occur even when the bank is not directly attacked by wave or current action. Failure of the bank may be induced by the presence or absence of water within the particle interstices, and the resultant creation of differential hydrostatic pressures and subsurface flows. The movement of water is restricted in varying degrees by the different bank materials.

Subsurface flow may result from a change in river stage, pool drawdown, fluctuating water levels induced by wave action, temporarily backed-up water, and groundwater flow. Simons et al. (1979) reviewed the forces that cause movement of water through the bank material:

1. On the rising stage a gradient develops, sloping from the river channel into the bank material. On the falling stage the energy gradient reverses direction and water moves through the banks toward the river channel, decreasing the stability of the bank.

2. If the water table is higher than the river stage, flow is from the banks into the river. A high water table may result from many conditions: (a) a wet period during which water draining from adjacent watersheds saturates the floodplain level, (b) poor drainage, resulting from deterioration or failure of drainage systems, (c) increased infiltration resulting from changes in land use that caused an increase in water level, and (d) development of the adjacent floodplain for homes and businesses that use septic tanks and leach fields to dispose of waste water and sewage.

3. In general, the release of stored water for hydroelectric and navigation purposes causes fluctuations in river stages. These changes in stage, even though relatively small, can cause water flow in the river banks.

4. Wind-generated waves cause localized variations in stage that induce inflows and outflows of water from the banks. However, because the duration of changes in stage is brief, the inflow and outflow phenomena are usually concentrated locally on the surface of the banks.

5. Boat-generated waves have an effect similar to that of wind-generated waves, but the characteristics of the waves

generated are different. This difference must be considered when one compares bank erosion caused by wind-generated and boat-generated waves.

6. The formation and loss of backwaters caused by ice flows and ice jams leads to seepage into and out of the banks.

The movement of water within the river bank toward or away from the river affects bank stability and bank erosion in various ways. Simons et al. (1979) noted that as water flows from the river into adjacent banks, a stabilizing seepage force is generated. Rivers of a particular discharge that continuously seep water into their banks tend to be narrower and deeper than rivers that continuously gain water by an inflow from their banks. The inflowing water creates a seepage force that makes the banks less stable and induces such erosional processes as (1) piping, (2) flow slides, and (3) sloughing (erosion types 4-6 of Keown et al. 1977).

3.3.1. Piping

Piping is an erosional process common to noncohesive soils and stratified river banks. Layers of cohesionless soils frequently provide conduits for groundwater, which seeps out and down the bank face, causing erosion. In banks that are stratified, flow is induced in the more permeable layers by changes in river stage and, to some degree, by wind- and boat-generated waves. With a rise in the river stage, a gradient is developed that induces flow into the more permeable layers of the bank. As the stage drops, the energy gradient is reversed and significant flow occurs toward the river in these more permeable layers. If this flow is capable of dislodging and transporting particles from these layers, the material is slowly removed, undermining portions of the bank. Pore pressures within these layers may also be increased to a point where shear strength and slope stability may be lost. In any event, the net result is bank failure induced by seepage forces, piping, and mass wasting (Simons et al. 1979).

3.3.2. Flow Slides

Flow slides are initiated in layers of saturated sands of low relative density, in the substratum portion of the river bank. These sand layers liquefy when strain or vibration produces excessive pore pressures that reduce the effective stress, and consequently the shear strength, to zero (Keown et al. 1977). The actual flow slide may be triggered by any of a number of factors (Tiffany 1963), including fluctuations in groundwater levels, vibration of the slope, or erosion of the toe (Simons et al. 1979). Large flow slides are also known as landslides, and the process of flow sliding may alternatively be called mass wasting.

The potential for bank erosion caused by flow slides is great. In 1950, at Free Nigger Point on the Lower Mississippi River, more than 4 million cubic yards of bank slid into the river in a matter of only a few hours, leading to the destruction and removal of a considerable length of bank revetment. The flow slide extended so far laterally into the bank that it crevassed the main-line levee 800 ft from the bank and caused overbank flooding behind the levee line (Tiffany 1963).

3.3.3. Sloughing

Sloughing is a crumbling or falling away of the embankment slope. According to C. H. Pennington (personal communication) sloughing can result when any of four conditions occur:

1. The toe of a sand or silt bank is undercut, causing a slide of the surface material. If the bank is wet, sloughing may not result immediately; however, as the bank drys out, failure may occur.

2. The toe of a cohesive bank is undercut. If the shear strength of the bank material is low enough, failure occurs and the surface material slides down the bank.

3. Surface erosion over part or all of a sand or silt bank face leaves the material at an angle greater than the angle of repose. If the bank is moist, it may stand; however if the bank drys out it will slough.

4. A rapid drawdown of the water surface elevation may cause a saturated cohesive bank to fail.

3.4. SUMMARY OF PREVENTIVE MEASURES AGAINST EROSION

Mitigating slope failures due to erosional processes such as piping, flow slides, and sloughing is difficult because the integrity of bank material cannot be readily altered. Nevertheless, U.S. Army Engineer Waterways Experiment Station (1956) identified certain actions that potentially may reduce or prevent flow sliding:

1. Allow a minor failure to run its normal course. When the extent of the unstable sand deposit is small, it is not advisable to attempt to stabilize or protect this deposit, but rather to let it be removed by normal scour and minor failures until more stable soils are exposed; alternatively a minor setback of the levee might be considered, rather than an attempt to prevent a bank failure by revetment.

2. Partial stabilization by advanced grading, particularly by flattening steep slopes in overburden deposits.

3. Partial stabilization by causing preventive failures. Such failures might be induced by dredging or the use of explosives. The reasoning behind this approach is that experience seems to indicate that the potential danger of flow failure in once-failed or remolded stratified sands is smaller than that in undisturbed soils.

4. Partial stabilization by compaction.

5. Partial stabilization by drainage of the surface sands by means of vertical drains consisting of coarse sand or gravel to lower, more pervious and stable sand series.

6. Partial stabilization by grouting.

In addition, vegetation and conventional bank stabilization structures may be used. In areas where subsurface flows and differential hydrostatic pressures are expected to create problems, gravel or sand filter beds or artificial filter mats may be used beneath the bank revetment. If adequately designed, these filter beds or mats should provide sufficient permeability to relieve hydrostatic pressure buildups.

Currents, wind- and boat-generated waves, and the hydraulic forces within the bank impact on the shoreline in varying combinations. The relative contribution of any one factor to bank recession is highly site-specific (Camfield et al. 1980), and can vary significantly with channel width, bank materials, presence of vegetation, depth of water or stage of river flow, duration and frequency of vessel traffic, etc. Simons et al. (1979) noted that the forces causing bank instability may be increased by as much as 60% by variations in these types of site-specific characteristics. This variability in geomorphologic and hydraulic conditions makes it difficult to assess the relative magnitude of these forces.

Nevertheless, some attempts have been made to assess the relative importance of the forces causing bank instability. Simons et al. (1979), who assessed the magnitude of these forces on the Connecticut River, found that the natural river is roughly 1.3 times more susceptible to major erosion than are pools formed by hydroelectric dams. This greater susceptibility is a result of shear stress being the dominating destabilizing factor. The second most important factor, pool fluctuation, contributed only 18% as much as shear stress to bank instability. The other factors, in descending order of importance, were boat waves, gravitational forces, seepage forces, stage variations, wind waves, ice, flood variations, and freeze-thaws. C. H. Pennington (personal communication) found that streambank surface erosion can also be caused by changes in channel alignment, structures in the streamflow,

debris abrasion, chemical reaction, and changes in land use.

On the Sacramento River, Limerinos and Smith (1975) found that, in a narrow channel subject to winter flood flow and heavy boat traffic, about 20% of the annual energy dissipated against the levees could be attributed to boat-generated waves, about 10% to wind-generated waves, and 70% to tractive shear stress. In a channel relatively unaffected by winter flood flows, energy dissipation from boat-generated waves was shown to range from 45% to as much as 80% of the total, depending on what assumptions were made about wind movement in the computations. Limerinos and Smith did not evaluate other factors that are generally accepted to be minor or secondary, such as levee subsidence, damage from rodents, seepage forces, direct wind erosion, and vegetation changes.

Ouellet and Baird (1978), who investigated wave action on the St. Lawrence River during the ice-free season and during winter, found that wave action was the primary source of bank erosion and that the formation of ice tended to protect the shores from wave damage. Where the river is relatively wide, most erosion of the banks was produced by wind waves. Where the river is narrow, however, waves generated by ship passage were relatively more damaging than wind waves.

On the basis of laboratory experiments on the effect of seepage on bank stability, Burgi and Karaki (1971) reported that side slope erosion was directly related to the hydraulic gradient as well as to the flow velocity in the channel. At relatively low velocities (less than 1 fps), erosion of the side slope was due primarily to the hydraulic gradient (seepage forces); at higher channel flow velocities, bank erosion was dominated by the channel flow velocities (tractive forces).

Determination of the relative importance of the factors contributing to bank recession may be economically desirable. This knowledge allows river managers to direct often limited funds toward bank protection measures that will mitigate the erosive force causing the proportionately greatest damage, at least cost. If, for example, structures are built to control erosion when bank recession is the result of slope instability due to other causes, the structure may be lost and the whole effort may prove futile (Camfield et al. 1980). Similarly, Simons et al. (1979) noted that wave action and fluctuating water levels impinge mostly on the upper banks, whereas the tractive force exerted by current flow is greatest at two-thirds the flow depth. Consequently the impacts of wave action and shear stress on the shoreline are most effectively reduced by applying appropriate protection measures to the upper and lower banks, respectively. The various impacts and erosive forces (i.e., currents, wave action, and slope failure) encountered on UMRS were discussed in Part IV of this guide. In addition, our discussion of bank stabilization techniques in the following chapters (Chapters 4-20) contain other information on the erosive forces in UMRS and other large river systems.

Based on the general manner in which they function, there are five general categories of bank stabilization measures that could be used within UMRS and other large river systems. We identify them here and indicate the chapters in which they are discussed:

1. Structures such as revetments and bulkheads, that provide some form of parallel bank cover that protects the bank from direct erosion and scouring processes (Chapters 4 and 5).

2. Structures that guide or train river flow and thereby indirectly protect banks from the scouring processes of river flow (Chapter 6).

3. Breakwater structures that are designed to reduce wave impact and are parallel to, but separated from, the shoreline (Chapters 7-9).

4. Measures that reduce, prevent, or mitigate soil instability or the buildup of hydrostatic pressure within the bank or beneath a hydraulic structure, such as the planting of vegetation, or use of chemical soil stabilizers, erosion-control mattings, filter fabrics, hydraulic wells or drains, or other soil stabilizers or hydrostatic pressure relief devices. Some of these measures serve to reduce wave and current actions on the bank, and generally increase bank stability (Chapters 10-16).

5. In addition to the above structures and measures, several others could be used to reduce erosive forces, such as regulating boat traffic to reduce the impact of boat-generated waves on the shoreline or creating islands to reduce fetch length (Chapters 17-20).

CHAPTER 4. RIPRAP REVETMENTS

4.1. SITUATION TO BE MITIGATED OR ENHANCED

The installation of riprap is considered to be a bank stabilization technique. Riprap can also be used to inhibit degradation of the channel bed near bridge piers or culvert outlets, or as toe protection for other bank stabilization structures and bulkheads, particularly impermeable ones.

As we indicated previously, the purpose of any bank stabilization structure is to reduce lateral migration of the channel or to induce bed scouring for navigation purposes (Lindner 1969). Riprap can be designed to reduce erosion due to wind- and boat-generated waves, high flow velocities, and local scouring, and may therefore be used for both upper and lower bank protection.

Riprap protects the upper bank by dissipating wave energy and by preventing soil particle movement caused by fluctuating water levels and differential hydrostatic pressure. Wave energy is dissipated by wave runup on the revetment surface and by creating turbulence and scour in the vicinity of the stones. As Bumm et al. (1973) pointed out, the "scour of riprap is of no importance (assuming adequate design and construction) since the subsequent settlement of the rock does not change the already irregular surface of the riprap." Soil particles are further stabilized, in both the upper and lower bank, by appropriate blanket and bedding gradation or the use of filter fabrics beneath the riprap blanket.

Riprap protects the lower bank from erosive forces by reducing flow velocities and increasing the critical boundary shear. Flow velocity is reduced essentially by increasing the boundary roughness as measured by Manning's "n." The increased critical boundary shear is directly related to the weight of the median riprap stone and can be approximated by the equation proposed by Myers and Ulmer (1975)

$$\tau_c = 4(D50)$$

and expressed in pounds per square foot.

The critical boundary shear, τ_c, is defined as the minimum force required to initiate movement of stones of the median diameter. The critical boundary shear must therefore always be larger than the maximum boundary shear to maintain its stability. The maximum local shear in straight, trapezoidal channels can be evaluated by the following formula (Myers and Ulmer 1975):

$$\tau_o \text{ (max)} = 1.5\, \gamma\, dS$$

where γ = specific weight of water; d = depth; and S = channel slope

Simons et al. (1979) described a method of riprap design that relates the maximum boundary shear to the critical boundary shear and thus enables the development of a more stable revetment.

4.2. DESCRIPTION OF TECHNIQUES

Riprap consists of natural rock or quarry stone that is dumped or hand-placed on embankments, levees, island heads, around hydraulic structures, and in other areas subject to wind- and boat-generated waves, high current velocities, or local scouring. Before placement of the rocks, the bank is usually graded if the slope is irregular or too steep. A bed of gravel or porous filter material may be placed between the bank and riprap blanket to allow seepage but still prevent erosion of the bank material.

Where stones of sufficient size are available, Keown et al. (1977) considered riprap to generally be the first choice among bank protection methods because it offers certain distinct advantages:

1. A riprap blanket is flexible and is neither impaired nor weakened by slight movements of the bank resulting from settlement or other minor adjustment.

2. Local damage or loss is easily repaired by the addition of more rock.

3. Construction is not complicated and no special equipment or construction practices are necessary.

4. Appearance is natural, and therefore acceptable in recreational areas.

5. Vegetation often grows among the rocks, adding structural value to the bank material and restoring natural roughness.

6. Riprap is recoverable and may be stockpiled for future use.

In addition, riprap stones reduce wave runup more than other revetment surfaces (Richardson et al. 1975), and may have potential fishery enhancement value.

Myers and Ulmer (1975) noted that, although riprap is perhaps the oldest and most widely used form of streambank protection, it is also often the "most misused" form; placement of rock riprap is often random--which it is not intended to be. Rather it should be based on specific design criteria, with

appreciation for the dynamics of river channel response. A major factor contributing to inadequate riprap construction has been the lack of a straightforward design that a field engineer can confidently use, even though most theoretical design work related to streambank protection has been directed toward riprap (Keown et al. 1977).

Much recent literature pertains to riprap revetment design (e.g., Anderson et al. 1970; Campbell 1966; Crews 1970; Maynord 1978; Myers and Ulmer 1975; Powell and Brasfield 1957; Richardson et al. 1975; Simons et al. 1979). Reviews of riprap design for riverbed protection around hydraulic structures (e.g., bridge piers) or culvert outlets were given by Nece (1974) and Schilling (1975), respectively. The following summary of important factors to be considered in designing effective riprap protection for river banks is intended to make the resource manager aware of design criteria, but is not intended to be an intensive or exhaustive analysis of riprap construction.

The effectiveness of a riprap blanket is evaluated in terms of the stability of the blanket under excessive hydraulic flow conditions, the ability of the bedding material to prevent erosion of the natural bank material through the riprap, and the resistance of the riprap revetment to toe erosion and raveling at the ends of the blanket (Keown et al. 1977). To meet these design objectives, one must know the (1) shape, size, and weight of riprap stones needed (and their availability); (2) optimum blanket and bed thickness; (3) height of the revetment required to prevent overtopping by waves; (4) optimum bank slope; and (5) proper placement methods for the riprap blanket.

No analytical method has been developed for determining the optimum stone shape. Selection of the stone shape is usually a compromise between subjective experience and what is available. Keown et al. (1977) suggested that, in general, no stones used should have length-to-width ratios greater than 3.0 and no more than 25% of the stones should have a length-to-width ratio greater than 2.5.

Riprap consisting of angular stone is probably more stable than that consisting of rounded stones. Fenwick (1969) noted that when a bedding material is used, the particles should be angular, or somewhat so, to prevent the blanket from slipping down the slope. The angle of repose for riprap is directly dependent on the size of the stone (Fig. 5 and 6). McCartney et al. (1976) found that rounded boulders were about as stable as a stone overlay of angular quarrystone, but because of their shape, more boulders per unit area were required to obtain the same coverage. However, some mobility (instability) may be desired. Thompson and Jackson (1977) suggested that the stones tend to move so as to present a surface that is progressively smoother and more resistant to wave attack. In addition, tests of riprap stability under wave attack demonstrated that when a stone was removed from its place in a structure, stone or rubble near to it often tended to move into this hole

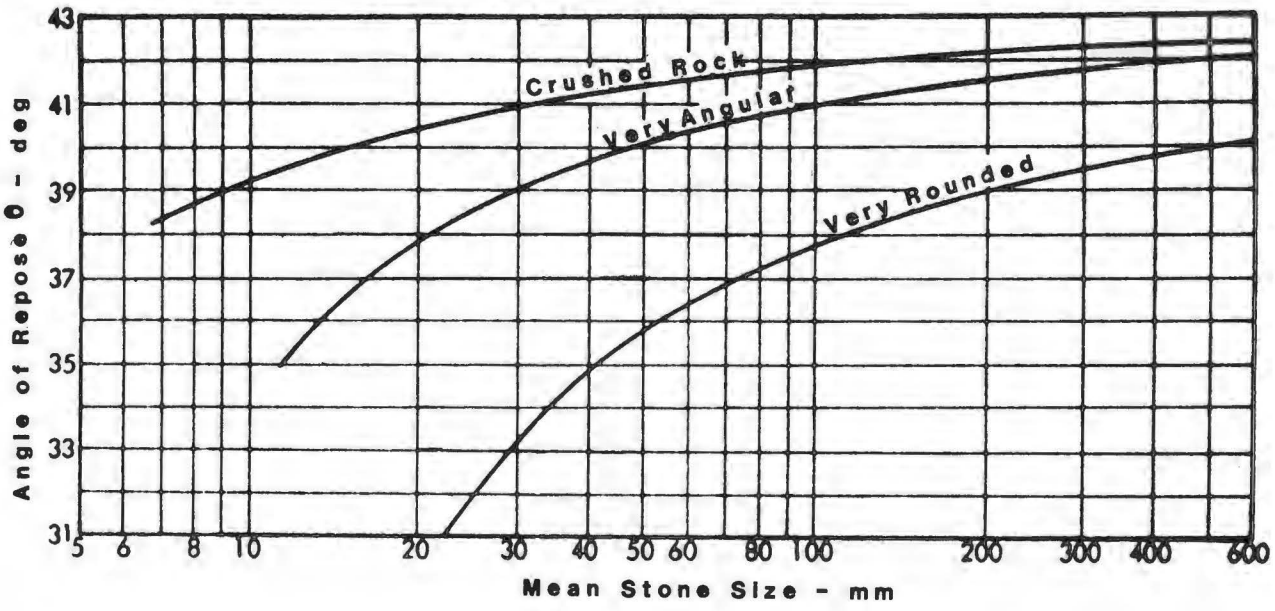


Fig. 5. Angle of repose of riprap in terms of mean size and shape of stone (Meyers and Ulmer 1975).

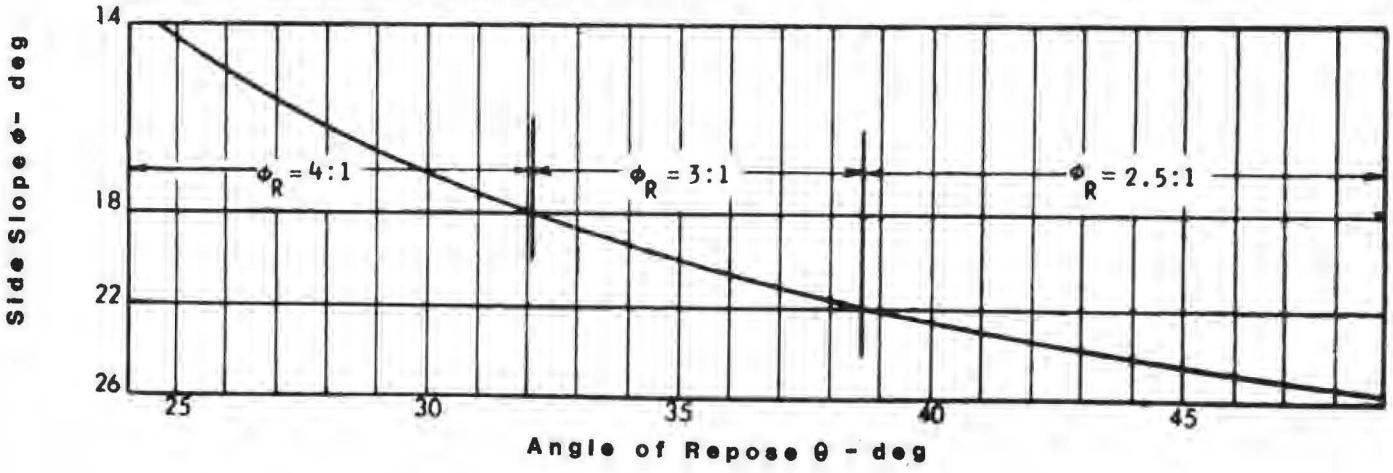


Fig. 6. Recommended side slopes of trapezoidal channels in terms of riprap angle of repose (Myers and Ulmer 1975).

and "reheal" the damaged section (Saville 1967).

Riprap stone size and weight is often determined by the gradations that are commercially available from quarries (Myers and Ulmer 1975). For each gradation, the median diameter of the stones, or D_{50}, should be determined. This value indicates that 50% of the stones used in the blanket must have diameters greater than D_{50}, and no more than 50% of the stones can weigh less than the weight of a stone with diameter D_{50}. The ideal gradation would have the largest stones about twice the size of the median diameter or about 6.5 times the weight of the median stone (Richardson et al. 1975). If this size distribution is used, the interstices formed by the larger stones are conveniently filled with the smaller sizes in an interlocking fashion, preventing the formation of open pockets. This configuation prevents penetration of jets of water (Brater 1979) or removal of smaller particles.

Oswalt (1968), however, in an investigation of six riprap gradations for use on subimpoundment dams, found that provision of the 50% size is more important than holding to the exact gradation. Similarly, hydraulic tests performed at the Waterways Experiment Station (U.S. Army Engineer Waterways Experiment Station 1964) indicated that the effective critical size stone of a particular gradation represents 60 to 65% of the weight of the maximum stone. In any event, Keown et al. (1977) pointed out that provision of the ideal riprap gradation is seldom economically justified.

The optimum D_{50} stone size and weight that would be stable for maximum hydraulic flow conditions expected for a channel reach or around a hydraulic structure can be estimated by a number of empirical relations, most of which consider the shear stress or tractive force at the boundaries as known quantities (Simons et al. 1979). For example, Myers and Ulmer (1975) showed that D_{50} can be expressed as

$$D_{50} = .0016\ V^3\sqrt{d}\ (\text{ft})$$

where d = depth of flow in feet and V = velocity in fps.

The velocity value used in this equation is $\sqrt{1.5}$ times the average velocity necessitated by the nonuniform shear distribution over the channel bed. The maximum value of the local shear on the bed of a straight, trapezoidal channel is generally 1.5 times the mean shear. The American Society of Civil Engineers (ASCE) Committee on Sedimentation (1972) and Crews (1970) suggested measuring the current velocity within 10 ft of the bank (in a large river), rather than modifying the mean current velocity.

Other authors (Blinco and Simons 1974; Yang and Stall 1974) have shown that the shear stress may vary randomly with respect to sediment discharge, kinematic viscosity of the water, or the roughness coefficient of the channel.

On the basis of this concept, Li et al. (1976) developed a model to predict the probabilities of riprap failure.

Anderson et al. (1970) showed that Manning's "n" for a riprapped surface can be approximated if the D_{50} diameter stone is known by the equation

$$n = 0.0395 (D_{50})^{1/6}$$

Thus the greater the stone size, the greater is the boundary roughness. The ASCE Committee on Sedimentation (1972) concluded that a rock revetment should be rough enough to create a zone of intensified turbulence and low velocity in the vicinity of the rock. This roughness tends to hold the high velocity flow away from the revetment rather than in contact with it. As a result, the revetment is less apt to be undercut by scouring. An excessively large stone or one that protrudes from the face of the blanket may create too much turbulence, however, and contribute to riprap failure. Investigations at the U.S. Army Engineer Waterways Experiment Station (1964) showed that failure of riprap on overflow embankments was initiated by intense fluctuations of pressure, indicative of an excessive degree of turbulence.

Hence, the thickness of a riprap blanket should be sufficient to accommodate the largest stones in the riprap. For a well-graded riprap with no voids, this thickness should be adequate (Simons et al. 1975). Since the ideal riprap gradation should have the largest stones twice the diameter of the median stone, most investigators have suggested a minimum thickness of 1.5 to 2 times the D_{50} diameter (ASCE Committee on Sedimentation 1972; Anderson et al. 1970; Keown et al. 1977; Oswalt 1968). Keown et al. (1977) also pointed out that the largest stones are usually eliminated by the contractor.

The thickness of the riprap blanket may often be increased at the toe, where local scouring forces are greatest (Fenwick 1969). Crews (1970) recommended increasing the thickness of the underwater layers by 50%. Simons et al. (1975) also suggested that if strong wave action is anticipated, the overall thickness of the riprap revetment should be increased by 50%.

As an alternative, the median stone diameter rather than the overall blanket thickness, can be increased to cope with wave attack. Thompson (1977) found that irregular wave damage to impermeable slopes in relatively deep water depends on the ratio of the significant wave height to the D_{50} diameter, in addition to embankment slope and duration of wave attack. Furthermore, the roughness of the riprap surface, which is a function of D_{50}, determines the height of wave runup and overtopping (U.S. Army Engineer Waterways Experimen Station 1962). In general, for a given slope and wave steepness (H/L), a riprapped surface should have a relative runup ratio (R/H) about 50% less than that of a smooth-surfaced slope (Saville et al. 1962). Ahrens et al. (1975) developed methods for predicting stable riprap weights for a given wave steepness and for estimating wave runup on riprap. Saville et al. (1962) gave

sample computations for freeboard allowances in inland reservoirs.

Providing adequate protection from wave overtopping and runup may be an important economic concern under certain situations. In an effort to protect a greater length of shoreline with the same amount of money that was used in the two previous years for a similar shore protection project, budget planners in St. Clements, Maryland, reduced the height of the revetment originally designed by 2 ft to effect a supposed saving of $7.32 per linear foot (Ziegler 1973). Whereas the original revetment performed well for over 8 years, with additional years of life anticipated, frequent wave overtopping of the new revetment caused removal of soil behind the riprap and subsequent collapse of the armor. Within 3 years, the revetment had become ineffective in protecting the shoreline from erosion.

Additional protection for riprap revetments from wave attack may be provided in the form of wire mesh, grouting, and an overlay of larger rock or concrete rubble (Saville 1967). The use of wire mesh is discussed in subsection 5.2.5 on gabions. The use of grouting is limited, and provision of adequate drainage is critical (Lindner 1969). Grouting reduces permeability of the bank and may lead to revetment failure due to hydrostatic pressure under the blanket (Keown et al. 1977). McCartney et al. (1976), investigating the use of a single layer of large armor stone as a protective overlay on underdesigned riprap revetments, found that, although a 100% average overlay is about as stable as a conventional two-layer riprap blanket, the overlay provided only about half the "reserve stability" (protection from the design maximum wave). A single-layer stone overlay can be useful for upgrading small riprap revetments.

If the gradation of riprap is such that movement of the underlying natural material through the blanket is likely, a filter bed of sand, crushed rock, gravel or synthetic fabric must be put in place before the stone blanket is laid down. It is important that the filter be permeable, to prevent hydrostatic pressure buildup beneath the riprap revetment. The thickness of the filter bedding needed depends on the type of filter used, the median diameter of the riprap stone, and the particle size distribution in the underlying soil. In addition to protecting embankment or levee material from washing through the riprap, the use of filter bedding, such as a plastic filter fabric, often reduces the median size stone required in the riprap blanket (Crews 1970). Examples of design specifications for gravel bedding were given by Richardson et al. (1975), and U.S. Environmental Protection Agency (1976). Filter fabric design and use were reviewed by Dallaire (1977), Littlejohn (1977), and Keown and Dardeau (1980). The details of plastic filter bedding material are discussed separately in Chapter 14 because these filters can be used with other types of bank protection.

The D_{50} value can also be used to determine what slope an embankment should be graded to. Anderson et al. (1970) proposed that once the D_{50}

diameter and rock angularity are identified, the natural angle of repose can be determined from Fig. 5, which yields the side slope allowable in Fig. 6. Most authors, however, have simply suggested that an embankment slope be no steeper than 2H:1V (Keown et al. 1977; Mifkovic and Peterson 1975; Myers and Ulmer 1975). Mifkovic and Peterson (1975) originally used a slope of 3H:1V but later recommended 2H:1V as a means of preserving as much of the existing berm width as possible. Keown et al. (1977) suggested that the maximum slope can be increased to 1.5H:1V for hand-placed stone.

Hand-placement of riprap, either grouted or ungrouted, is one method of installation. Stones are generally laid in a more or less definite pattern, usually resulting in a relatively smooth surface. This form of placement is rarely used in the United States--particularly on large rivers, where the largest stone may weigh 2000 lb--because of the high cost of labor (Shanklin 1974).

Riprap is usually placed on graded slopes by simply dumping or casting the stones. Richardson et al. (1975) cautioned that rock should never be placed by dropping it down the slope in a chute or pushing it downhill with a bulldozer. These methods tend to segregate the stone sizes. Draglines with orange-peel buckets, backhoes, and other similar equipment are better suited for installing riprap.

It is important that sufficient toe protection be provided to prevent the undermining of the revetment. Crews (1970) suggested that the rock toe should extend at least 6 ft beyond the bank with a minimum thickness of 3 ft. If the channel bed consists of sandy or silty material, he recommended carrying the riprap to a minimum depth of 5 ft below the channel bed, and omitting the rock toe.

Paving of the lower bank may be facilitated by using rock-filled trenches or by windrowing rock piles along the bank line. Rock-filled trenches are structures used to protect banks from toe erosions. A trench is excavated along the toe of the bank and filled with rocks. As the stream bed adjacent to the toe is eroded, the trench is undercut and the rock fill slides downward to pave the bank. The size of the trench needed depends on the expected depths of scouring.

Rock-filled trenches need not be placed at the toe of the bank. An alternative method is to excavate a trench above the waterline along the top of the river bank and fill it with rocks. As the bank erodes the trench, the rocks slide down and pave the bank. Simons et al. (1975) noted that this method is applicable in areas of rapidly eroding banks of medium to large rivers.

McEwan (1961) mentioned a unique method of riprap placement used on the Lower Colorado River. Rock was windrowed along the desired bankline, the relocated channel was dredged, and the river was allowed to cut its banks until the windrow was reached. The rock then dropped down the eroded bank, stopped the cutting action, and retained the bankline along the planned alignment. This method was successful only where the banks were of noncohesive, alluvial materials. The windrowed revetment was also used on the Missouri River as part of the "Section 32 Project" (part of the Streambank Erosion Control Evaluation and Demonstration Act of 1974).

As an alternative to total bank protection, Simons et al. (1979) proposed placing riprap only on the lower bank of the Connecticut River. Lower bank protection would serve to prevent lateral channel migration. Waves, water level fluctuations, and high velocity flows at flood stage would erode the upper bank and create a shallow shelf or berm wide enough to dissipate the erosive forces caused by these flood-stage events. The extent of erosion landward would usually be limited to an average of 10 to 15 ft in a large river. Ideally, the berm would eventually become revegetated and further stabilize the bank. The berm would also serve to carry water when flows were high. In addition, Patrick (1974) pointed out that this shallow-water environment provides favorable wildlife habitat.

4.3. IMPACTS ON THE ENVIRONMENT

In general, the use of riprap does not adversely affect fish and wildlife resources. Like any bank stabilization measure, riprap may create problems associated with construction and stream channelization, and may result in reduced species diversity. Only a few adverse impacts caused specifically by the use of riprap were identified in the literature we reviewed, and most of these were a result of inadequate or inappropriate design. For instance, Nunnally and Keller (1979) reported that oversized stones were unstable and caused excessive scouring and were unsightly because they were not adequately covered by riparian vegetation. Smaller stones often created maintenance problems near residential areas when "children almost denuded the bank in a few places by heaving stones into the channel." Patrick (1974) also noted that when riprap is placed on very steep, nearly vertical slopes, algal growth is inhibited because surface exposure to sunlight is reduced. However, if riprap gradation and bank slope are suitable, problems should be few.

The advantages of using riprap over other bank protection methods include the relatively natural appearance of stone and the fact that vegetation often grows among the rocks, adding structural integrity and restoring natural roughness (Keown et al. 1977). Vegetative growth can be encouraged by covering the riprap with a soil blanket down to the high-water mark and seeding and planting the bank (Lund 1976). Vegetation eventually provides shade and cover for fish and a more aesthetic natural-appearing streambank (Hunt and Graham 1972). However, because riprapped banks are usually

associated with high energy regimes, the blanket of soil may not stay in place. Such soil was lost, for example on the Section 32 Project of the Missouri River Division of the U.S. Army Corps of Engineers, which was part of the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (C. H. Pennington, personal communication).

Under certain conditions, the intrinsic properties of natural stone may make its use a possible enhancement technique for fishery resources. Lovejoy and Kennedy (1979), who reviewed the characteristics of riprap that make it "highly acceptable for enhancing habitat used by aquatic organisms," stated that it provided these features: substrate for benthos and periphyton; cover (and reduced current velocities); a stable channel bottom for mussel colonization; and gravel beds (the preferred substrate of mussels), through weathering of riprap stones. In addition to the potential for creating gravel beds, the riprap itself may provide spawning beds for fish (Francis et al. 1979).

Witten and Bulkley (1975), who investigated the effect of bank stabilization structures on the biological and physical characteristics of some Iowa streams, showed that riprap revetments had no apparent effect on stream characteristics as measured by changes in turbidity, flow velocity, depth, or temperature. However, they noted that the stream had been "severely channelized" before riprap placement.

Burress et al. (1982) sampled bank stabilization structures (unprotected banks, stone-faced earth-core dikes, L-head dikes, wing dikes, hard points, and riprap revetments) on the Missouri River, North Dakota, for fish and invertebrate populations. Of the habitats sampled, dike fields had the most diverse fish communities. Nearly two-thirds of the total fish collected consisted of five species: common carp, yellow perch, white bass, white suckers, and river carpsuckers. The diverse invertebrate populations located on the dike fields and revetments provided food for walleyes, northern pike, white bass, burbot, and shovelnose sturgeon.

Increased primary productivity and abundance of invertebrates have been associated with riprap structures. Hansen (1971) observed that the production of attached flora and fauna in the Little Sioux River, Iowa, was limited to areas of riprap. In other Iowa streams, the abundance of trichopterans was found to be 22 times higher than that of ephemopterans and 5 times higher in riprapped areas than in control areas (Witten and Bulkley 1975).

Field studies have failed to demonstrate increased fish reproduction as a result of riprap use. At the very least, however, riprapped banks attract fish. The Wisconsin Department of Natural Resources (Fernholz 1978) assessed fish use of three habitat types on the UMR and found the highest percentage of invertebrates in the stomachs of fish collected along riprapped banks. Kern

(1977), who investigated the fish populations of four backwater areas in pools 5, 5A, and 6 of UMR by electrofishing, found that riprapped banks yielded the highest catch per unit of effort, among all habitat types checked. Freshwater drum were positively associated with riprapped banks, and black crappies were negatively associated. Witten and Bulkley (1975) found that, although Ephemeroptera and Trichoptera were present in disproportionately greater numbers in the stomach samples of channel catfish and green sunfish taken in riprapped areas, neither mean length nor abundance of these species differed significantly at control and riprapped sites. C. H. Pennington (personal communication) also stated that submerged riprap is valuable for benthic invertebrates and provides cover for fish.

Nevertheless, increasing the feeding substrate has been shown to increase fish productivity, not simply primary productivity (see discussion of Spawning structures, Chapter 22). For example, research by the National Marine Fisheries Service showed that artificial reefs, by improving habitat and increasing surface area of the production of periphyton, can increase total fish biomass associated with a reef (Stone 1978). Findings by Prince et al. (1975) may partly explain this observation. They demonstrated that the increased surface areas afforded by artificial reefs shortened and modified the typical lacustrine food web in isolated areas of a Virginia impoundment.

Although riprap used as a mitigation technique has less impact than other bank stabilization structures on populations of aquatic organisms, and may even have some potential as an enhancement technique, it does not have a favorable impact on wildlife. Lovejoy and Kennedy (1979) noted that riprap is not a preferred habitat type for waterfowl, furbearers, or upland game. The limiting factor appears to be the paucity of vegetation associated with most riprapped areas. This problem, which may be somewhat mitigated by covering the rock with soil and seeding, is discussed further in Chapter 11.

4.4. COSTS

Riprap is often considered to be the first choice among bank protection methods (Keown et al. 1977). Zeigler (1973), for example, reported that after authorities had evaluated structures to determine which would provide the most appropriate shoreline protection for historical sites in Maryland, they selected stone riprap over stone revetments, gabions, interlocking concrete blocks, precast concrete slabs, nylon bags filled with sand or mortar (Fabriform), precast concrete structures, asphaltic concrete, semi-compressed automobiles, bulkheads built with treated timbers, steel piles, and corrugated asbestos. As mentioned previously, riprap provides effective protection, has a relatively long life, is easily constructed, is easily repaired, requires little maintenance, is flexible and aesthetic, and may provide fishery enhancement benefits. These advantages must be considered when one compares the overall cost of riprap with other bank protection measures.

The use of riprap is limited by the availability of stone of appropriate quality and quantity and the prohibitive cost of transporting it. Keown et al. (1977) noted that the average estimate for in-place cost (in 1976) of riprap ranged from $3.50 per cubic yard in an area where stone was readily available to $30 per cubic yard in a metropolitan area where stone had to be hauled over long distances. Other economic factors that should be accounted for include the type of filter bedding used, if any, and provision of the design specifications (i.e., the D50). For example, Crews (1970) indicated that the use of filter bedding can reduce the size of the median stone required. Bush (1962) stated that experience has shown that bank protection equivalent to that provided by a 10-in. layer of graded stone underlain with a filter blanket of sand and gravel can be attained at a lower cost with about a 15 in. layer of suitably graded quarry-run stone with fines.

4.5. EVALUATION FOR USE ON UMRS

In general, riprap can afford effective protection against the erosive forces of river currents, wind- and boat-generated waves, and local scouring. As such, riprap can be used virtually anywhere, i.e., in upper and lower bank areas, at river bends, in backwater and discharge areas, as toe protection for other river training structures (jetties, breakwaters, levees, dikes, dams), around hydraulic structures such as piers and bridges, at island heads, along narrow channels exposed to extensive or intensive boat traffic, or near any discharge area where velocities are high and scouring may occur.

A problem unique to riprap may occur because it has been used so extensively in the past. Resource managers on the Lower Mississippi River tend to disfavor its further use because it has already been used so extensively that this part of the river has been channelized (D. Kennedy, personal communication). Managers and river biologists should therefore be cautioned not to advocate unrestricted use of riprap. Regardless of its relatively benign impact on fish and wildlife resources when compared with other forms of bank stabilization, it can still pose problems like those associated with any channelization measure.

An ad hoc panel of UMRCC deemed it appropriate to limit the extent of riprap that should be applied in the various subsections of UMRS. Total shoreline riprap includes that placed before inundation by the navigation dams. If use of riprap exceeds (or has exceeded) the limits recommended by the panel, the loss of habitat diversity must be compensated. Panel recommendations related to selected portions (rivers) of the UMRS follow:

1. Head of navigation to lock and dam (LD) 10 of UMR--allow up to 50% total shoreline riprap on the main channel border on a pool-by-pool basis.

2. From LD 10 to LD 27 of UMR--allow up to 30% total shoreline

riprap on the main channel border on a pool-by-pool basis.

3. From LD 27 to Cairo, Illinois, of UMR--90% of the shoreline is currently riprapped; accept no additional riprap except in emergency situations. Some removal of riprap in low energy areas is desirable. Other bank stabilization techniques should be used.

4. Kaskaskia River--shoreline is 100% riprapped along the lower 30 miles. Riprapping of the remaining 6 miles of navigable stream should be limited to 10% of total shoreline length.

5. Illinois River--no riprapping currently exists and none is anticipated due to the low energy regime of the river.

6. St. Croix River--accept riprapping of an additional 5% of total shoreline length.

7. Black River--accept no additional riprapping.

8. Minnesota River--accept riprapping of up to 50% of total shoreline.

Lovejoy and Kennedy (1979) identified sites within the GREAT I study area that require shoreline protection. These sites were assigned priorities on a scale of 1 to 30 on the basis of evaluations by three Work Groups of GREAT I--Fish and Wildlife, Sediment and Erosion, and Dredging Requirements. The authors recommended the use of riprap to protect these areas.

CHAPTER 5. OTHER REVETMENTS AND BULKHEADS

5.1. SITUATION TO BE MITIGATED OR ENHANCED

Revetments and bulkheads are built to protect a shoreline from erosive processes or to prevent movement of the soil behind the structure, or both. (See Chapter 4 for a detailed discussion of the situation to be mitigated or enhanced.)

5.2. DESCRIPTION OF TECHNIQUES

Revetments and bulkheads are continuous structures that parallel the shoreline and directly protect the bank from erosive processes. According to Mulvihill et al. (1980), revetments are sloped structures built to protect existing land or newly created embankments against erosion by wave action, currents, and weather. Bulkheads, on the other hand, are normally vertical and are primarily designed to prevent sliding of land behind the structure. They serve a number of secondary functions, including the creation of shorefront lots for real estate and moorage space for vessels, and protection from erosive forces. Seawalls are far more massive than either bulkheads or revetments and are not discussed here; they are built to resist the full force of ocean waves.

River bank revetments are generally located on the concave side of bends, where bank recession is most active as a result of river currents (Simons et al. 1975). They may be used elsewhere to provide protection from wave action or from local scouring around hydraulic structures such as railroad fills, bridge piers, or culverts.

Revetments may consist of two structural components: one is placed above the water surface and is termed upper bank paving, or simply paving, and the other is below the water and is known as the mattress. Bondurant (1972), however, believed that there is no basic reason for such delineation and that revetments of willow or lumber deteriorate rapidly above the waterline. Any structural separation of upper and lower bank protection devices creates a line of weakness at the junction of mattress and paving, lacks self-healing capacity, and lacks sufficient tightness to prevent leaching (Bondurant 1972).

Simons et al. (1979) noted that the use of upper, lower, or full bank protection, and the selection of various combinations of construction materials depend, in part, on the erosive forces to be mitigated. If wave action is a problem, appropriate upper bank protection should be considered. Mattresses are designed to reduce the impact of river flow on the bankline.

However, upper and lower bank protection are not mutually exclusive. Although mattresses may be used in the absence of upper bank protection, the upper bank paving cannot be used without appropriate lower bank protection because undermining of the revetment will cause the collapse of the paving. The lower bank usually represents about 75% of the area to be protected and about 90% of the total cost of river bank protection (Keown et at. 1977).

The ASCE Task Committee on Channel Stabilization (Weller 1965) identified materials that have been used in revetment construction on large rivers in the United States. Materials widely used in the construction of mattresses have included concrete, wood cribs, riprap, wire and brush, and gravel covered with wire mesh. Willow brush, asphalt, and gravel grouted with sand and cement are other materials that were once used in mattress construction, but their use has been discontinued for various reasons. Riprap and asphalt paving are the most common types of upper bank protection used. Paving blocks, monolithic concrete, and articulated concrete have largely been discontinued as paving materials.

Other materials used in revetment construction are being evaluated by the U.S. Army Engineer Waterways Experiment Station (Section 32 Program) as part of the implementation of the Streambank Erosion Control Evaluation and Demonstration Act of 1974. These materials include used tires, auto bodies, gabions, Fabriform, and various combinations of revetments in conjunction with vegetation (U.S. Department of the Army, Chief of Engineers 1978).

The following description of materials used in revetment construction includes a discussion of any unique differences in the way in which the materials are used or incorporated into the revetment design.

5.2.1. Cellular Concrete Grids

Precast cellular concrete grids can serve as modular building units for banks and shoreline revetments. They differ from other concrete blocks in having holes or cells that extend through the block. According to Parsons and Apmann (1965), these cells serve at least four purposes:

1. They mechanically hold subgrade material in place, thereby reducing the erosive forces that act on the fine material on the face of the bank.

2. They reduce the weight of the block and facilitate its hand placement.

3. They permit the establishment of vegetation.

4. They create a rougher boundary surface, which increases energy

dissipation at the surface and reduces local shear velocities.

The cells allow for the release of hydrostatic pressures from beneath the revetment but a filter mat or cloth must be placed beneath the blocks to prevent the "wash through" of bank material (Amber 1975).

Cellular concrete grids are manufactured commercially under such trade names as Monoslabs, Ambigrid, Grasscrete, Unigreen, Checkerblock, and Gobi block. They come in a variety of sizes, shapes, and weights. It is reasonable to assume that their ability to protect a bank against erosive forces depends on the degree of interlocking between grids, on the space-to-concrete-area ratio, and on the total weight of the blocks. In addition, the surface geometry appears to be an important factor. Day (1980), who investigated five commercial brands of cellular concrete grids, found that the ability of a grid to absorb and detain rainwater tends to be more a function of its surface geometry than of the percent of open bottom area.

Cellular concrete grid revetments may be unstable in severe wave situations because wave rundown may remove bank material or trapped debris from the cells. Furthermore, uplift pressures created by wave action may be greater than the weight of the blocks. Uplift pressures range from 12 to 14 lb for Gobi blocks to 90 lb for Monoslabs. Amber (1975) reported that Monoslab grids (and presumably other cellular grids) performed well when subjected to tangential hydraulic forces, such as river flow, but that they were not intended to withstand the direct attack of breaking waves. Similarly, Giles (1977) reported that a revetment of cellular concrete building blocks could withstand breaking heights up to 5 ft but that degrees of damage increased as the wave height increased.

Nevertheless, cellular concrete grids may be an economical and visually attractive alternative to riprap where waves are moderate. McCartney and Ahrens (1975) found that a Gobi block revetment was 15% cheaper than a conventional riprap revetment of the same stability, based on a 3-ft wave design and 1974 costs in the Great Lakes area. Parsons and Apmann (1965) investigated a cellular concrete revetment on a streambank in western New York that was constructed of blocks 16 X 24 X 4 in. and that weighed 83 lb each. During an 8-year period, the revetment had been subjected to estimated velocities of 3.2 fps at its surface and to the impact of massive ice floes. Only 3 of the more than 600 blocks originially laid were lost under these conditions. In contrast, riprap of quarried stone placed in adjacent areas, with a median stone size of 17 in. and maximum stone weights of 1500 lb, was unable to withstand the forces. On other waterways, another cellular concrete revetment (Grasscrete) resisted flows of 15 fps and the manufacturer expects it to protect banks against flows as great as 30 fps (Grass Concrete Limited 1979).

The appearance of cellular concrete grids, like that of riprap, can be enhanced by promoting the establishment of vegetation. Concrete grids are cited in Chapter 11 as a form of site preparation if the intent of using these grids is the eventual establishment of bank cover. Ryan (1976) reported on the most satisfactory bedding for Monoslabs (and presumably other cellular concrete grids) on waterway embankments:

1. Level and compact the natural soil bank. Where the natural soil is heavy clay, it is suggested that a 30-cm layer of sandy loam be spread before laying the filter cloth. This facilitates root penetration beneath the filter cloth.

2. Lay filter fabric (such as Terra Firma, Bidim, or Polyfilter X) with anchoring in a trench, 30 cm deep, on all edges of the reveted area. (See Chapter 14 for further information on filter fabrics).

3. Lay concrete grids directly on top of filter fabric with the long axis of grids parallel to stream flow. For slopes of 1.5H:IV or greater, the bottom row of grids should be staked.

4. Fill with sand loam and add plant seed. If it is difficult to establish grass due to frequent storm flows, it may be necessary to fill the lower rows of grids with 19-mm "screenings" or crushed rock.

5.2.2. *Articulated Concrete Mattresses*

The following description of articulated concrete mattresses is based on Lindner (1969) and Keown et al. (1977).

The basic unit of the mattress is a slab of concrete ($46^{1}/_{4}$ X 14 X 3 in.). These slabs are cast on and tied together by corrosion-resistant reinforcement wire to form rectangular units or 'squares' that are 4 ft wide and 25 ft long when allowance is made for the 1-in. space between the slabs and for the space between adjacent squares. Because the mattress is made up of squares connected by articulated joints, it is somewhat flexible in all directions. This flexibility permits the mattress to adjust to irregularities in the bank and to scour pockets that may develop after installation. The major disadvantage of the concrete mattress is that bank material may erode and escape through the interstices of the articulated joints.

An articulated concrete mattress, because of its weight and flexibility, functions effectively on parts of the bank that are subject to excessive hydraulic flow conditions. Since 1945, this type of mattress has been used almost exclusively for subaqueous revetments on the Lower Mississippi River.

The mattress normally extends from 6 ft above mean low water to a point 50 ft past the thalweg of the river. Shaping of the bank and mat-sinking operations are generally restricted to low river stages (15 ft or less above mean low water).

After the submerged bank has been shaped in preparation for placement of a mattress, the squares are assembled on a launching barge that is anchored over the underwater bank. A mattress up to 140 ft wide, measured parallel to the bank, is assembled by placing the squares side by side on the launching barge and connecting them with corrosion-resistant wire and clamps. When the squares have been assembled into a 25- by 140-ft unit, the configuration is termed a "launch." After the launch has been assembled and connected to successive launches, the completed mattress is moved off the barge into place on the embankment and secured to the bank. Successive portions of the launch are placed by backing the barge toward midstream.

Before 1940, squares were cast entirely in a concrete plant aboard a barge. However, as the volume of work increased, it became apparent that this procedure immobilized too many barges during the concrete curing period. To speed up casting operations, casting plants have been placed at convenient locations on the bank along the Lower Mississippi River. As of 1976, there were seven land-based casting sites between Cairo and New Orleans, each capable of producing 200 squares per hour.

By 1976, two mattress-sinking plants were in operation on the Lower Mississippi River, each designed to place a mattress 140 ft wide. Both of these units are capable of placing 10,000 squares per day. At this rate, about 20 bank miles of mattress can be laid by each unit during a normal working period (i.e., low-water season) of 5 months. In the Lower Mississippi River, articulated concrete mattresses may be preferable to riprap for stabilizing clay banks because they also increase habitat diversity (C. H. Pennington, personal communication). However, Littlejohn (1977) stated that the present standard for bank protection on the Lower Mississippi River is a combination of articulated concrete mattresses for the underwater portion of the bank and riprap stone for the upper bank.

5.2.3. Enviroblox

Enviroblox is the trade name for precast, trapezoidal-shaped concrete blocks made by Terrafix Erosion Control Products, Inc. The blocks are used in a patented interlocking and articulated revetment, with space between the blocks (Fig. 7). In this respect, an Enviroblox revetment is a synthesis of articulated concrete mattresses and cellular concrete grids with all the advantages of both. To the best of our knowledge, Enviroblox is the only commercial revetment product of this type, although the ASCE Subcommittee on Slope Protection (Buzzell 1948) mentioned the unsuccessful use of a similar

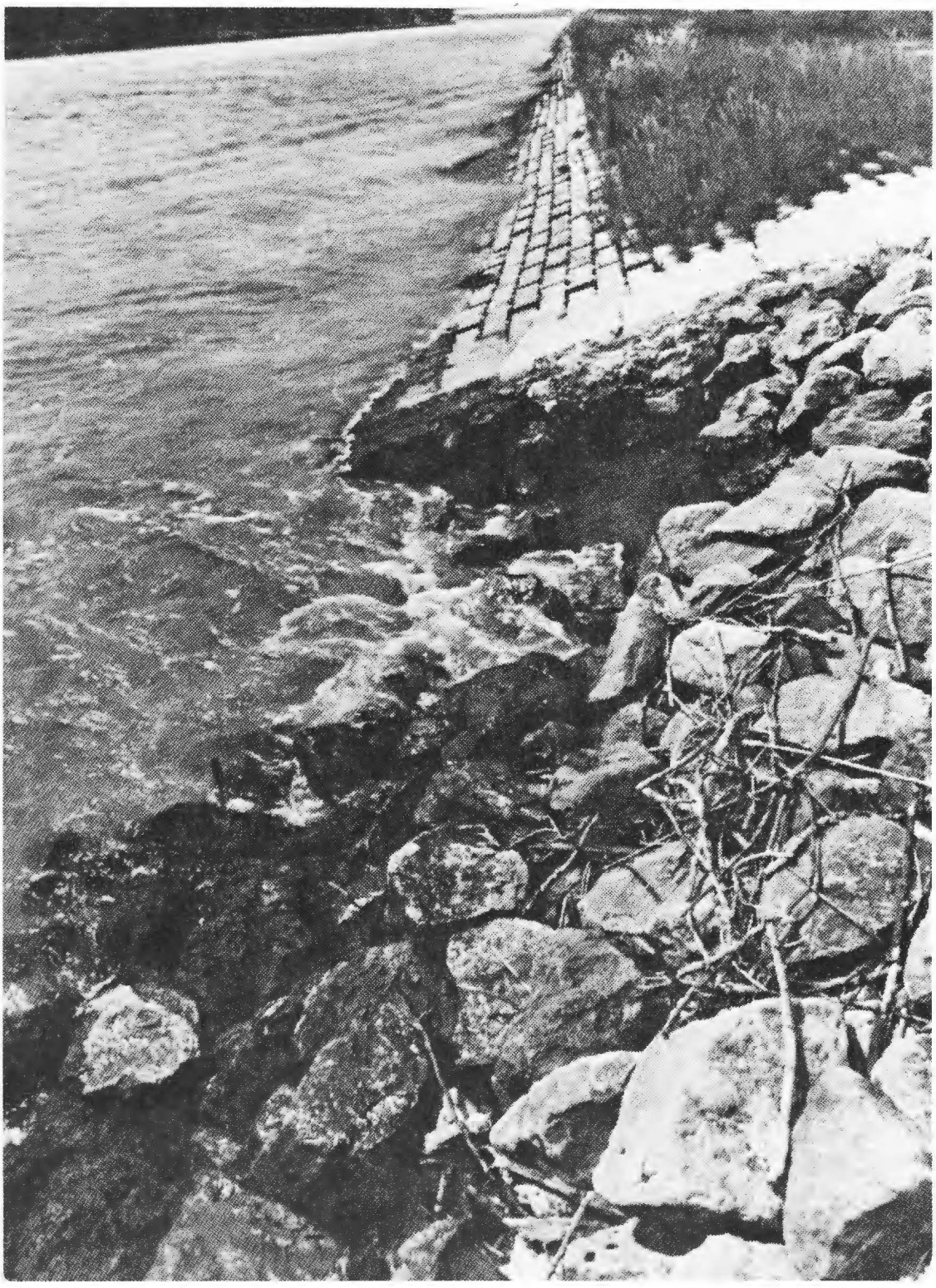


Fig. 7. Enviroblox on a test site in a major barge canal in comparison to an eroding riprapped revetment. Vegetation is shown established on the Enviroblox (Anonymous [ca. 1980]).

revetment on the Kingsley Dam in Nebraska.

The block design is trapezoidal and the larger surface normally faces the filter mat placed beneath the revetment. The two long edges of the blocks are formed with mortise and tenon connections to provide interlocking and load transfer throughout the system. Under high stress conditions, continuity of the block system is further ensured by reinforcement with stainless steel or monel wires. These wires run through each block along the length of the slope and can be attached to anchors at the top of the slope. This arrangement results in a "hanging" revetment, similar to gabion mats, which allows the revetment to conform to irregularities in the bank or to scour holes that may develop after installation.

According to the manufacturers of this product, revetments constructed of Enviroblox offer three other advantages:

1. The slope revetment allows dissipation of imposed wave energy over a larger area and thereby eliminates the two most serious problems usually associated with revetments, i.e., the formation of standing waves or "seiches," and scour at the toe of the revetment.

2. A multitude of interstitial spaces is provided to promote colonization by aquatic flora and fauna.

3. Interstitial spaces above the waterline allow for the establishment of vegetation along the bank.

The interstitial spaces also allow for the release of hydrostatic pressure from beneath the revetment and, depending on the revetment design, may provide spaces large enough to provide fish cover (C. Fuller, personal communication).

According to C. Fuller (personal communication), an Enviroblox revetment can handle waves 5 to 6 ft high and current velocities up to 12 fps. Additional reinforcement can further extend capabilities of the system. This revetment is functionally applicable to UMRS, and has been used on large alluvial rivers in Europe, Canada, and Australia.

An Enviroblox revetment may be installed manually, with assembly decks to facilitate installation under dry conditions, by preassembly of panels hoisted into position by crane, or by using specially designed twin-hulled barges that allow for underwater placement of sections without the use of a crane. In addition, the manufacturers offer a mobile production plant that can be set up at the project site for production of blocks on jobs of sufficient magnitude to justify its use.

5.2.4. *Polypods*

Several unique precast concrete shapes have been used as breakwaters, groins, revetments, and jetties for shore protection in areas of heavy wave action. Polypods can be used as armor facing on structures made from other materials (Hudson 1974). Because they interlock and have great mass, polypods provide greater stability than that obtained from stone of the same size (Shiraishi et al. 1969; Singh 1969; Wilder and Koller 1971). Units used in the United States to protect various rubble-mound structures include tetrapods, quadripods, tribars, tetrahedrons, and dolos (Hudson 1974).

The tetrapod was developed by French engineers in 1950. Since then, tribars, quadripods, dolos, and hexapods (among others) have also been designed for use alone or as armor units for rubble mound structures (Fig. 8). The structures range in weight from 10 to 43 tons, depending on the design used (U.S. Coastal Engineering Research Center 1977).

Tetrapods have been used mostly in marine coastal areas for constructing jetties and breakwaters, and sometimes for use in conjunction with revetments. They are made of precast concrete consisting of four legs joined at a central block, each leg making an angle of 109.5° with the other three. Their shape and mass make tetrapods stable under extreme hydraulic forces (Keown et al. 1977).

Quadripods are shaped much like tetrapods, except that three of the legs are in one plane and the axis of the fourth leg is perpendicular to that plane. According to Weymouth and Magoon (1969) and Wilder and Koller (1971), quadripods have been used effectively in the harbor at Santa Cruz, California to protect the toe and cap of a stone breakwater (Fig. 9).

Tribars have three parallel legs attached to a base bar. They have been used successfully to protect jetties and breakwaters in Hawaii and along the California coast. In a harbor on the island of Maui, Hawaii, tribars were used in 35- and 50-ton sizes; a total of 1224 units were cast at the job site (Wilder and Koller 1971).

A precast H-shaped unit (dolos) developed in South Africa, and a device with a similar configuration (Sta-bar) developed in the United States, have been used to protect harbors and banks (Wilder and Koller 1971).

Sta-pods are barrel-shaped, and have four feet placed at 45° angles to the center portion. The units can be installed quickly and easily. In one location, 160 linear feet of beach was covered in 3 h by a small crew using a

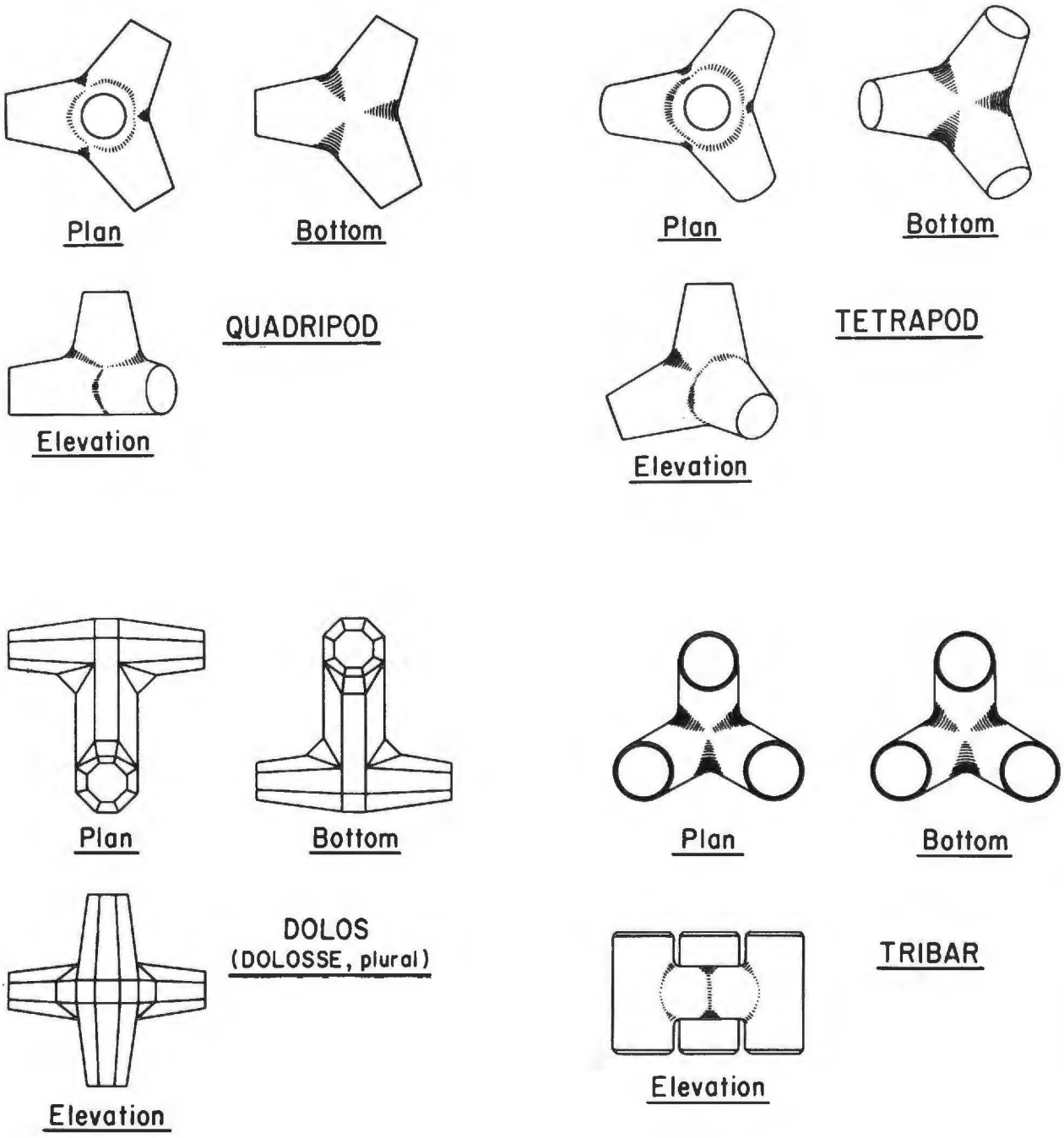


Fig. 8. Polypods, precast concrete shapes for use in protecting shores and banks (U.S. Army Coastal Engineering Research Center 1977).

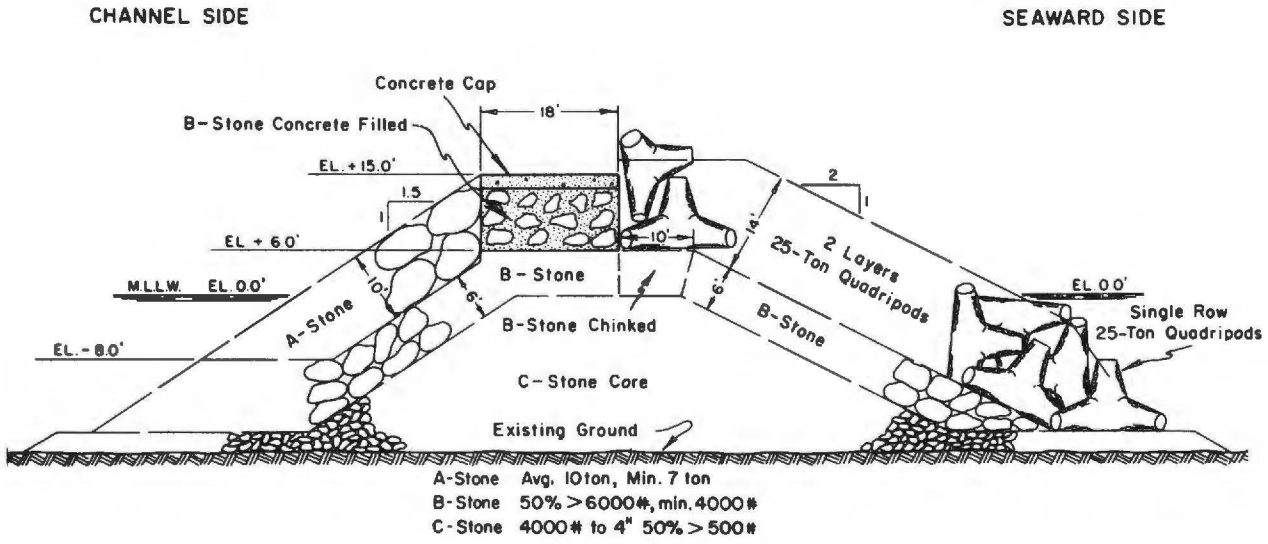


Fig. 9. Quadripods protecting the toe and cap of a stone breakwater (U.S. Army Coastal Engineering Research Center 1977).

front end loader. If the area is subjected to severe wave action or scouring conditions, the units must be placed on plastic filter material and stone (Wilder and Koller 1971).

Casting facilities are needed to fabricate polypods. Transportation costs are excessive if the manufacturing facility is located far from the placement site. Another cost factor may be the need for heavy equipment to put the structures in place (Keown et al. 1977).

5.2.5. *Gabions*

Gabions are metal cages, filled with large gravel or rock. They may be stacked and wired together to form a permeable, flexible wall or barrier. These modular units have typically been used to construct revetments along river banks, and groins or jetties along coastal shorelines (Fig. 10). They

have also been used to construct wing deflectors, check dams, sills, and fishways (U.S. Forest Service 1969; Nelson et al. 1978), and fish screens (McSwain and Schmidt 1976) in streams.

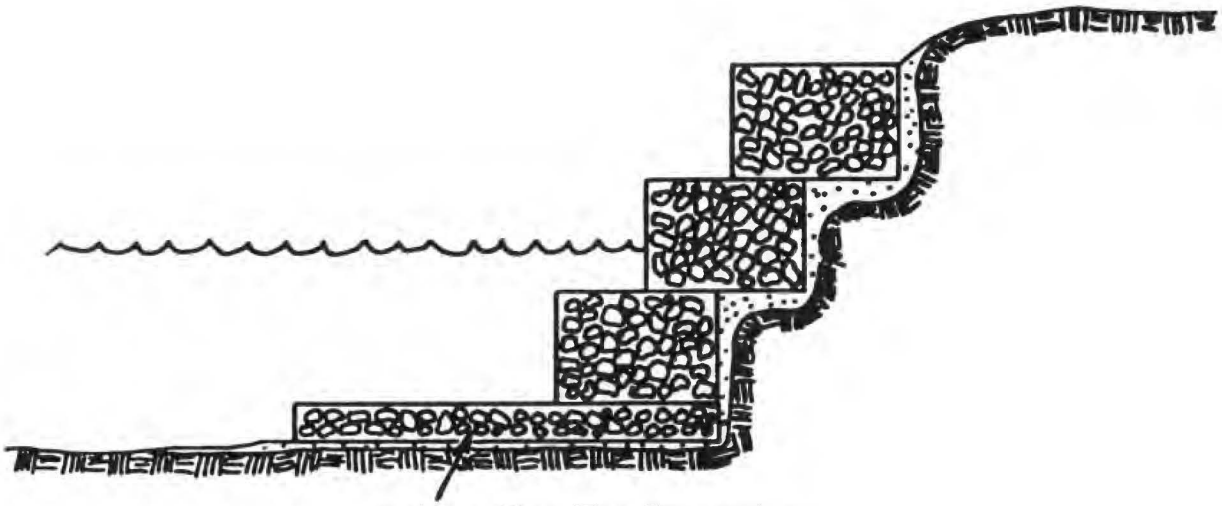


Fig. 10 Rock-filled gabion revetment construction. Filter fabric or graded granular filter may be required between the foundation and gabions (Hanson et al. 1978).

Gabions have been used extensively during the last 100 years in Europe, where large stones are not readily available (Harza Engineering Co. 1964). Their primary advantage over loose riprap is that gabions do not require minimum stone size to provide adequate bank protection. Any stone with a diameter greater than the mesh openings can be used. Blast furnace slag has been used effectively in gabion revetments in Great Britain (Gilbert 1970).

Despite their widespread use abroad, gabions have been used in the United States for only the last 15 or 20 years (Keown et al. 1977). Gabion works are

on several large rivers in the United States, including the Susquehanna River (Crews 1970), the Eel River (Lavagnino 1974), and the Potomac and Guadalupe rivers (Burroughs 1979). To the best of our knowledge, gabion revetments have not been used on UMR. However, the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, is testing gabion revetments, along with several other bank stabilization measures.

A gabion cage may be fabricated or shaped in the field (Simons et al. 1979). The manufactured cage is usually rectangular and divided by diaphragms into cells to prevent bulging at the sides. The U.S. Forest Handbook (U.S. Forest Service 1969) lists the standard sizes of gabion cages available. Mamak (1964) reported on some of the designs and construction methodologies of gabions shaped in the field.

The manufactured cage is generally constructed of galvanized steel wire (11 gage or heavier) and may be coated with corrosion resistant material such as polyvinyl chloride (PVC). Materials used for the construction of gabion cages or baskets have included chicken wire, plastic, willows, continuous tubes of fabric or thermoplastic sheeting (Harza Engineering Co. 1964), and polypropylene monofilament netting (Pillai and Verma 1977). The present discussion is limited to steel wire gabions because this material has been used most often.

Gabion revetments are somewhat flexible and can accommodate minor changes in bank geometry (Keown et al. 1977). Nevertheless, the design of a gabion revetment varies with site-specific characteristics. Simons et al. (1979) described the arrangements and dimensions of gabions for shallow and deep rivers and for inclined and vertical banks.

As Lavagnino (1974) noted, gabion revetments are sometimes based on a counterfort design (Fig. 11). They function by buttressing the bank, as well as by protecting it from erosive forces. The bank slope may thus be as steep as $^{3}/_{4}$H:1V (Lavagnino 1974), rather than graded to the slope of 2H:1V suggested for riprapped embankments. This attribute may be important in areas where the width of the berm, or conversely, the width of the channel bed, may be subject to design or environmental constraints.

In addition to the counterfort design, gabion revetments have also been used as continuous mattresses or platforms to protect banks from current and wave action on the Humber River in Great Britain (Gilbert 1970) and the Susquehanna River in eastern United States (Crews 1970). Gabions used in this type of revetment are thinner (6 to 18 in.) than the standard gabion (1 to 3 ft) and, according to Crews (1970), provide the same level of protection as thicker gabions, but at a lower cost.

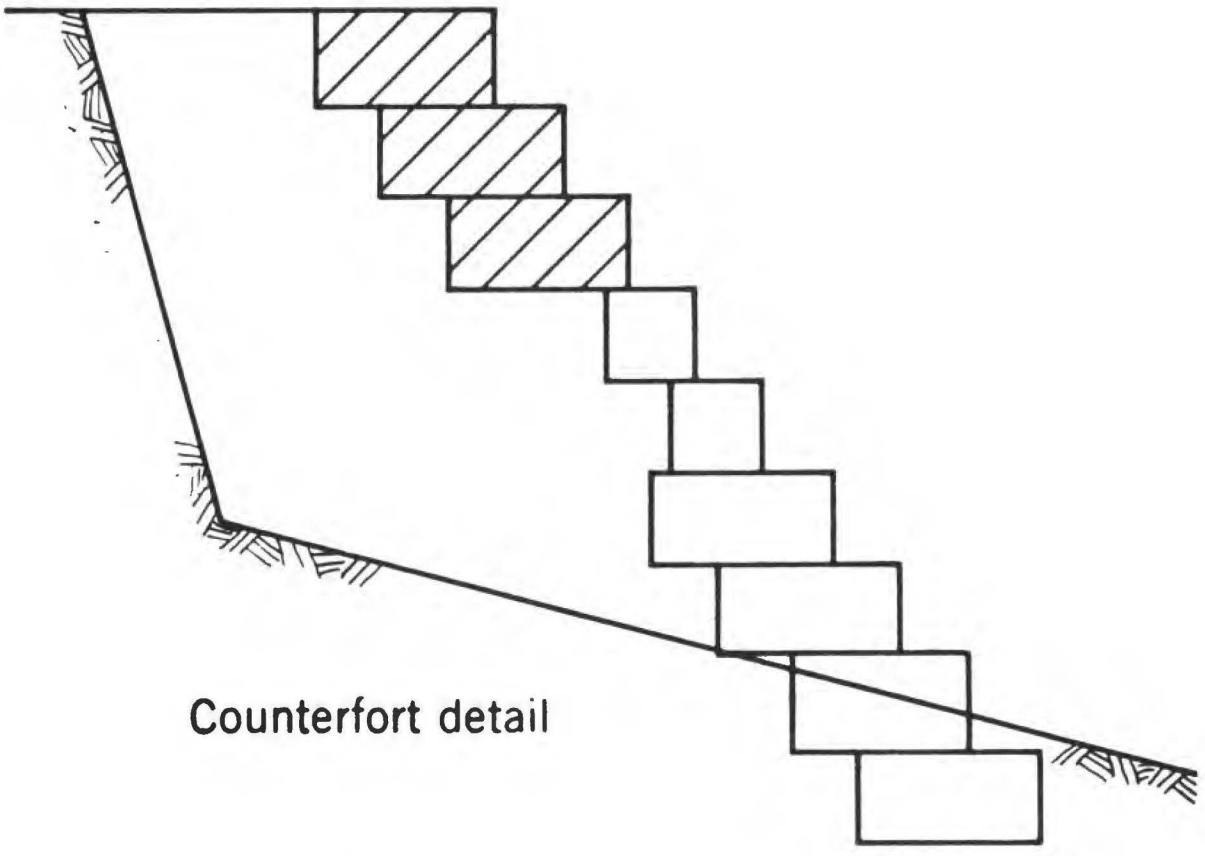


Fig. 11. Counterfort detail for gabion placement (Lavagnino 1974).

A gabion revetment functions slightly differently than riprap as a bank stabilization measure. The gabion acts as a permeable structural unit, and provides more weight and interlocking between the armor units than provided by loose riprap or sand bags (Harza Engineering Co. 1964). The stepwise tier or counterfort design used in gabion revetments buttresses the bank, in addition to protecting the bank soil from current and wave action.

Gabion revetments also require less stone than do riprapped banks. Burroughs (1979) noted that gabion revetments with a thickness of one-third to one-half that of a riprap blanket provide equal protection. These attributes may be critical when one is comparing the cost effectiveness of riprap and gabion protection for a given site, since the cost of riprap varies considerably with the availability of suitable stone.

River flow is dissipated by impact against a gabion structure and by a reduction in flow velocity near the surface of the gabion. The uneven surface of a stone-filled gabion provides some boundary roughness, although probably

not as much as riprap does. Wave energy may be dissipated more efficiently by gabions than by more impermeable revetments. The Docks and Harbour Authority of London noted that revetments with permeable armor units or interlocking armor units, such as gabions, rely less on the mass of individual structural components to withstand wave energy than do more solid structures (Mulvihill et al. 1980).

Voids between the stones in gabions allow free bank drainage, thereby preventing the buildup of hydrostatic pressure. Graded granular filters or filter fabrics are sometimes used beneath the gabions to prevent excessive loss of fine soil particles (Lavagnino 1974; Keown et al. 1977; Simons et al. 1979). A supporting apron of material extending 6 or 7 ft beyond the toe of the revetment is also recommended. The suggested minimum height of the apron is 1.5 to 2 times the expected depth of scour at the toe (Simons et al. 1979; Keown et al. 1977).

A major drawback of gabions is that their construction is relatively labor intensive. Even though filling of the cages with stone may be done partly with draglines, front end loaders, clam shells (Burroughs 1979), or a section of pipe (Lavagnino 1974), the handling of the cages, rearranging of the stones, and wiring of the cages must be done by hand.

Some authors have reported that gabion structures are relatively maintenance-free. Gilbert (1970) noted that a PVC-coated gabion revetment used for river bank stabilization in Great Britain was completed in 1964 and had required no maintenance by 1970. Wesche (1976) and Maughan et al. (1978), on the other hand, reported rusting out and loss of rock from gabions. Gabion groins used in Jennings Creek, Wyoming, have required maintenance every 4 to 6 years to repair broken wire sections and to replace rock fill (Maughan et al. 1978). Nevertheless, gabions are fairly easy to repair (Tobiaski and Tripp 1961) and at least some commercial gabion cages are made of triple-twisted wire mesh (Maccaferri Gabions of America, Inc. [ca. 1979]); the triple twist in the wire prevents unraveling if a break occurs.

Cox and Chen (1977) and Cox et al. (1975) investigated alternate revetment wire fabric materials (stainless steel, bimetallics, and organically coated low-carbon steel) for use in articulated concrete mattresses on the Lower Mississippi River. The results of their evaluations may provide insight to better wire fabrics that could be used in gabion construction.

Crews (1970) and Burroughs (1979) reported that gabions, because of their shape and flexibility, are compatible with box culverts, bridge abutments, and other hydraulic structures. Although gabions would probably function well around these and other artificial structures (e.g., marinas, housing developments), alternatives to gabion for use in urban areas should be investigated because of potential safety hazards and possible vandalism

associated with these wire structures.

The following advantages of gabion revetments have been identified by various investigators:

1. Durability. Although the durability of gabions in the United States is unknown because they have been used in this country for only about 15 or 20 years, some gabion systems in Europe have lasted up to 75 years (Burroughs 1979).

2. Flexibility. Gabion revetments are somewhat flexible and accommodate to minor changes in the bank geometry (Keown et al. 1977).

3. Porosity. The interstices between the stones prevent the building of excessive hydrostatic pressure (Lavagnino 1974) and also help to dissipate wave energy (Mulvihill et al. 1980).

4. Ease of placement. Gabions are compatible with box culverts, bridge abutments and other hydraulic structures (Crews 1970; Burroughs 1979).

5. There are no problems with graffiti in urban areas, as there are with channels lined with concrete or asphalt (Burroughs 1979).

6. Stone of any size may be used, as long as it consists of durable material and is larger than the mesh openings of the cage (Keown et al. 1977; Burroughs 1979).

Several disadvantages of gabions have also been identified:

1. Vandalism. In urban areas people sometimes cut the gabion cages and remove the stone to build dams or rock gardens (Burroughs 1979).

2. Heavy debris, such as ice, can tear the baskets or break the wire coating (Burroughs 1979).

3. Gabion wire may be hazardous to bathers because of the sharp edges of spliced areas (Brater 1979).

4. Gabion placement may be restricted to relatively shallow depths. Although a gabion wall was constructed underwater in the Potomac River completely by feel (Burroughs 1979), this procedure is both time consuming and labor intensive.

5.2.6. *Sand- or Concrete-filled Synthetic Revetments*

Synthetic revetments built or filled with sand or concrete, were preceded by burlap sacks filled with soil, sand, or mixtures of soil or sand with cement. Unfortunately, burlap bags are subject to rot or scour (Simons et al. 1979). Unless the bags are filled with concrete and protected from scour, the useful life of the revetment is short (Keown et al. 1977; Simons et al. 1979). The general concept has considerable merit, since such a revetment can be used in place of riprap in areas where suitable stone is not locally available. In addition, synthetic casings can be filled in place with locally available sand that is prevalent along alluvial rivers such as those in UMRS. Ray (1977) reported widespread use of nylon sandbags as revetments along much of the eastern coast and the upper Great Lakes.

These revetments have several names: sand pillows, giant sandbags, or soil-filled bags. Brand names for some of the casing products are Longard tube, Fabriform, Dura-bag, and Perma-bag. Most of the information on trade-name products was provided by the manufacturers.

Longard tubes are made of high density, UV-stabilized polyethylene, and are available in 28-, 40-, and 69-in. diameters. The outer tube is a tough protective coating with a tear strength of 500 psi. An epoxy and sand coating that can be sprayed on is so hard that the tube cannot be cut. The Longard system requires only a water pump and standard contractor's equipment and a tube can be filled within a few hours. Longard tubes can be used with or without a filter fabric.

Longard tubes were first used in Europe in 1970. They have since been used successfully in Belgium, Germany, Denmark, Canada, and the United States as seawalls, groins, bulkheads, and breakwaters. Up to 2.6 miles of continuous beach have been protected in a single project. Although the heights of waves on the North Sea have often exceeded 6 ft, all European installations have proved to be durable and stable.

The Great Lakes Shore Protection Demonstration and Research Program experimented with synthetic casing structures for revetments and groins. Longard tubes were placed at the toe of a Lake Huron bluff for a distance of 400 ft. Although there was some shifting of the structure, it resisted back pressure from the slumping bluff and withstood the effects of a major storm (Armstrong 1976). On the other hand, at a site on Lake Michigan, a single Longard tube did not withstand a 14-h storm during which waves reached a height of 11 ft. The structure failed because the area behind the tube was not filled and partly because of the slippery interface between the filter fabric used and the tube (Marks and Clinton 1974). At another site on Lake Michigan, three Longard tubes were installed along the toe of a bluff for 300 ft and giant sandbags were installed in different stacking patterns at the toe

of a bluff for 250 ft. Although there was some shifting and settling, the structures have remained stable and performed effectively against severe storms and protected the eroded bluff from major erosion; however, some sandbags were vandalized (Armstrong 1976). Marks (1977) believed that Longard tubes offer a promising low-cost device for erosion control. Hanson et al. (1978) recommended that filter fabric extend offshore from the revetment to avoid undercutting of the structure. They also urged filling of the bags with concrete grout to prolong the life of the structures.

Hanson et al. (1978) illustrated how sand-filled polyethylene tubes could be used to provide intermediate protection for a sand bluff over 60 ft high with a slope of 49°. Two tubes were terraced with filter fabric beneath them and backfilling between them (Fig. 12). The tubes were coated with protective asphalt after placement, to resist cutting.

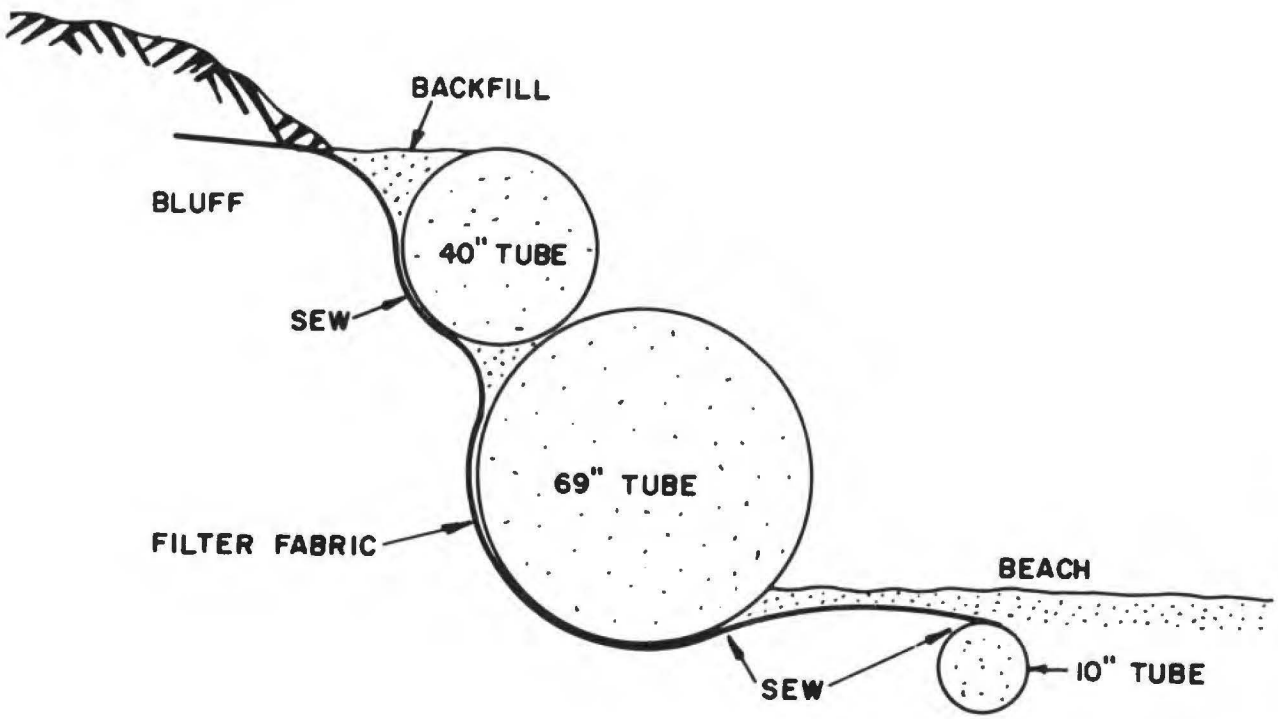


Fig. 12. Terraced tube revetment. The filter fabric was sewn to the tubes at the points indicated (Hanson et al. 1978).

The State of Massachusetts has tried several systems in which sand-filled

fabric bags are used either as groins, revetments, bulkheads, or sills. Gutman (1979) found the sandbag structures to be stable, free from major settling, durable, and resistant to ice, but easily subject to vandalism and damage by foot or vehicular traffic.

Fabriform is a double-layered fabric of textured nylon, in a multifilament warp. The material is available with filter points (space between tacking points) of 5, 8, and 10 in. or up to 24 in. in customized mats made for severe conditions. When the fabric panels have been placed on a slope and sewn together, they are pumped full of sand and cement mortar. Fabriform has five advantages:

1. It can be placed on steep slopes.
2. No filter underlay is necessary on most soils.
3. There is no need to revet an entire slope.
4. It can be quickly installed; a 5- or 6-man crew can average 5000 ft^2 per 8-h shift.
5. Installation and mobilization costs are low; only a pickup truck, a grout pump and some hose, and a small portable sewing machine are required.

The manufacturer (Contech Construction Techniques, Inc., Cleveland, Ohio) has stated that Fabriform revetments are not intended or recommended for exposure to the continuous heavy action of waves on unprotected shorelines of the Great Lakes or the oceans. Fabriform can protect the shores of inland lakes, reservoirs, and inland waterways from wind waves and ship wakes of moderate wave action. At Mile 15 of the Intracoastal Waterways along the eastern coast of the United States, Fabriform and riprap were recommended by the U.S. Army Corps of Engineers to restore a concave shoreline that had eroded badly due to waves caused by boat and barge traffic. Nearly 0.6 miles of the waterway bank was stabilized with Fabriform and riprap. About 1.4 miles of the banks of a major waterway connected to the Great Lakes were covered with Fabriform to protect against erosion from current and from the wave action of ship wakes. Fabriform was also used to stabilize river banks where boat wakes and propwash were undermining barge-loading facilities at a major refinery along the Des Plaines River. On the Savannah River, Fabriform withstood waves 5 ft high (from vessel traffic) and a current of 3 knots (A. McDougald, personal communication). Water velocities at other installations ranged from 13 to 18 fps. At one installation Fabriform withstood flood conditions with a maximum flow of 7640 cfs.

A sand pillow system, in which a fabric called Acrilan is used, is being tested on the Red River, Louisiana, the Tennessee River, Alabama, and on slopes of irrigation dams. The stability of the sand pillow is primarily a

function of wave height, wave period, embankment slope angle, and weight of the individual pillows (McCallister 1979; Stephenson et al. 1980). A field test on the banks of the Tennessee showed that there was no loss of strength after 36 months, even though the bags had been submerged at times or were exposed to a variety of weather conditions. The results of laboratory and field tests indicated that the sand pillow offers excellent slope protection. A minimum particle size must be established, because some soil was lost through the fabrics when it was subjected to repeated wave action. Maintenance costs would be lowered as a result.

5.2.7. *Used-tire Revetments*

Used tires offer an effective and inexpensive material for constructing bank and shoreline revetments. As discussed in the chapters on fish attractors (Chapter 22) and flexible breakwaters (Chapter 9), used tires are durable, nontoxic, inexpensive (often free), and provide a great deal of surface area for colonization by periphyton, as well as spaces for fish cover. Several ways of constructing used-tire mats or revetments are briefly discussed here.

Keown et al. (1977) reported that tires can be laid flat over the surface to be protected and lashed together with wire or nonbiodegradable rope to form a mat structure. The mat is held in place by deadman anchors to prevent it from sliding down the bank or floating free. The U.S. Army Corps of Engineers, Rock Island District (1980), estimated that this method costs $30 per bank-foot of protection and that the cost can be reduced if used oil-field cable is used to bind the tires. Holes are sometimes drilled in the sidewalls of the tires to allow trapped air to escape and prevent flotation.

Candle and Fischer (1977) noted that the manual process of drilling or punching is both costly and time consuming. Also, the relatively small holes are not totally effective in venting trapped air from the tires during rapid changes from non-submerged conditions, such as would occur on the banks durin the passage of a barge. Therefore, they recommend circumferentially slicing the tire into halves to eliminate the possibility of air being trapped in the tire cavity. Because the slit tires are compact, twice as many are required to form a revetment of the same size as one built of uncut tires. Doubling the number of tires increases the stability of the mat because of the additional ballast, and decreases porosity of the mats because of the increased tire density. A disadvantage of using cut tires is that the high relief of a tire revetment is diminished, resulting in decreased habitat for fish, less wave-energy dissipation, and less area for aufwuchs colonization.

Another method for stabilizing tire mats and preventing flotation is to fill the cavity with gravel or coarse rock. This technique has been applied to tire mats used on a tributary of the Allegheny River and on the Monongahela

River in Pennsylvania with satisfactory results (U.S. Department of the Army, Chief of Engineers 1978). An advantage of using this method is that the gravel provides substrate for the establishment of vegetation, in addition to providing spawning substrate for fish if gravel spills out on the embankment.

Svensson and Sweeney (1979) evaluated scrap tire revetments that had been used at eight different erosion sites and were constructed in four different designs: One method of construction was designed to protect a channel bank from ship-generated waves. The tires were laid horizontally and bolted side-to-side and top-to-bottom, to form a structure four tires high and four to five tires wide. Steel rods, 6 ft long were driven into every fourth or fifth tire. In another method, designed to arrest bank slumpage, a single-layer tire mat was used that incorporated drain tile to reduce hydraulic pressure in alluvial soil. The tires were bolted and staked, as described above, and placed on a 2H:1V slope. The other methods of construction were merely modifications of these two designs: In one method, a single-layer tire mat was used without the drain tile, and in the other, a single row of tires, four to five tires high, were arranged in a 100-ft semicircle, to prevent a 40-ft red oak tree from slumping. Three of the finished tire revetments were covered with bank fill and seeded with a mixture of long-rooted grasses to anchor the soil and tires. Svensson and Sweeney (1979) judged finished areas to be "more aesthetically pleasing than the more commonly used methods of bank stabilization." The revetments at all eight of the sites controlled erosion effectively and were installed for $50 per linear foot as compared with $1000 per foot for pilings.

An experimental tire revetment structure was designed and constructed for use in the Great Lakes (Armstrong and Petersen 1978). Rather than laying the tires flat, the revetment incorporated upright modular bundles of tires, similar to the modular systems used in fish attractors (Chapter 22) and in floating tire breakwaters (Chapter 9). The leading edge (toward the water) of the structures was designed to float, thus acting both as a wave damping mechanism and as a revetment protection on the shore (Fig. 13). A filter fabric was placed beneath the tire structure to prevent the erosion of fine soil particles from the shoreline. Pilings were used to secure the trailing edge. The design was successful in arresting erosion. Sediment accretion was observed shortly after installation.

Webb and Dobb (1977, 1978) described a tire structure that, though not technically a revetment, certainly deserves mention as a possible bank stabilization measure. Two tiers of tires, one above the other, were strung on a steel cable attached to metal posts at the bottom of a 2% slope along a bay shoreline. The purpose of the device was to dampen wave activity on the shoreline and allow for the establishment of transplanted cordgrass. A 0.5-ft buildup of sediment occurred directly behind the barrier and the structure was considered a success. (This wave-stilling device is also mentioned in Chapter 11 as a form of site preparation if the eventual establishment of vegetation is desired.)

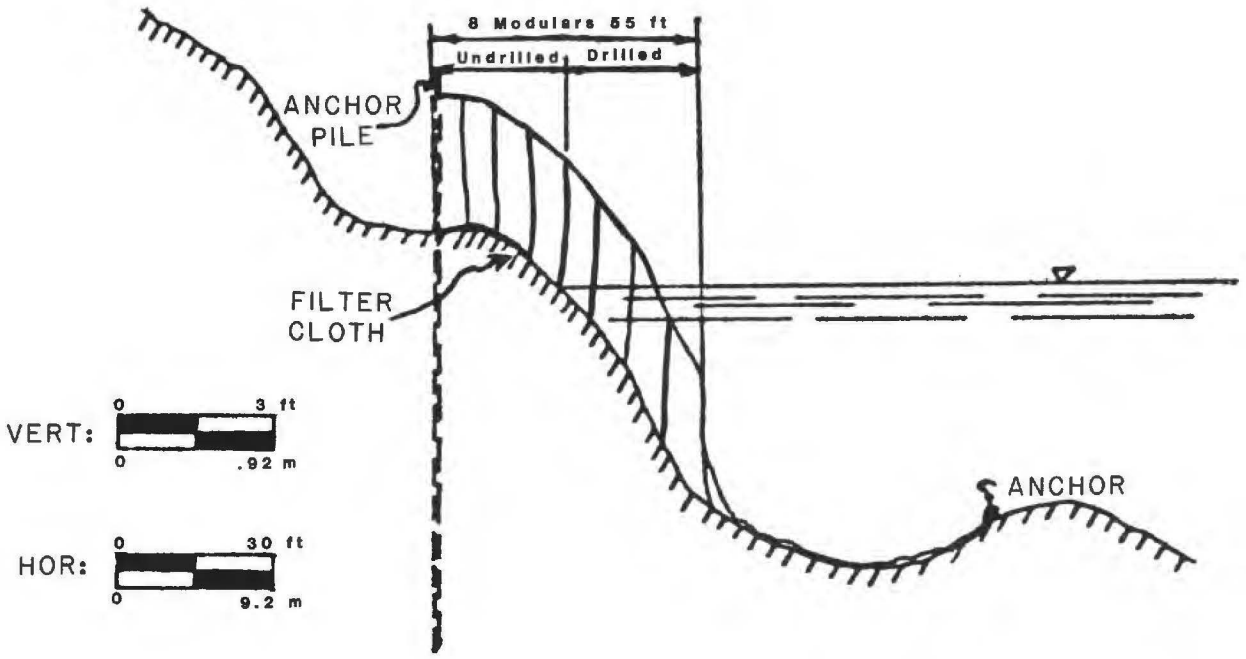


Fig. 13. Tire mattress at Rogers City, Michigan, with offshore modules vented (Armstrong and Petersen 1978).

The U.S. Army Corps of Engineers, as part of the Section 32 Program of the Streambank Erosion Control Evaluation and Demonstration Act of 1974, is evaluating a number of used-tire erosion-control structures. Tire mats are being used on St. Catherine Creek, Mississippi, and on the Connecticut River, Vermont. The south fork of Tillatoba Creek, Mississippi, in the Yazoo River basin received a rubber tire revetment on a graded bank with willow sprouts (U.S. Department of the Army, Chief of Engineers 1978). A tire-post retard and a wire crib retard filled with used tires are being used on other streams in Mississippi. All are effectively arresting erosion along streambanks.

Candle and Fischer (1977) noted the use of used-tire mats for stabilizing an estuary marsh in North Carolina. The technique is further described in Chapter 40.

5.2.8. *Bulkheads*

Bulkheads are vertical or nearly vertical structures used to support a natural or artificial embankment. A bulkhead prevents the bank from sliding into the water, as well as protecting it from wave attack. Materials used for bulkheads on streambanks include wood, concrete, asbestos fiber, and metal. Timber bulkheads require extensive maintenance to preserve the structure. Asbestos fiber and metal bulkheads consist of interlocking sheets that are driven into the ground with compressed air jets or mechanical aids. As a result, piles and concrete forms are not needed (Keown et al. 1977). Foundation conditions, exposure to wave action, availability of materials, and costs should be considered when one selects the type of bulkhead to use (U.S. Army Coastal Engineering Research Center 1977).

When there is little or no littoral drift to support groins, bulkheads have proved to be the most popular structure used to protect coastal shorelines in Virginia (Givens 1976). Timber is used most often, but is not recommended for extreme exposures. Failures are usually due to overtopping or scouring at the toe. Givens (1976) recommended stone revetments wherever wave action is extreme.

The U.S. Army Corps of Engineers, Washington, D.C. (1971) found that bulkheads are usually replaced by seawalls in ocean-exposed locations because bulkheads cannot withstand the forces to which they are subjected.

Timber and concrete cribs have also been tried as bulkheads or retaining walls in riverine systems to protect and hold steep embankments (Fig. 14). Cribs may be slanted or vertical and are filled with rock or earth (Simons et al. 1975). Timber cribs are not recommended for use in areas of severe wave action (U.S. Army Coastal Engineering Research Center 1977). Timber pile bulkheads built along a 3000-ft river bank at Bethel, Alaska, to control erosion consisted of timber piling backed with 2-in. planks, plywood, and plastic sheet; the structure deteriorated completely within 5 years as a result of erosive forces from a flood and normal energy regimes (U.S. Army Corps of Engineers, Alaska District 1981).

Aluminum has certain advantages for use as bulkheads. It does not rot like wood, rust like steel, or crack under stress or impact like asbestos and concrete; it is not susceptible to failure because of the freeze-thaw cycle; and it is not affected by variations in pH. The manufacturers of Shore-all, an aluminum bulkhead, claim that their product can resist wave or current actions up to hurricane force without buckling or cracking.

Aluminum bulkheads consist of corrugated sheets 5 ft wide and up to 30 ft long. The bulkheads can be installed quickly and easily with air hammers,

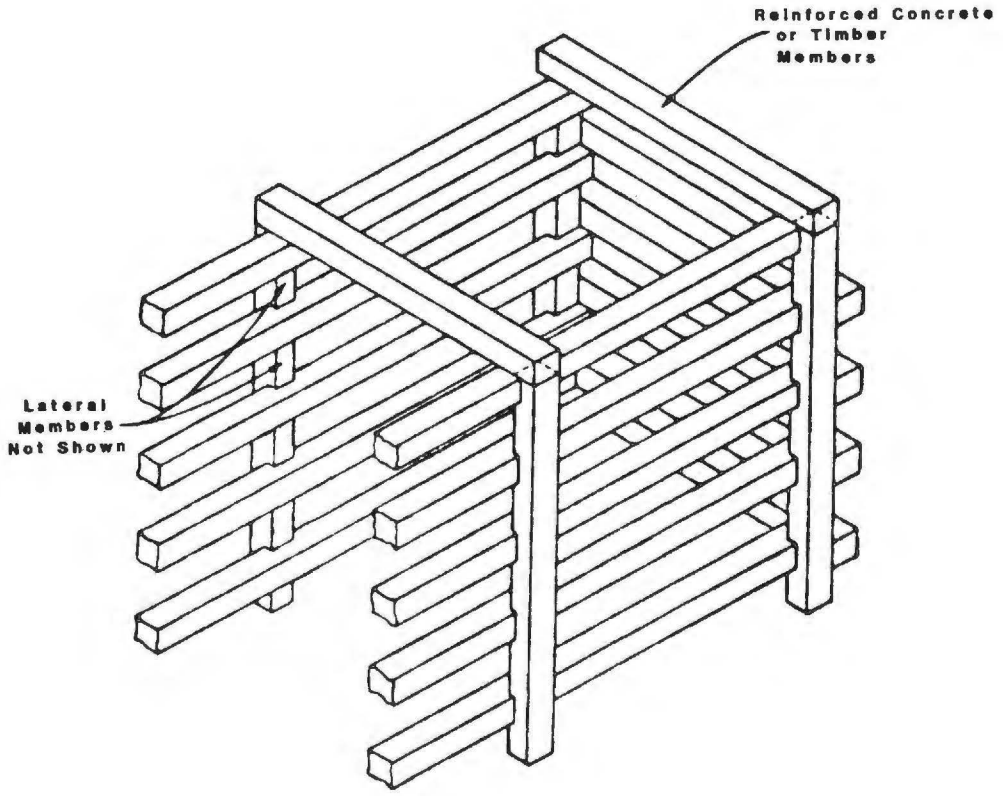


Fig. 14. Timber or concrete crib bulkhead. Stones may be placed in the crib to provide habitat for aquatic organisms (Simons et al. 1975).

vibratory drivers, jet pumps, or pile drivers. Up to 350 linear feet of panel can be installed in 1 day. Only one-third to one-half the length of the sheet needs to be buried in earth or sand, depending on soil or site conditions.

Aluminum bulkheads have been used successfully along many coastal shorelines and inland waterways, including lakes and rivers. Shore-all installations in Florida survived frontal waves and tides 7 ft above mean high tides caused by Hurricane Agnes (June 19-22, 1972), whereas many retaining walls made of other metals, wood, and reinforced concrete failed.

5.2.9. *Miscellaneous Revetments*

Various other bank protection materials have been used in the past: automobile bodies; porous concrete; bituminous paving; asphalt mattresses; concrete slabs; and monolithic concrete and other stone aggregate products. Many of these materials have adverse effects on fish and wildlife and are not aesthetically pleasing. In addition, many concrete structures must be put in place "dry" (i.e., the water must be drained away or rechannelized), to allow

the cement to set or harden. Many of these structures--particularly those of asphalt mix--have failed due to destructive forces, development of hydrostatic pressure, and penetration by vegetation (Keown et al. 1977). A new low cost revetment using concrete filled barrels in a stair configuration has protected shorelines on the Magdelen Islands in the Gulf of St. Lawrence. Further investigation of this material is warranted (Ouellet and Drouin 1980).

5.3. IMPACTS ON THE ENVIRONMENT

In general, the impact of bank revetments on fish and wildlife is a function of the intrinsic properties of the materials used and the construction practices that are required to put those materials in place.

Several of the permeable revetments such as cellular concrete grids, Enviroblox, gabions, and used-tire revetments tend to hasten the establishment of vegetation. Some grids, such as Ambigrid, have larger cells than other grid types and foster the establishment of large shrubs and small trees. An advantage that mattress type revetments such as concrete grids or Fabriform have over riprap is that many of them can be laid on slopes as steep as 1H:1V (45°). Gabions can also be placed on steeper slopes (1H:2V) than riprap (Thackston and Sneed 1982). One commercial grid, Ambigrid, can be placed vertically because of its interlocking design. Vertical placement may be important in areas where the width of the berm, or conversely, the width of the channel bed, is subject to design or environmental constraints.

All bank protection methods have some effect on the environment because they change the natural processes of erosion and deposition (Thackston and Sneed 1982). Like many bank stabilization measures, revetment placement often creates problems associated with stream channelization and construction (see Section 1.5 on Bank stabilization). As noted previously, revetments can be placed on steep slopes, and the absence of extensive grading of the embankment may minimize the effects of construction activities (e.g., increased turbidity).

FWS anticipated that any bank protection method will in time reduce lateral erosion, total stream length, number of islands, amount of land-water interface, and diversity of riparian vegetation. FWS recommended that bank stabilization be done only when absolutely necessary, and then only in a way that will not reduce channel widths, eliminate oxbows, or induce erosion at new locations (Gritman 1978).

Used-tire revetments offer unique surface areas for colonization by invertebrates and for fish cover (discussed in Chapters 9 and 22). Used-tire matting stabilized with gravel can provide additional substrate.

It is assumed that revetments that most resemble riprap will provide some degree of useful aquatic habitat. This is true of gabions, in particular. Presumably, the intrinsic properties of stone that apply to riprap also apply to gabions, although to a lesser degree, because of the relatively smoother surface of gabions. Specifically, gabion revetments provide substrate for benthos and periphyton, may create spawning beds for fish, provide cover, and reduce local current velocities. However, because gabion revetments are often terraced (in a counterfort design), the depth of water covering the horizontal surface of the revetment fluctuates with river stage. Riprapped banks and gabion mattresses are sloped, and roughly the same area of stone is exposed by changes in water level regardless of the stage of river flow.

The aesthetic quality of revetments is relative. Revetments that encourage vegetation can be very attractive, but are unattractive if they are not completely covered. Lavagnino (1974) and Burroughs (1979) favored the natural appearance of gabions, as compared with concrete- or asphalt-lined channels, whereas the U.S. Forest Service (1969) stated that a disadvantage of these "rock and wire structures" is their unnatural appearance. However, all three sources reported that gabions can be covered with soil and seeded. Burroughs (1979) stated that the appearance of gabions improves with age. If the earthen banks above the gabions are initially seeded, vegetation should spread as the voids between the stones silt in, and eventually obscure the revetment.

Bulkheads generally have more adverse impacts on the environment than do revetments. Gantt (1975) evaluated the impacts of timber bulkheads and riprap revetments on the ecology of the Chesapeake Bay. Her findings about bulkheads are summarized here:

1. Timber bulkheads require constant maintenance, or they become weakened and are destroyed.

2. Frequent scouring at the toe produces turbidity.

3. Overtopping results in scouring landward of the bulkhead.

4. Bulkheads severely alter the estuarine edge; resulting in reduced productivity, loss of habitat for fish and wildlife, and changes in tidal flow and silt transport.

She recommended rock riprap because it usually does not have these adverse effects, and has many beneficial attributes.

Penney (1978) found that bulkheads can destroy wetlands if they are used extensively in an area where wetlands are adjacent or contiguous. The State of Virginia developed regulations to protect wetlands that have been effective in reducing the historic rate of bulkheading and loss of wetlands.

Because of the intense use of nearshore areas by fish and other animals, the State of Washington has developed criteria to control the design and construction of facilities such as bulkheads, which may adversely affect fish and shellfish resources. General provisions include regulations of the timing and methods of construction, so that biological events such as fish migration are considered (Washington State Department of Fisheries 1971).

Bass et al. (1977) considered breakwaters to protect the shoreline of the Johnston Atoll, Pacific Ocean, but rejected them because they were too expensive and there was uncertainty about their effectiveness. Steel sheet piling was selected for use as a bulkhead because it can be driven through hard surfaces and produces tight joints. However, it corrodes rapidly in salt water and reflects rather than absorbs wave energy--thus merely transfering erosive forces to adjacent shorelines. Scouring undermined the piling and overlapping eroded the shoreline behind the piling.

The placement of a bulkhead can adversely affect the adjacent shore. Waves reflecting off the face of the structure can increase erosion in the area that receives the additional wave energy. Erosion of adjacent beaches may also be accelerated due to alterations in water circulation patterns (Mulvihill et al. 1980).

Aluminum bulkheads can be used to help reclaim lost land if the bulkhead can be placed at the original shoreline and the space between the panels and the current shoreline can be backfilled to the original grade.

5.4. COSTS

Costs for various revetments and bulkheads vary considerably, depending mainly on construction materials and the manufacturing and placement process. However, costs of most of the structures mentioned in this section are competitive with those of riprap.

Total cost for installing a cellular concrete revetment in 1956 was about $1.10 to $1.40 per square foot, depending on the quantity. In comparison, contract costs for placing high quality riprap, in which stone of a 17-in. median diameter was used, averaged $1 per square foot on the same stream in 1954.

Among commercially made cellular grids in 1981, Turfstone (22 X 11 X 4.33 in., 44 lb) cost about $2.40 per square foot, installed; and Monoslabs (24 X 16 X 4½ in., 92 lb) cost $2.80 each plus installation costs ranging upward from $102 per square foot, depending on the application, and exclusive of sub-grade and sub-base construction.

The average cost estimate in 1976 of installed articulated concrete mattresses, including bank preparation, was $84 per square (100 ft^2).

The estimated (1981) cost for installation of an Enviroblox revetment ranged from $2.27 to $3.62 per square foot. This cost included the block, delivery, filter fabric, reinforcement cable, and anchors. The total cost varied with delivery charges and the level of protection required. In general, the cost compared favorably with that of riprap.

The construction of gabions is relatively labor intensive and the overall cost of installation depends largely on the cost of labor. Manufactured gabion cages are shipped flat and must be wired together by hand, placed by hand, stretched to put tension in the wire, and stretched as they are loaded with stones. Some hand arrangement of the stones is necessary and the gabions must be wired shut manually. In the Santa Clara Valley Water District in California, bids for installing gabion works jumped from $45-$50 per square yard in 1975 to $83 in 1979. During this same period, the price of stone rose only from $4 to $9 per square yard. The increases in cost were mostly attributable to the rise in wages of unskilled laborers (Burroughs 1979).

Nevertheless, the cost of installing gabions is in the low to medium range for bank stabilization structures. A construction engineer in St. Louis County, Missouri, reported that, if government subsidized labor is available, gabions cost much less than concrete walls, and that even without subsidized labor, gabions are competitive (Burroughs 1979). Crews (1970) compared cost curves for standard gabions, riprap, and the "Reno mattress," a modified gabion only 6 to 9 in. thick, for use on the Susquehanna River. The Reno mattress provided the same level of protection as the thicker, standard gabion, but at a lower cost. Furthermore, for a given depth, this modified gabion was comparable to riprap in cost and in the level of protection provided.

A gabion system used in Lincoln, Nebraska, cost 20 to 30% less than a rigid lining (i.e., concrete). This cost saving occurred because gabions could be installed without drying the creek bed and because the ground beneath them does not need to be compacted. The cost of installation, including bank preparation, materials, and seeding, averaged $50 to $60 per cubic yard (Burroughs 1979).

Costs of other projects in which gabions were used have been within the low to medium range. Nelson et al. (1978) reported that gabions cost $43 to $50 per cubic yard and Lavagnino (1974) estimated $33 per cubic yard. Keown et al. (1977) stated that in-place costs for gabion works in 1976 were $40 to $47 per cubic yard. Costs are somewhat reduced for very large projects constructed near economical sources of stone (Keown et al. 1977).

Armstrong (1976) reported that it cost $60 to $65 per foot in 1974 to install Longard tubes and giant sandbags to protect bluffs in the Great Lakes. Hanson et al. (1978) estimated the 1977 cost of Longard tubes to be $20 to $35 per linear foot for the material or $35 to $80 per linear foot for total construction costs. Sandbags cost $40 each, or $75 each installed. There was an additional average cost of about $2500 per project for equipment mobilization.

Fabriform cost ranges from $0.61 to $0.66 per square foot, depending on the amount purchased.

Costs for installing used-tire revetments in the Great Lakes were about $56 per linear foot in 1976 (Table 2). The cost of a used-tire revetment with willow sprouts, installed in the Yazoo River Basin in 1977, was $33 per linear foot (U.S. Department of the Army, Chief of Engineers 1978).

Table 2. Construction costs (per linear foot) for tire mattress protection structures (revet mattress with eight modulars) at Rogers City, Michigan, summer 1976 (modified from Armstrong and Petersen 1978).

Item	Cost
Tires	$ 4.24
Chain	23.77
Mooring and pilings	5.16
Filter cloth	2.94
Labor	15.06
Equipment usage	4.79
Totals	$55.96

Prices for installed bulkheads in 1976 ranged from $14 to $105 per linear foot. The cost of materials averaged only $50 per linear foot when the materials were readily available (Keown et al. 1977). Payne (1980), who compared the costs for timber, steel, asbestos, and aluminum bulkheads, reported that at 1975 prices, sheltered aluminum and the asbestos bulkheads were the least expensive, ranging in price from $40 to $80 per linear foot as compared with $250 to $750 for steel bulkheads and $90 to $200 for timber bulkheads. A concrete block revetment cost $200 per foot. Shore-all, an aluminum bulkhead, was available at 1981 prices ranging from $26 to $63 per linear foot depending on the length of the panel and the quantity purchased. The price as quoted included the panel, anchor plate, and anchor rod but did not include delivery or installation.

5.5. *EVALUATION FOR USE ON UMRS*

The use of riprap as revetments was discussed separately in the preceding chapter because of its benign, even potentially beneficial, effects on fish and wildlife, in comparison with other construction materials. This separate treatment does not imply that other types of revetments and materials should not be investigated for use on UMRS. Other types may not only be more aesthetically pleasing when used in conjunction with vegetation, but also be less costly when used in locations where stones for riprap are not economically available.

Cellular concrete grids, articulated concrete mattresses, Enviroblox, and gabions are excellent replacements for riprap where natural stone is in short supply. These units can provide protection that is as good as, or better than, that of riprap, and they may be no less attractive. They are generally easy to install, are reasonably inexpensive, and do not adversely affect the environment.

Since the structural integrity of gabions relies on the durability of the wire fabric, abrasion due to high sediment loads and ice floes may shorten the expected life span of gabion works, particularly in the main channel of UMR. Simons et al. (1979) stated that gabions are recommended for use on rivers having small sediment loads, since large sediment loads can cause the abrasion of the galvanized wire mesh and lead to corrosion and failure. On the average, there is comparatively little sediment (about 50 ppm) in the upper reaches of UMR. On this basis, the gabions should be functional in most parts of UMR except in areas of localized high sediment loads, such as those at the confluence of UMR with sediment-laden tributaries (e.g., Chippewa River) and possibly in the Middle Mississippi River area, where sedimentation also is higher.

Heavy debris, such as ice, can tear the baskets or nick the wire coating (Burroughs 1979). Wesche (1976) reported that one of seven gabion structures used for habitat improvement on the Black's Fork River in Wyoming was destroyed by spring ice floes during a 1-year evaluation period. One commercial producer of gabions, however, reported that, when properly installed, gabions last many years and on a number of streams they have withstood severe floods and ice floes without damage (Maccaferri Gabions of America, Inc. [ca. 1979]). The effect of abrasion due to ice floes should be investigated before gabion works are used in UMRS.

Gabions adequately protect coastal shorelines from wave damage. Gabion revetments may be useful on UMR in pools and sloughs where wave action caused by boat traffic or wind is heavy and there is little river flow. More information concerning the applicability of gabion revetments in UMR should become available after the U.S. Army Engineer Waterways Experiment

Station, Vicksburg, Mississippi, completes current testing of bank stabilization structures (Section 32 Project of the Streambank Erosion Control Evaluation and Demonstration Act of 1974).

Sand- or concrete-filled synthetic revetments are not as attractive as other revetments that promote vegetation, and they may not be as permanent as cellular concrete grids or polypods. Nevertheless, they have potential for intermediate protection on most eroding slopes in UMRS. Sand located on the construction site can be used--which is a real advantage. In addition, such revetments are an inexpensive alternative to riprap.

Used-tire revetments should not be overlooked as a possible bank stabilization measure on UMR because they are both inexpensive and effective for reducing erosive forces. The most obvious disadvantage of used tires is their unsightly appearance, but the establishment of vegetation enhances visual attractiveness considerably. A tire mattress is initially an eyesore, but as vegetation is established, the area develops a more natural appearance. The underwater portion of the tires may provide desirable aquatic habitat and the vegetation above water becomes wildlife habitat. Access may be slightly restricted because the tires are difficult to walk over (U.S. Army Corps of Engineers, Rock Island District 1980).

Bulkheads probably have their greatest use along shorefront property and at marinas on the major pools. Aluminum bulkheads are preferable to those made of wood, steel, asbestos, or concrete because they require little maintenance, are easy to construct, and are relatively more durable than those made of the other materials.

CHAPTER 6. RIVER TRAINING STRUCTURES

6.1. SITUATION TO BE MITIGATED OR ENHANCED

River training structures guide, direct, or train river flows and thereby indirectly protect banks from scouring processes. Structures that are built perpendicular, or nearly perpendicular, to the river channel either reduce flow velocities or deflect the flow of a river toward midstream. Thus they indirectly protect streambanks, shorelines, and beaches associated with the rivers. River training structures would be particularly beneficial if vegetated banks are being undercut or barren banks are being washed (Simons et al. 1979).

Another adverse effect that can be mitigated by river training structures is the loss of habitat due to clearing and snagging operations. When the U.S. Corps of Engineers began a clearing and snagging program on UMR in 1824 to facilitate navigation, one result was that much of the instream cover for fish in the main channel of UMR was removed. In a study to assess the effects of a proposed clearing and snagging project program, Hickman (1975) found that there were 15% fewer fish in sample areas without snags than in those with snags. Populations of catchable-size fish were 51% lower at sample sites without snags than at those with snags. Marzolf (1978), who summarized the potential effects of clearing and snagging on a stream ecosystem, concluded that biological consequences of these activities were reductions in benthos and plankton production and losses of fish cover, shelter, and spawning and nursery habitat.

River training structures include wing dams, wing dikes, wing deflectors, spur dikes (dykes), jacks, groins (groynes), jetties, retards, cribs, and fences. A distinction is made here between permeable and impermeable structures and between their intended purpose for installation--whether for training river flow for navigation (wing dams and dikes) or for shoreline or beach maintenance (groins). Closing dams (closure dikes) are river training structures that parallel the shoreline. Because they do not deflect the flow to protect the banks, they are not considered to represent a bank stabilization technique. Information on these structures is given in Chapters 27 and 30.

6.1.1. Groins

Groins protect shoreline or beaches because they are usually built perpendicular to the shore to trap littoral drift or to retard erosion of a beach or shore. They are narrow and range in length from 100 ft to several hundred feet in inland lakes and along coastal shorelines. Groins and wing dams function similarly, but differ mainly in their intended purpose. Wing

dams and dikes are designed primarily to train river flow for navigation purposes (Mulvihill et al. 1980). Wing dams are generally used in the main channel and groins can be used in the main pools behind the locks and dams of UMR and elsewhere in UMRS where the water is flowing. Groins, like dams, function effectively only if there is a constant flow of water. Along coastal shorelines, groins are effective only where there is longshore transport of sand (Magoon and Edge 1978). In the Great Lakes, the effectiveness of groins depends on littoral drift (Armstrong 1976). Groins could effectively stabilize the shoreline in main pools of UMRS where secondary currents are present.

Magoon and Edge (1978) stated that, for many years, groins were the most frequently used methods of coastal shoreline stabilization in the United States and the world. The Michigan Demonstration Erosion Control Program has evaluated various types of groins in the Great Lakes constructed with Longard tubes, sandbags, gabions, asphalt mastic (a mixture of sand, mineral filler, and asphalt), wood and steel pilings, and timber cribs (Armstrong 1976). (Gabions are discussed in Chapter 5.) Because gabions used as groins provide the same basic results as other impermeable groins, they are not further discussed in the present chapter.

General information on design considerations for groins and groin fields was provided in the Shore Protection Manual of the U.S. Army Coastal Engineering Research Center (1977). Mulvihill et al. (1980) noted that basic design criteria for groins in the Great Lakes differ little from those for groins in the ocean. Presumably the same is true of groins installed in rivers.

6.1.2. Wing Dams and Dikes

Impermeable training structures include stone wing dams, stone-filled timber pile dikes, earth- and stone-filled wood cribs. They are designed to confine the flow to the main channel thalweg by deflecting it away from the bank. Sediments that may be deposited in an impermeable dike field increase the protective capability of these structures (Simons et al. 1975).

Examples of permeable training structures used on rivers in the United States are timber pile dikes, wood or wire fences, steel and concrete jacks, tree retards, and tire- or brush-filled wood cribs. According to Simons et al. (1975), permeable training structures permit flow through the structure at reduced velocities, to induce deposition of suspended sediments. This flow prevents erosion and causes a buildup of beaches or shorelines. Permeable dike fields require the deposition of sediments in order to be effective as a contractile measure (Degenhardt 1973). For this reason, the ASCE Committee on Channel Stabilization Works (Weller 1965) noted that permeable structures are most effective on streams with relatively high sediment loads, whereas

structures that are more impermeable are generally required on streams with low sediment concentrations.

Garde and Ranga Raju (1977) wrote that permeable dikes are most effective in streams where the desired increase in low-water depth at the point of channel constriction does not exceed 3 ft. The authors did not explain this observation, but presumably the permeable dike field relies on adequate sediment deposition between dikes to be efficient. It is unlikely that a 3-ft bank, without appropriate bank stabilization measures, could be maintained.

Permeable dikes are usually less expensive than impermeable ones, even though the maintenance cost of permeable structures is rather high (Garde and Ranga Raju 1977). Hartke (1966), for example, reported that unless timber pile dikes are covered with sediment, they deteriorate within 5 years and are virtually ineffective after 15 years. Permeable dikes are easily damaged by floating logs, debris, ice floes, and towboats (Garde and Ranga Raju 1977; Hartke 1966). Permeable structures become more cost-effective where certain conditions pertain: the sediment load is high, the slope is not steep (i.e., flow velocities are low), there is no economical supply of stone, depths are extreme, or foundation problems exist (Hartke 1966; Garde and Ranja Raju 1977).

The advantages of using impermeable dikes, such as stone wing dams, is that they are "vastly more effective" than permeable dikes, and can therefore be spaced farther apart within a dike field (Hartke 1966). Their durability and ease of maintenance are also important considerations.

Both permeable and impermeable dikes or dams have been used to create and maintain the channel in navigable rivers. Types of dikes and dams built for this purpose include stone and brush wing dams and timber pile dikes.

6.2. DESCRIPTION OF TECHNIQUES

6.2.1. Stone Wing Dams

Stone wing dams (Fig. 15) are impermeable channel training structures. Their purposes as used in UMR are primarily to constrict the river flow and secondarily to stabilize or realign the main channel (Degenhardt 1973). The net result of using wing dams, in conjunction with closure dams, is the eventual formation of a single, confined channel for navigation.

Wing dams are constructed at an angle to the flow, beginning at the bank of a channel with a root and ending at the regulation line with a head (Mamak 1964). This angle may be oriented upstream, downstream, or perpendicular to

the bank. Simons et al. (1975) reported that wing dams should generally be perpendicular to the river bank along straight reaches and angled slightly downstream at bends. On the other hand, Garde and Ranga Raju (1977) noted that wing dams oriented upstream produce a more desirable curvature in the flow downstream, which leads to pronounced sediment deposition.

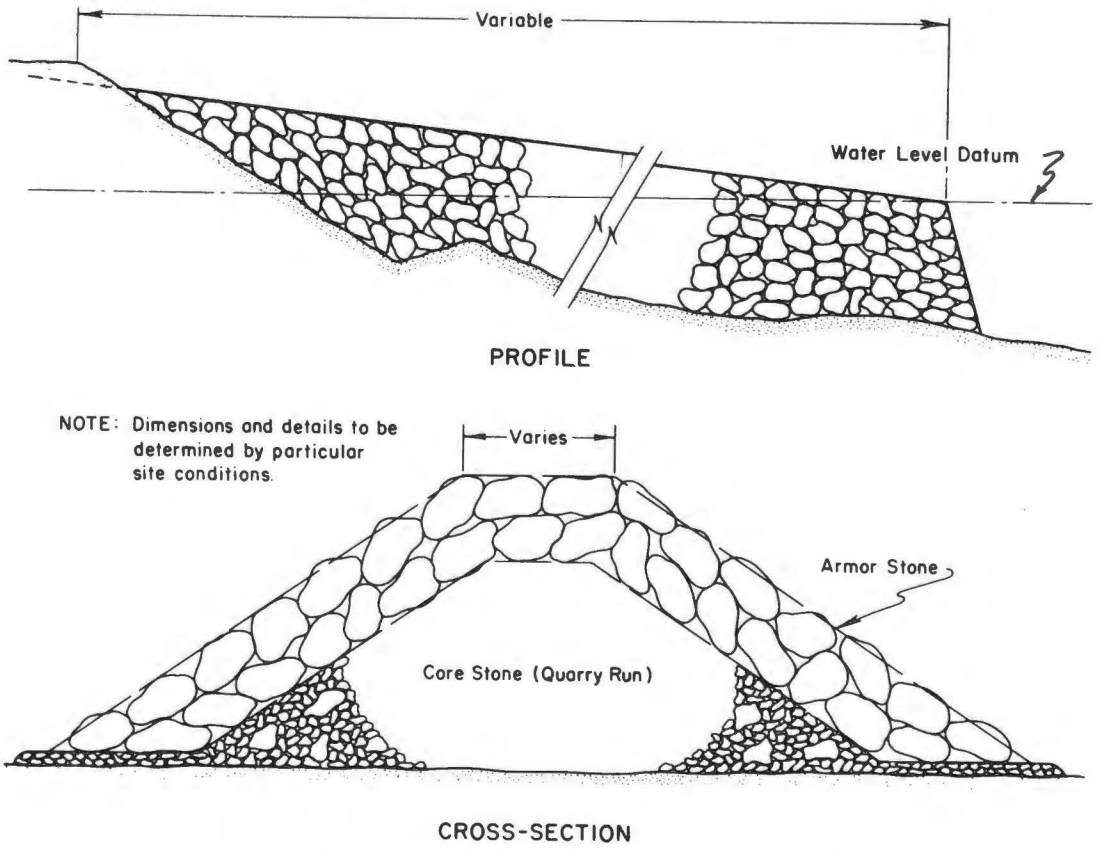


Fig. 15. Stone wing dam, showing construction details (U.S. Army Coastal Engineering Research Center 1977).

Some wing dams terminate with extensions parallel to the flow to form L or T shapes, and are correspondingly referred to as L- or T-head dikes (Simons et al. 1975). Other variations used in wing dam construction to adjust to site-specific characteristics (e.g., depth, flow velocity) have included altering the height of the structure, using a sloped crest, changing the length of the dike, varying the distance between dikes, or incorporating combinations of these variables into the dike field. (Further information on these variations is given in Chapter 29.)

Stone and brush wing dams were used on UMR between 1873 and 1911. Thereafter, lumber was substituted for willow brush until the 1930's, when

construction of the lock and dam system was completed (Tweet 1975). The wing dams built to achieve the original 4.5-ft channel were low dikes with a crest at 6 ft above the 1864 low-water level. To achieve a 6-ft channel, the existing wing dams were extended and others were constructed of rock and brus (Chen and Simons 1979). Tweet (1975) reported that, by 1907, 336.4 miles of UMRS were controlled by wing (stone and brush) and closure dams. Turner (1969) described the history and construction of wing dams on UMR. More recently, Boland (1980) found that 36% of the original wing dams built along the Iowa border of UMR have been eroded, covered with bottom sediment, or completely removed.

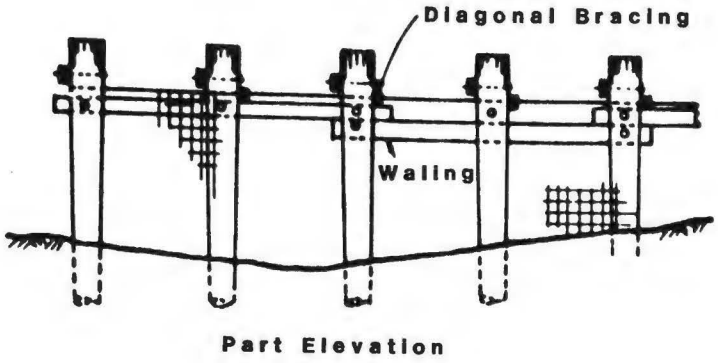
Stone dikes and timber pile dikes filled with stone have been used on the Middle Mississippi River since the 1930's (Hartke 1966). Both high and low elevation stone dikes have been built to constrict flow in this reach of the river. High wing dams are designed to contract flows during medium river stages. They are built to a level equivalent to about two-thirds bank full, and are usually out of water and ineffective during low-water stages. Low wing dams are designed to work during low river stages but have little effect during high river stages. Low wing dams are usually built in concave bends where depths exceed 40 ft, whereas high wing dams are used in wide, shallow reaches of the river (Simons et al. 1975; Degenhardt 1973; Stevens et al. 1975).

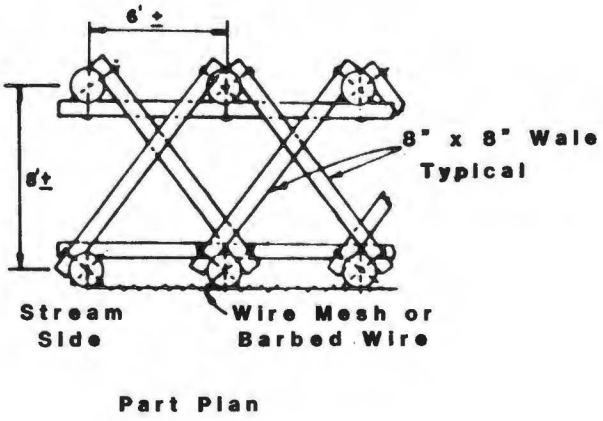
References for general wing dam design and dike system considerations include Bottin (1978), Degenhardt (1973), Fairley and Easley (1967), Franco (1966, 1967), Lindner (1969), Littlejohn (1969), Pickering and Murphy (1969), Simon et al. (1975), Thackston and Sneed (1982), U.S. Army Coastal Engineerin Research Center (1977), and Walton and Chiu (1977).

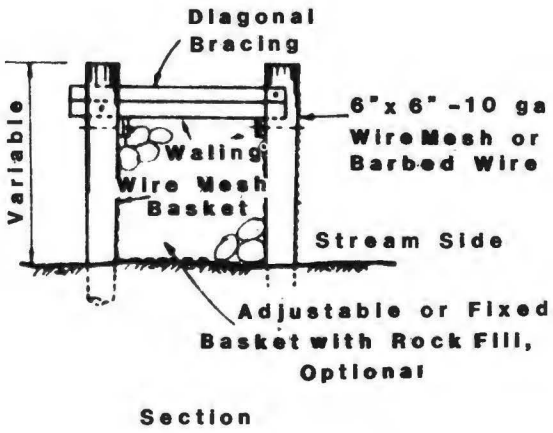
6.2.2. Timber Pile Dikes

Unlike stone wing dams, timber pile dikes are permeable structures (Fig. 16). They were used on navigable rivers in the United States to develop and maintain the channel, but their popularity has diminished and most structures now built for this purpose are made entirely of stone. By 1950 stone wing dams had almost completely replaced pile dikes as a standard construction method of the U.S. Army Corps of Engineers (Thackston and Sneed 1982). Timb pile dikes are vulnerable to failure due to scouring; however, such failure can often be prevented if the piles are driven to a greater depth or the base of the piles is protected with a rock blanket. The length of each dike depends on channel width, the position relative to other dikes, flow depth, and available pile lengths. Spacing between dikes varies from 3 to 20 times the length of the upstream dike; close spacing yields the best results (Simons et al. 1975).

Originally, timber pile dikes were developed to create a navigation







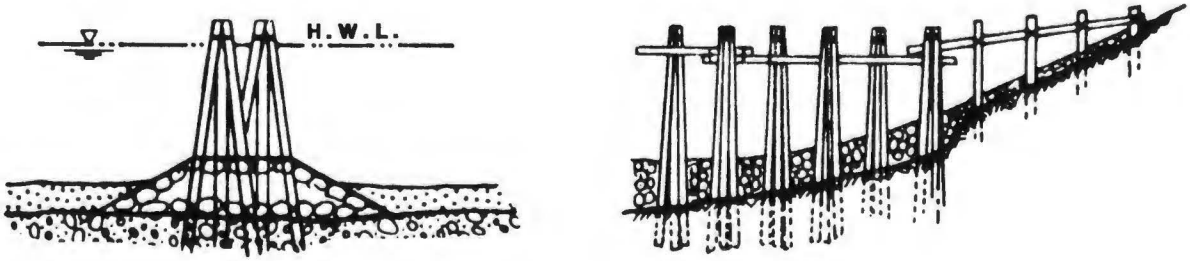


Fig. 16. Timber pile dike configurations including a single row of timber piles with a wire fence (upper panel), a double row of timber piles filled with rocks surrounded by a wood fence (center panel), and a cluster of timber piles (lower panel) (Simons et al. 1975).

channel, but now timber pile dikes are being recommended as possible streambank erosion control structures (Simons et al. 1979). Armstrong (1976) found that a timber pile groin was adequate for shoreline protection in Lake Michigan. It was inexpensive and did not deteriorate during 3 years of use.

6.2.3. Jacks

Jacks are structures in the shape of a toy "jack" or a tetrahedron, and constructed of wood, metal, or concrete. Although the tetrahedron is a more stable structure than the jack, the jack is most often used because it requires only three linear components rather than the six that are used in constructing a tetrahedron (Fig. 17).

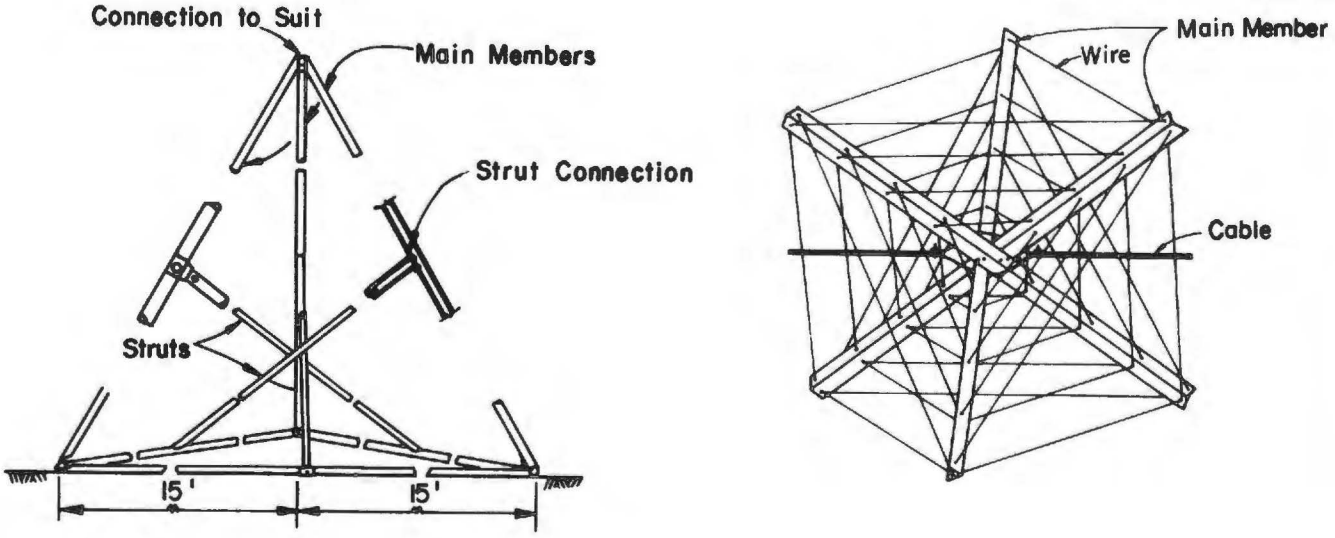


Fig. 17. Jacks, showing diagrams for a typical tetrahedron (left panel) and a Kellner jack (right panel) (Richardson et al. 1975).

The most common jack consists of three sections of angle iron, 16 ft long, bolted or welded together at their midpoint, so that each member is

perpendicular to the other two. Cable is laced through the angle iron in a standard pattern to connect the arms of the jack. The jacks are then arranged in a linear array and connected at intervals of 15 to 30 ft with cable. Arrays that are parallel (often in two rows) to the stream flow are called "diversion lines," and arrays that are transverse to the flow are "retard or tie-back lines." Retard lines are attached to the bank with deadmen and extend into the channel, where the free end is anchored to a diversion line. Such a system is called a Kellner jack field (Keown et al. 1977).

Lindner (1969) noted that the Kellner jack field is, in effect, a series of permeable dikes that are connected at their outer ends. Like any permeable dike system, Kellner fields function by providing channel boundary roughness, thereby reducing flow velocities and inducing deposition of suspended sediment. Keown et al. (1977) reported that an effective Kellner field may reduce flow velocity from a peak of 5 fps to 0.25 fps.

The use of jacks is limited to sediment-laden streams. Lindner (1969) stated that jack dike systems are the most permeable of the permeable dikes in general use. Since they accomplish their purpose solely by reducing flow velocity within the dike field, substantial amounts of suspended sand must be present to settle out in the area of reduced velocity. The rate at which a line of jacks can be expected to develop sufficient sediment deposition to form a new, stabilized bank line depends primarily on debris trapped by the wire, suspended sediment carried by the stream, and the reduction in stream velocity behind the jacks (Frogge 1967). Similarly, the effect of jacks on aquatic habitat depends on the height of the jacks, the amount of space between them, and river stages. McEwan (1961) reported that a concentration of sediment approaching 700 ppm was required for dikes constructed of railroad rails and wire mesh to function effectively on the Lower Colorado River. When the sediment concentration averaged 300 ppm or less, the turbulence caused by the jacks induced erosion rather than deposition.

The placement of Kellner fields has found wide application in southwestern and midwestern states where wide, shallow, silt-laden streams are subject to severe scouring during high-velocity flows (Keown et al. 1977). Jack systems have been used successfully on the Canadian River in Texas (Byers 1962), Frenchman River in Nebraska (Frogge 1967), Middle Rio Grande in New Mexico, Russian River in California (Weller 1965), and the Arkansas River (Bush 1962).

Jacks are not always effective. Although the Kellner field was developed in the 1920's as an economical alternative to pile dikes (Keown et al. 1977), attempts to protect the banks of the Red and Arkansas rivers with jacks failed where pile dikes had been used successfully for years (Weller 1965). On the other hand, steel jack systems proved more effective than either fences or timber pile dikes on the Frenchman River (Frogge 1967) and the Middle Rio Grande (Woodson 1961). Carlson and Dodge (1962) presented a method for

predicting the rate of deposition to be expected in a field. This information may be helpful not only in designing the field, but in deciding whether a steel jetty system may be expected to operate satisfactorily (Lindner 1969).

To the best of our knowledge, Kellner jack fields or similar jack and wire dike systems have not been used in UMR.

Designs for steel jack systems were published by Carlson and Dodge (1962), Frogge (1967), and Bush (1962). Designs were provided for concrete jacks by Myers and Ulmer (1975), and for wood jacks by the U.S. Soil Conservation Service (1979). Other jack systems have been composed of steel fascine boxes and steel abatis dikes, which were used on the Red River (Weller 1965), and steel automobile frames, which were used on the Canadian River (Byers 1962).

6.2.4. Fences

Fences or fence jetties are groins used on low-gradient streams with discharges of less than 500,000 cfs, to provide protection to river banks. Fences may be either transverse or parallel to the streambank, and can be built in one, or more rows. Only transverse fences are discussed here. Several types of materials can be used in the construction of the fences--e.g., wooden or steel pipes for the posts and wood or wire for the fencing (Fig. 18). Fences can be made permeable, partly permeable, or impermeable to water and sediment (Simons et al. 1979; Keown et al. 1977; U.S. Army Corps of Engineers, Rock Island District 1980).

Transverse fences either trap material or deflect it from the river bank. When a fence is constructed at an oblique angle downstream to the flow, debris is deflected into the main channel. Such devices are particularly useful in debris-laden streams. When sediment deposition is desired, the fence is constructed at an oblique upstream angle (Keown et al. 1977; Simons et al. 1979).

The use of fences is not considered to be one of the most effective techniques for bank protection; however, fences have been commonly used because they are easy to construct and the simple materials needed are usually available. Unfortunately, however, fences are easily damaged, and thus require frequent repair and maintenance.

Fences have little effect on fish and wildlife habitat. If sediment is built up, vegetation may become established in the area. Fences have little effect on existing vegetation. The structures are visually unappealing and tend to look progressively worse as the fence deteriorates (U.S. Army Corps of

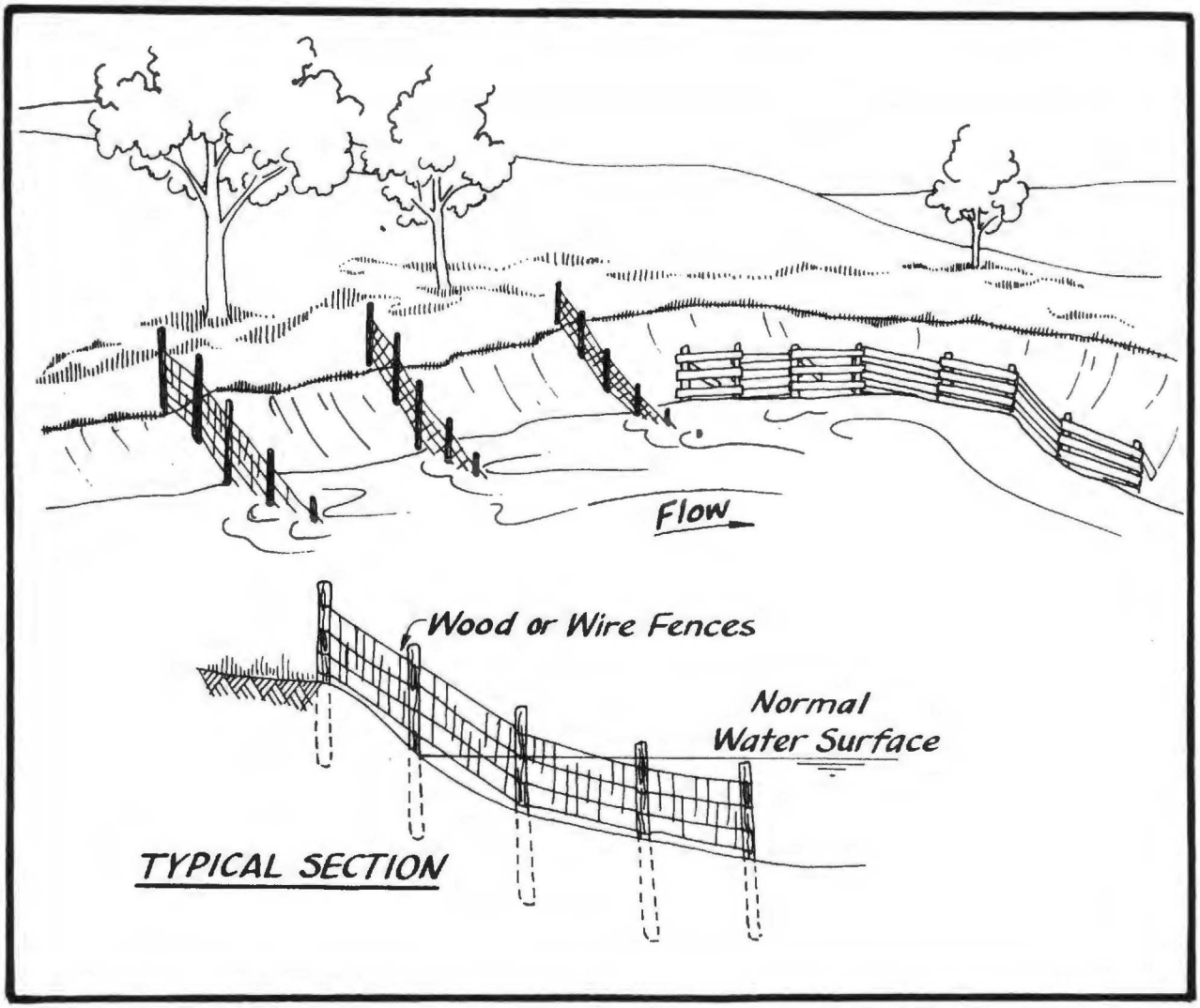


Fig. 18. Typical section and installation of fences (U.S. Army Corps of Engineers, Rock Island District 1980).

Engineers, Rock Island District 1980).

6.2.5. *Tree Retards*

Tree retards are permeable groins constructed by installing trees in a horizontal position, transverse to the flow of the river. The 30- to 40-ft trees are anchored with stone fill on the shore and with cables attached to concrete anchors both in the water and on shore (Fig. 19). This method of bank protection is recommended where trees are plentiful (U.S. Army Corps of Engineers, Rock Island District 1980).

The construction of tree retards is an excellent mitigation or enhancement technique. The trees protect the bank by slowing the current and accumulating debris, and the branches provide fish habitat. This erosion control method is aesthetically appealing because it simulates the natural appearance of undercut trees falling into the stream. Although the trees need to be replaced rather frequently, and the protection is only marginal, tree retards are inexpensive to construct and maintain.

6.2.6. *Timber Cribs*

The function of timber cribs is similar to that of tree retards and other groins--namely to divert flow away from eroding banks. Timbers or railway ties are placed perpendicular to the shore, one on top of another (Fig. 20). This protective structure is less attractive than tree retards because timber cribs are not as aesthetically pleasing and do not provide as much natural cover for aquatic organisms. Timber cribs limit the use of the river and access to it and require maintenance, particularly after high water and storms. On the other hand, they effectively protect short stretches of streambank and are easily constructed and repaired. They cost about $200 per bank foot in the mid 1970's (U.S. Army Corps of Engineers, Rock Island District 1980). Timber cribs have usually been used on small streams, but are now being tried on a limited basis in large rivers of the western United States (Keown et al. 1977). Armstrong (1976) reported that a timber crib helped hold fill sand in place on a Lake Michigan beach, and helped trap additional sand. Inasmuch as the cribs required little maintenance, they may be of long-term value.

6.2.7. *Sand-filled Synthetic Bags*

Both Longard tubes and giant sandbags are made of synthetic fabric filled with sand. Longard tubes consist of high-density polyethylene casings lined with low-density polyethylene, and giant sandbags consist of nylon bags measuring either 2 X 5 X 10 ft or 1.5 X 6 X 20 ft (Armstrong 1976). These products have been used for constructing revetments and groins, particularly in the Great Lakes and coastal areas. The present discussion is limited to the use of these materials for groins.

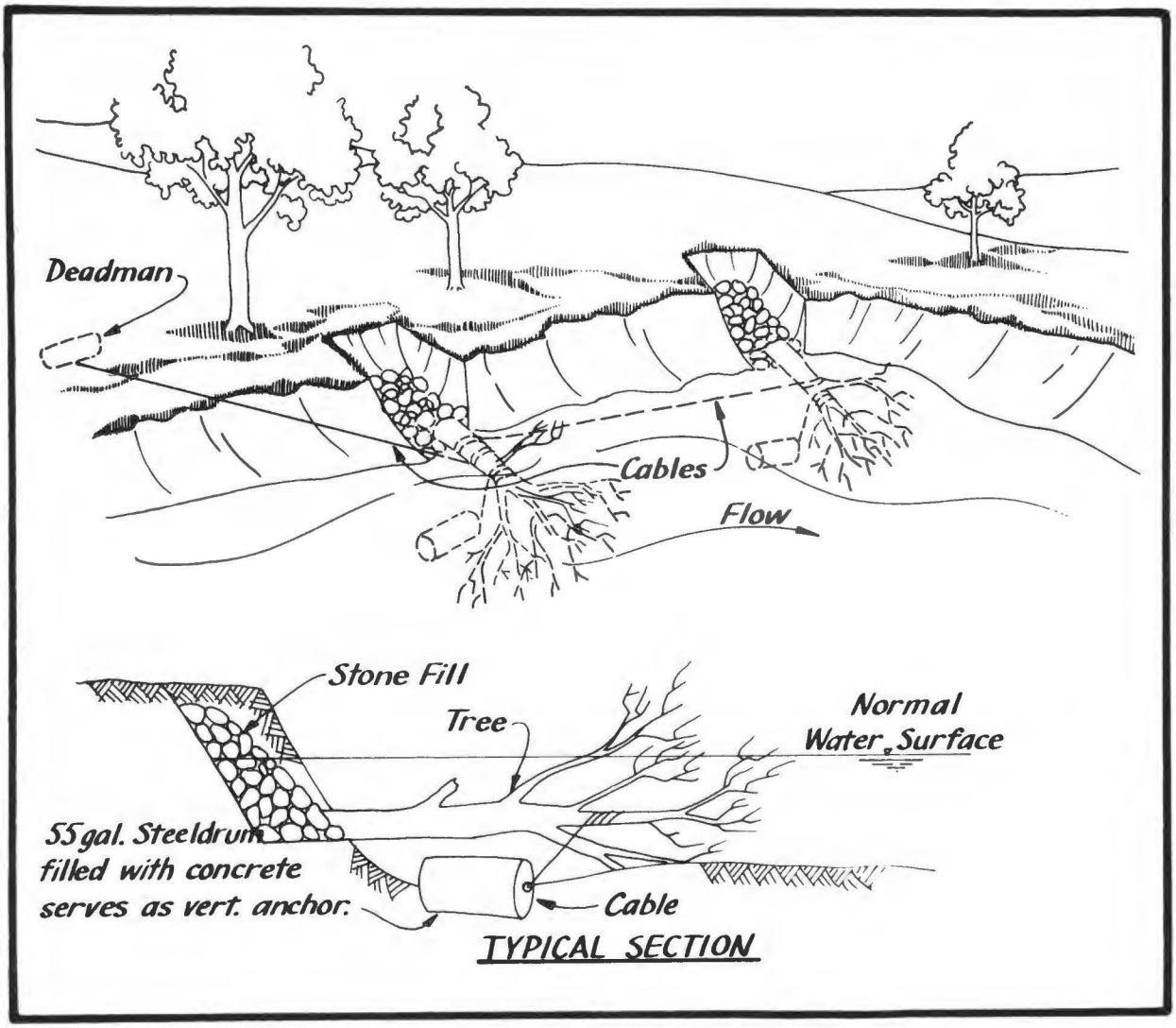


Fig. 19. Tree retards protect the bank by slowing the current and accumulating debris. The submerged branches provide cover for fish (U.S. Army Corps of Engineers, Rock Island District 1980).

Armstrong (1976) reported on a program, begun in 1973, where both Longard tubes and giant sandbags were used along the coast of Lake Michigan. These structures were selected because they were inexpensive and easy to install. They varied in length from 50 to 120 ft. Both types can be used effectively but they may settle in sandy areas, and sandbags must be replaced yearly. If

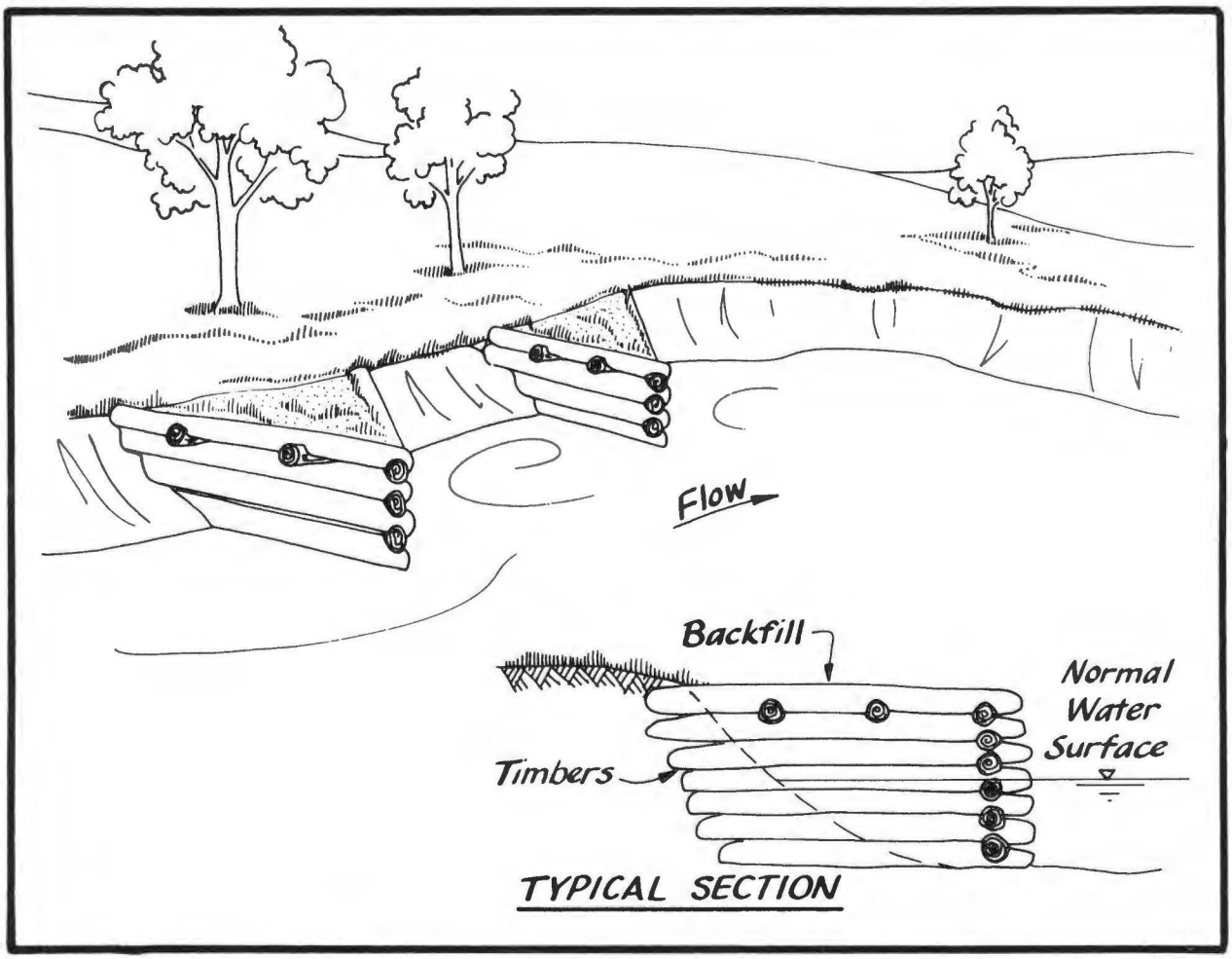


Fig. 20. Typical section and installation of timber cribs (U.S. Army Corps of Engineers, Rock Island District 1980).

there is insufficient littoral drift, additional sand placement may be required. De Ment (1977) discussed the use of Longard tubes as groins and as a beach stabilizer (berm) to protect Grand Isle, Louisiana, from erosion. The groins were 300 ft long and 40 in. in diameter, and the berm was 2000 ft long and 40 in. in diameter. The structures withstood winds of 40 to 50 mph that blew continuously for 4 days and developed waves nearly 25 ft high.

6.2.8. Miscellaneous River Training Structures

Steel piling, gabions, asphalt mastic, and similar structures can be used as groins to provide effects similar to those noted in the preceding section. Armstrong (1976) found all these structures to be generally effective and inexpensive. He learned that steel piling was often improperly anchored and that consequently the structures required additional repairs and maintenance. Steel sheet piling is normally effective as a shore protection structure, if properly installed. Luedtke et al. (1973, 1976) successfully used gabions as groins to increase shelter and spawning substrate for fish in a western stream. (Gabions are discussed in detail in Chapter 5.)

6.3. IMPACTS ON THE ENVIRONMENT

The use of river training structures is an indirect approach to bank protection. These structures can be effective in controlling erosion (they may even promote deposition) and can be very helpful in enhancement of fish and wildlife habitat. Unlike revetments, these structures do not form a distinct, abrupt, land-water interface, and thus may provide an important transition zone between the aquatic community (main channel) and the terrestrial community (bank). In addition, some of the structures can provide important instream cover for fish and provide substrate for colonization by periphyton.

As in revetments, the material used in construction is the characteristic that most affects the impact of river training structures on fish and wildlife. Both the inherent properties of the material and the construction practices needed to use that material affect natural resources to various degrees. In addition, the porosity and density of the material used affects the overall permeability of the structure. These are important considerations when one is evaluating the merit of the river training structures for mitigating fish and wildlife losses, and for protecting the river bank or shoreline against erosive forces.

Variation in the impacts of stone wing dams depends on several factors, one of which is their height at normal water levels. Stone wing dams built on UMR (St. Paul, Minnesota, to St. Louis, Missouri) between 1890 and 1930 were low-level structures. When the locks and dams were built between 1930 and 1940, most of the dams were submerged or occasionally slightly emerged during low water levels (Lagasse 1975). Studies indicate that structures with less than 5 ft of water over the top at low operating pool levels and located on outside river bends create the most diverse aquatic habitat and attract the greatest numbers and species of fishes (Pitlo [ca. 1981]).

Before the locks and dams were developed on UMR, the low-level wing dams had some geomorphic effects. Chen and Simons (1979) determined that flood stages and the position of the river were not changed by the wing dams. However, the river's surface and width had decreased, the riverbed elevation had fluctuated, depending on conditions, and the island area had increased.

Emergent stone wing dams were build on the Middle Mississippi River (St. Louis, Missouri to Cairo, Illinois) after 1965, replacing inadequate timber pile dikes, to contract the channel to a width of 1500 ft. About 800 such dikes, with a total length of 91 miles, were built in only 195 miles of river (Lagasse 1975; Simons et al. 1981a). As a result of these dikes, island areas decreased, the riverbed lowered (11 ft in one 14-mile reach between 1889 and 1966) and halved in area, the flow area was reduced to two-thirds that of the natural river, and natural side channels were eliminated (Lagasse 1975; Simons et al. 1974, 1981a). Fish and wildlife habitats have given way to agricultural lands in some of the former backwater areas. This situation has developed with emergent dams because the high dike crests force flow around the nose, where sand deposits form bars. When more dikes are added, the channel on the opposite side degrades; a possible consequence is a dewatered area below the dams during periods of low flows (Simons et al. 1974). The combination of dikes and levees in the Middle Mississippi River has reduced the carrying capacity of the river for flows greater than bank full (Simons et al. 1981a; Stevens et al. 1975).

The following discussion deals basically with submerged wing dams.

Stone wing dams have some fishery enhancement value because they provide cover and boundary roughness in the main channel of the river. Because sedimentation does not always occur behind impermeable dikes, slack water may occur in this area. Garde and Ranga Raju (1977) reported that the standing eddy behind a short dike is generally on the order of 4 to 5 times the length. The stones used for constructing wing dams also provide surface area for colonization by periphyton. It is generally acknowledged by biologists and fishermen on UMR that main channel wing dams provide some of the best fish concentrations and catches on the river.

Although sampling near wing dams is difficult because of the deep water and high-velocity flows (Fernholz 1980; Robinson 1977), the value of stone wing dams as a source of food and cover has been well documented. Hall (1980) investigated macroinvertebrate populations associated with the bottom sediments and rock substrate of six submerged wing dams in Pool 13 of UMR. The results attest to the value of wing dams as a suitable substrate for macroinvertebrate colonization. Basket samplers placed on the rock dikes collected 26.5 times more macroinvertebrates and 14.3 times more biomass per unit of area than did Ponar grab samples of the bottom sediments near wing dams. These findings imply that the substrate provided by the stones and debris trapped on the wing dams offers a localized source of food for fish and

creates habitat diversity.

Many species of fish take advantage of the habitat provided by wing dams. Robinson (1977) reported that flathead catfish, blue suckers, white bass, and skipjack herring preferred the fast water near wing dikes in the Missouri River. Fish collected there accounted for 56% of the 5487 fish taken in Robinson's survey of dikes and water near mud banks. Only 1% of the fish collected were from slack water areas associated with dikes. Of the 33 species collected, 26 were from fast water, 29 from mud banks, and 13 from slack waters. The author admitted that the slack water areas may not have been properly sampled because the sampling methods used were inadequate. Burress et al. (1982) sampled invertebrate and fish populations near bank stabilization structures in the Missouri River in North Dakota. Of the habitats sampled, dike fields had the most diverse fish communities. Nearly two-thirds of the total fish sample consisted of five species: common carp, yellow perch, white bass, white suckers, and river carpsuckers. The diverse invertebrate populations located on the dike fields and revetments provided food for walleyes, northern pike, white bass, burbot, and shovelnose sturgeon. Pierce (1980) found that 38 of 52 species collected by electrofishing in Pool 13 of UMR were on or near wing dams. Personnel of the Wisconsin Department of Natural Resources (Fernholz 1978, 1980), who electrofished near wing dams in UMR during the day and at night, found that the largest smallmouth bass, bluegills, black crappies, walleyes, saugers, and gizzard shad preferred wing dams as habitat, over sand flats and riprapped banks.

Pitlo (1980) sampled adult fish at 595 current modification structures (mostly stone wing and closing dams) in Pools 9 to 19 of UMR. Spring and summer sampling produced over 2000 fish, a total of 35 species. Redhorses, carpsuckers, and freshwater drum dominated the catch. Most of the fish were caught immediately downstream from the structures.

Sedimentation diminishes the value of wing dams as fishery improvement structures because it reduces the quality and quantity of substrate for colonization by periphyton and the area of slack water. Pitlo (1980) reported that the predominant types of substrate associated with stone wing dams surveyed in Pools 9 to 19 on UMR were sand and silt (77.5 and 15.1%, respectively). All structures lacked aquatic vegetation. In areas below wing dams on the Missouri River, so much sediment accumulated that terrestrial habitat replaced aquatic habitat, and resulted in a tremendous loss of fish and wildlife cover (Jennings 1979). In a section of the Missouri River studied by Funk and Robinson (1974), 98% of the island surface area, 50% of the original water surface area, and 8% of the river length were lost during the period 1879 to 1972 (Thackston and Sneed 1982). Substrates at wing dams in UMR that consist of gravel or silt-clay support a greater biomass and diversity of macroinvertebrates than do dike substrates that consist of sand originating from sediment deposition (Hall 1980).

Sedimentation may be inhibited if wing dams are modified so that scouring is promoted. Modifications used on the Missouri River have included notching, eliminating the root, and lowering the height of the structure (Burke and Robinson 1979). (These modifications and their enhancement values are discussed in Chapter 29.)

The wide variety of wing dam designs that can be used in response to site-specific characteristics or fishery needs has caused many investigators to conclude that wing dam design is best left to competent engineers. Degenhardt (1973) stated that "it would be futile and foolish to attempt to describe optimum design criteria and procedures for the utilization of dikes in any specific location since no two situations in even the same river are alike."

Other impermeable structures such as earth and stone and wood cribs, Longard tubes, giant sandbags, gabions, and asphalt mastic provide some of the same beneficial and adverse impacts as those provided by stone wing dams. These structures, however, do not develop gravel or silt-clay substrates that could provide habitat for macroinvertebrates. The structures provide slack water areas that provide some favorable habitat for fish, but their most beneficial effect is that of bank protection.

The possible effects of jack fields on riparian fish and wildlife resources were mentioned in the literature we reviewed. Like any stream channelization measure, successful jack fields eventually cause a reduction in cover and boundary roughness within the channel. Several authors (Keown et al. 1977; Frogge 1967; Byers 1962) reported that vegetation became rapidly established in the built-up areas behind retard lines.

The undesirable visual impact of Kellner jack fields is one of the major disadvantages of this bank protection measure. Keown et al. (1977) stated that Kellner jack fields are "not aesthetically harmonious with a flood landscape." Nevertheless, the fencelike appearance of jack fields may be used to advantage. In areas where erosion due to livestock activity is a problem, jack lines may help prevent uncontrolled access to the stream edge.

Other disadvantages may place further restrictions on the use of jack field systems. Keown et al. (1977) reported that jacks should not be used where the banks are higher than the jacks, or where flow velocities are excessively high. Myers and Ulmer (1975) also indicated that jack fields should not be used in wide river bends because the channel flow tends to leave the jack lines and meander to the opposite side, rendering the jacks ineffective.

The major advantages of jacks are their proven durability and

flexibility. Because jack dikes are flexible and self-supporting, undermining is not a major concern, and it is not necessary to construct a protective apron at the base of the dike. The durability of jacks depends on the construction material used. Lindner (1969) reported that timber units are shorter lived than steel units, and that, depending on where they are used, concrete units may also be short lived. Concrete is especially subject to deterioration if exposed to successive cycles of freezing and thawing. Steel jacks used on the Canadian River have required little maintenance for 50 years (Byers 1962). Keown et al. (1977) recommended that jacks not be used in corrosive environments.

Timber pile dikes, because they are permeable, do not divert as much flow to the navigation channel as do stone wing dams or other impermeable structures. Timber pile dikes are effective as channel maintenance or bank protection structures if river flow velocities are moderate, concentrations of suspended sediments are high, and river depths are shallow.

Timber pile dikes were responsible for creating a single navigational channel in the Middle Mississippi River before the 1930's. However, these dikes are being replaced or converted by filling them with stone, because of their vulnerability to destruction by ice floes, tow boats, and debris and because maintenance costs are high (Hartke 1966). Timber pile dikes are still being built in some areas where foundation problems exist, and where there is no economical source of stone (Simons et al. 1975).

Timber pile dikes and other permeable structures such as fences, tree retards, tire- and brush-filled wood cribs, and steel pilings can provide desirable cover where natural habitat has been reduced or eliminated. Robinson (1977) found that fallen trees, old pilings, and brush habitats in the Missouri River were heavily used by flathead catfish. According to Holz (1969), flathead catfish were found almost totally in brush piles in the unchannelized section of the Missouri River and around pile dikes in the channelized portion. These fish were vulnerable to angling, because they were concentrated in the only habitat remaining in the channelized section of the river. Care must be taken in the placement or modification of structures because the habitat associations of fish species are not completely understood. In their study of structures in Iowa rivers, Witten and Bulkley (1975) found no invertebrates associated with steel pile dikes or with fences.

Some of the suggestions that have improved aquatic habitat in the Missouri River include the anchoring of felled trees to mud banks and placement of brush piles, pilings or other suitable structures in chutes and backwaters, and within L-heads (FWS 1980a).

6.4. *COSTS*

Costs of river training structures vary, depending on material, location, and situation. Part of the cost of stone wing dams depends on the availability of local stone. Stone groins built to protect low sand bluffs on Lake Michigan near Sheboygan cost $95 per linear foot of shoreline (Hanson et al. 1978). Keown et al. (1977) reported that stone transverse dikes ranged in cost from $40 to $65 per linear foot. The installation cost for loose rock groins at 1975 prices was $60 per linear foot (Payne 1980).

Timber pile dikes cost $50 per foot at 1976 prices when used as a shoreline protection device on Lake Michigan (Armstrong 1976); pile board transverse dikes cost $40 to $55 per linear foot (in place) at 1976 prices (Keown et al. 1977); and timber groins cost $75 per foot at 1975 prices, according to Payne (1980).

Kellner jack fields often prove to be a cost-effective method of bank stabilization, particularly when used in locations where timber and riprap are too expensive (Keown et al. 1977). Bush (1962) estimated that the cost of a series of stone dikes on the Arkansas River would have been roughly twice that of a jack field ($65,000) that was installed. Frogge (1967) found that fences and timber pile dikes would have been "much more costly" than steel jacks used on the Frenchman River.

Byers (1962) provided a complete cost analysis for a steel jack system. Almost 8500 jack units were placed in the Canadian River between 1926 and 1946, at a cost of only $205,000 ($24 per unit). During the next 16 years, maintenance costs totaled only $20,000 ($1250 per year). Byers (1962) noted that maintenance costs were highest immediately after installation and decreased thereafter.

Other estimates indicated that steel jacks cost $35 to $55 per installed unit (Carlson and Dodge 1962) or $16 to $47 per linear foot. These amounts include the cost of the jacks, cable to connect them to deadmen on the bank, and labor (Keown et al. 1977). Costs for installed concrete jacks--typically $30 to $40 per linear foot in the early 1970's--are generally higher than those for steel jacks (Myers and Ulmer 1975). The weight of concrete or timber jacks makes them more expensive to assemble than steel units (Lindner 1969). Richardson et al. (1975) noted that some steel fabrication plants contract for the production of jacks.

Fences or fence jetties cost $25 to $50 per linear foot in 1976 if new materials were purchased. Costs were considerably less where secondhand or free materials were available (Keown et al. 1977).

Tree retards are inexpensive to construct and maintain. The U.S. Army Corps of Engineers, Rock Island District (1980) estimated that tree retards cost $20 per linear foot of bank protection if trees are readily available.

Timber cribs vary in price. Costs are approximately $200 per bank foot (U.S. Army Corps of Engineers, Rock Island District 1980). On the other hand, Armstrong (1976) found that in the construction of a Lake Michigan beach nourishment project, timber cribs that were used cost $80 per foot of shoreline.

Longard tubes and giant sandbags cost $25 to $30 per foot of shoreline in the mid 1970's, when used in a demonstration project to protect certain selected sites on Lake Michigan (Armstrong 1976). Hanson et al. (1978) estimated that Longard tubes cost $20 to $35 per foot for materials or $45 to $80 per foot installed. Sandbags cost $75 each installed. "Dura-bags" (9.5 X 4.5 X 1.5 ft) filled with sand cost $13.50 per linear foot (Machemehl 1977).

According to Armstrong (1976), steel piling, gabions, and asphalt mastic used as groins on Lake Michigan were relatively inexpensive ($30 to $50 per foot). In August 1977, sheet piling ranged from $4 to $9.50 per square foot for materials, and from $6.50 to $13.90 per square foot installed (Hanson et al. 1978).

6.5. EVALUATION FOR USE ON UMRS

River training structures have various degrees of merit for protecting shorelines, river banks, and beaches and as fishery habitat in UMRS. Both permeable and impermeable structures can be used to protect shorelines, river banks, and beaches.

Impermeable structures efficiently provide bank protection because they deflect flow away from the bank. However, such structures must be designed properly. The dike must extend beyond the eroding currents, so that these currents are relocated in an alignment controlled by the location of the dikes. To protect banks, impermeable dikes must be angled downstream or constructed perpendicular to the bank. Spacing of the dikes is also important. When dikes are used to develop a navigation channel, it is recommended that they be separated by a distance 1.5 to 2 times the length of the upstream dike. For bank protection along a concave bank of the channel, a spacing of 4 to 6 times the length of the upstream dike is adequate. Dikes along braided or straight reaches can be spaced farther apart. The dikes should never be spaced farther apart than one-half the meander length of the thalweg; if they are, the river may impinge upon the bank upstream from the dike. Transverse stone dikes are the most widely used impermeable structures for bank stabilization and channel development (Simons et al. 1979).

Whereas impermeable structures act as a barrier between the bank and erosive water currents, permeable structures slow the current to noneroding velocity, encourage sediment deposition, and promote the establishment of vegetation (Simons et al. 1979). Because permeable dikes require that a stream have fairly high sediment loads if they are to operate effectively, they may not be applicable to the upper reaches of UMR. Timber pile dikes have been used successfully in the Middle Mississippi River where sediment loads are higher. Other types of permeable structures may also be practical for that stretch of the river as well. J. W. Robinson (personal communication) has suggested that jacks, and presumably other permeable structures, placed parallel to the main current may serve to stabilize banks without loss of habitat under conditions of average river stage. In fact, total habitat diversity may be increased by using these structures.

If impermeable structures are to provide habitat for aquatic organisms, little or no sedimentation must be involved. Consequently these structures have more applicability on the upper reaches of UMR, where sediment loads are low. However, even in low-sediment waters, accretion can occur, making it necessary to modify impermeable structures to offset this process (see discussion of Wing dam modification in Chapter 29). From the standpoint of economics and possible changes in the river stage, it is not recommended that impermeable structures be built merely to enhance fisheries in the UMR main channel border. Simons et al. (1975) and others have suggested that wing dam construction has caused higher flood stages in the spring. Consideration should be given to modifying the wing dams that are already in place if they are causing sedimentation that is detrimental to the aquatic habitat.

Sand-filled synthetic bags and gabions have been used successfully as groins in the Great Lakes for bank protection; certain areas of UMRS could benefit from the use of these structures.

The installation of permeable structures that are similar to natural structures (e.g., downed trees, brush) has potential as a fishery enhancement technique.

CHAPTER 7. INTRODUCTION TO FIXED AND FLOATING BREAKWATER STRUCTURES

Waves that cause bank or shoreline erosion may be generated by winds or boats. The primary function of breakwater structures is to reduce wave action on the shore by deflection and energy absorption. Breakwaters are unique structural mitigation measures because they are designed to dissipate wave energy before it reaches the shore (U.S. Army Corps of Engineers, Detroit District 1976).

Breakwaters are constructed or located offshore, parallel to the shoreline. They may be fixed or flexible, connected to or detached from shore and constructed of almost any material with structural integrity, such as rock, wood, concrete, metal, rubber tires, filled bags, or rubber-like synthetic materials (Mulvihill et al. 1980). Initially developed for the protection of marinas and harbors that lacked natural protection (Harms 1979a), breakwater structures have since been used to provide protection to beaches, to reduce wave damage to costly structures such as seawalls or power plants, to protect fish culture installations, and to create artificial reefs. Breakwaters are placed in high-energy areas, such as coastal areas, where there is a long fetch or where there is a high incidence of vessel-generated waves (Mulvihill et al. 1980).

Breakwater structures may be fixed or floating. Fixed breakwaters occupy the entire water column and can be built as solid, nearly vertical walls to reflect wave energy, or as rubble mounds with sloping faces to induce a partial breaking of waves. Often, a combination of these types is used. The cost of building fixed breakwaters is high and is justified only for permanent installations (Kamel and Davidson 1968).

Floating breakwater structures are generally moored or anchored off shore. They are oriented horizontally with respect to the water surface because wave energy is concentrated near the surface in short period waves in relatively deep water (Kamel and Davidson 1968; Bowley 1974). As a result, the beam size (width) of the floating breakwater often determines the amount (degree) of wave attenuation provided.

Conventional fixed breakwater structures require a very large volume of material just to build the structure to the upper water stratum where the wave energy is concentrated (Bowley 1974). The lower portion of a breakwater resting on bottom generally has little effect on wave action. However, the lower portion serves to obstruct incidental and reflected subsurface wave action, and consequently fixed breakwaters provide more effective protection than do floating breakwaters (De Young 1978).

Structural attributes of fixed breakwater structures may also cause them to function as obstacles to natural water currents, littoral drift, and fish migration or movement. Although floating breakwaters may provide only partial wave suppression, they have a much less adverse impact on the environment.

Miller (1974) reviewed practical applications of floating breakwater structures for the protection and creation of small craft harbors, and recommended that a floating breakwater be considered over a fixed breakwater when the following requisites can be satisfied:

1. A fixed breakwater cannot be reasonably used due to site, water depth, or bottom conditions that dictate excessively high costs.

2. Water in the area of the breakwater is not subjected to design waves with a period greater than 4 s or a height of 3 ft. The significant wave is often used as the design wave.

3. The degree of wave attenuation provided by the breakwater (as determined by experience and model testing) is appropriate for the design wave.

4. Resonance of the structure will not generate an adverse secondary disturbance (note: such disturbance is more likely to be associated with fixed than with floating breakwaters [Mulvihill et al. 1980]).

5. The structure and mooring system is designed for maximum (peak) storm forces, rather than for the design waves.

6. Maximum storm waves can be reduced to a level that will not cause excessive damage to inner harbor facilities.

7. Vessel owners are aware that waves generated by a storm will require proper, and probably additional, protection for moored vessels.

It should be apparent from Miller's recommendations that the applicability of floating or fixed breakwaters is determined by site-specific characteristics.

Fixed breakwaters provide better wave attenuation, require less frequent maintenance, and have a longer life span. Fixed breakwaters, however, also obstruct littoral drift (Richey and Nece 1974; Sanko 1975), contribute to wave resonance within a harbor (Mulvihill et al. 1980), are highly susceptible to scouring (particularly toe erosion), may decrease water circulation (Saylor 1966), may inhibit fish migration or movement (Richey and Nece 1974), and require more extensive construction activities, and are much more costly than floating breakwaters.

Principal advantages of floating breakwater structures are their greater potential for multiple use; little interference with water circulation, shore processes, and fish migration; capability to fluctuate with water levels; transportability; reusability; lower cost; and relatively low additional costs to accommodate increasing water depths at the site of installation (Sethness et al. 1974; Richey and Nece 1974). Conversely, floating breakwaters require more planning and more frequent maintenance, possess less wave-attenuating capabilities than fixed breakwaters, and are subject to vandalism (Brouha and van Geldern 1979) and debris accumulation (Shaw and Ross 1977). In addition, it may be necessary to remove floating structures during periods of ice cover to avoid damage or loss.

Both fixed and floating breakwater structures may interfere with navigation. Sediment accretion that may develop to the lee of a breakwater can have a positive or a negative environmental impact, depending on the original reason for constructing the breakwater. Both types of breakwaters may serve as artificial reefs for fish habitat (discussed in Chapter 22).

In any comparison of breakwater structures, one must consider the relative ability of each type to attenuate wave energy. Although fixed breakwaters suppress the oncoming waves completely, suppression by floating breakwaters may be as high as 100% for very short waves but be nil for extremely long waves and swells (Kowalski 1974).

The characteristic commonly used to describe wave attenuation by a floating breakwater is the transmission ratio, C_T, which is defined as either the ratio of transmitted wave height to incident wave height, or as the ratio of transmitted energy to incident energy (Richey and Nece 1974). The smaller the C_T value, the greater the wave-attenuating efficiency. The transmission coefficient depends on wave steepness (H/L), relative wavelength (L/B), draft of breakwater, water depth, and porosity. Any comparative evaluation of floating breakwater performances must also account for the wave characteristics under which the study was performed.

The transmission coefficient is related to the ability and efficiency of a floating breakwater to reduce wave energy (Kamel and Davidson 1968) and is calculated as follows:

$$\text{Energy dissipated} = 1 - C_T^2 - C_r^2$$

where C_T = transmission coefficient and C_r = reflection coefficient

For floating tire breakwaters, this equation, can be simplified (Gifford et al. 1977)

$$\text{Energy dissipated} = 1 - C_T^2$$

because this type of structure reflects little wave energy, as indicated by laboratory studies performed at the Hydraulic Laboratory of the Canada Centre for Inland Waters. Harms (1979a) confirmed that floating tire breakwaters reflect little wave energy (roughly 6 to 20%, depending on breakwater and wave characteristics).

The efficiency of a floating tire breakwater to reduce wave amplitude can be related to the transmission coefficient by the formula:

$$\text{Energy dissipated} = 1 - C_T$$

As we noted in Chapter 3, the energy of a wave is directly proportional to the square of the wave height. This relation means that, even if a floating tire breakwater reduces wave height by only 68%, the incident wave energy is actually reduced by 89% (Kowalski 1974).

CHAPTER 8. FIXED BREAKWATER STRUCTURES

8.1. SITUATION TO BE MITIGATED OR ENHANCED

Fixed breakwaters are usually constructed to protect an area such as a shoreline, harbor, or basin from wave attack. They can also serve navigational purposes by creating calm water and protecting mooring, and by promoting safe operation of vessels (U.S. Army Coastal Engineering Research Center 1977). Fixed breakwaters can also protect fish and wildlife habitat because they help reduce erosion. Erosion of the shoreline results in a steady loss of habitat and constant turbidity, caused by soil being continually washed into the waterway (Mulvihill et al. 1980).

8.2. DESCRIPTION OF TECHNIQUES

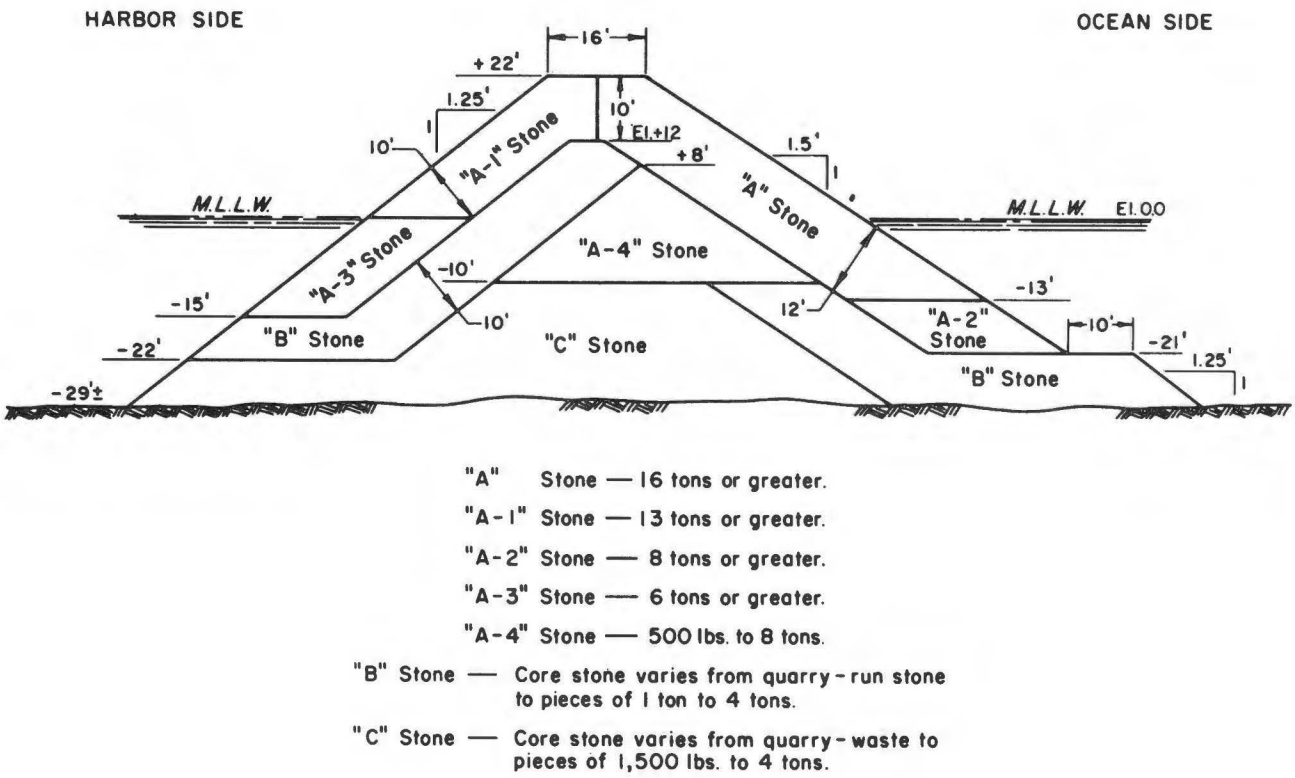
Fixed breakwaters protect shoreline areas from wave attack by reducing and reflecting wave action. Fixed breakwaters can be constructed of the following materials: rock, wood, concrete, metal, or nylon and sand (for sandbags). They can be connected to the shore or located offshore and used in conjunction with other structures (such as groins) or used separately (Mulvihill et al. 1980).

Because shore-connected breakwaters are designed to protect harbors, they are positioned to protect the target area from wave and surge action as fully as possible for as much of the time as possible. Depending on the needs of the area, it may not be necessary to build a breakwater high enough to prevent overtopping. A lower structure is less costly because construction and maintenance needs are reduced (U.S. Army Coastal Engineering Research Center 1977).

8.2.1. Rock Breakwaters

The most popular type of breakwater used in the coastal United States is the rock or rubble-mound breakwater. Such a structure can be used at almost any inshore depth and can withstand severe storms. Characteristics on which to base selection of rock materials include the specific gravity, abrasion, slaking, and freeze-thaw resistance (Fig. 21). Limestone should not be used because it abrades and dissolves easily (Mulvihill et al. 1980). Rock breakwaters are sometimes modified into a composite structure by using a concrete cap to increase stability. They are also vulnerable to erosion at the toe, which can lead to slope failure.

Hedar (1953), who experimented with rock breakwaters to determine rules



"A" Stone — 16 tons or greater.

"A-1" Stone — 13 tons or greater.

"A-2" Stone — 8 tons or greater.

"A-3" Stone — 6 tons or greater.

"A-4" Stone — 500 lbs. to 8 tons.

"B" Stone — Core stone varies from quarry-run stone to pieces of 1 ton to 4 tons.

"C" Stone — Core stone varies from quarry-waste to pieces of 1,500 lbs. to 4 tons.

Fig. 21. Diagram of a rock breakwater (U.S. Army Coastal Engineering Research Center 1977).

for design that would eliminate the collapse of these structures, found that the selection of size and weight of the stone and the slope of the gradient needed were dependent on the height of the waves that were likely to occur. Details on breakwater design and stone stability were given by Maynord (1978), Hudson (1961), and Sollitt and Cross (1976).

When stones of sufficient size are not available, precast concrete shapes, such as tetrapods or tribars can be substituted. These precast shapes can also be used to renovate stone breakwaters. A stone-asphalt mix (60 to 80% stone weight and 20 to 40% concrete mix) can also be used to stabilize rock breakwaters. If designed properly, rubble-mound breakwaters can remain intact for up to 50 years (Mulvihill et al. 1980).

8.2.2. *Concrete Breakwaters*

One common type of breakwater structure is the concrete caisson breakwater. Reinforced concrete shells are floated to a prepared foundation, filled with stone or sand for stability, and then capped with concrete or stone. Holes in the concrete reduce the undesirable conditions presented by a smooth vertical wall and dissipate part of the wave energy within the structure (U.S. Army Coastal Engineering Research Center 1977). Dick and Brebner (1969) found that a submerged permeable breakwater, for depths of submergence greater than 5% of the total water depth, transmits less wave energy than a solid breakwater over a certain wave frequency range. At very shallow depths of submergence, permeable and solid types behave similarly. Caissons can be used only in depths of 10 to 35 ft. The foundation used must be able to withstand scouring (U.S. Army Coastal Engineering Research Center 1977).

Armstrong (1976) reported on the use of precast, reinforced concrete panels bolted together to form zig-zag walls to protect bluffs and beaches in Pere Marquette Township, Michigan. The panels were placed only 50 ft from shore because the water depth increased too rapidly to enable their installation beyond that point. The structure was almost completely destroyed in 2 years. Such a structure would have to be completely redesigned before it could be used as an offshore breakwater and then would probably become too costly.

Mulvihill et al. (1980) reported that properly installed concrete breakwaters can last up to 35 years, depending on site-specific factors.

8.2.3. *Steel Breakwaters*

Cellular steel sheetpiling can be used where shore waves are not overly severe. This type of breakwater can be installed in depths up to 40 ft and on various types of sea floors, and can be constructed easily, quickly, and economically. The major problem is its vulnerability to storm damage and corrosion in sea water (U.S. Army Coastal Engineering Research Center 1977).

Efforts were made in the past to develop a mobile breakwater that could be floated into place and quickly and easily installed, that was capable of reducing the height of 15 ft high waves to 4 ft, and that could be moved from site to site. Marks (1967), experimented with a mobile breakwater having a perforated front wall made of steel sheeting and Styrofoam and a solid back wall. He found that the perforated breakwater experienced less wave force than caisson-type breakwaters when fixed to the bottom and that it did not promote scouring as the caisson-type breakwater did, but that it was no more effective in reducing waves. His perforated breakwater could reduce a 13-s,

15-ft wave to a 4-ft height shoreward of the breakwater. Marks and Jarlan (1969) modified this design further by also perforating the back wall, and mounting the system on piles. They recommended further use of this breakwater in shallow areas, such as the Chesapeake Bay. Terrett et al. (1969) continued this work by using a fixed, boxlike breakwater resting on a rubble mound. They recommended its use where the necessary stone is not readily available for rubble-mound breakwaters.

Mulvihill et al. (1980) estimated that steel breakwaters should last up to 35 years where environmental factors are favorable.

8.2.4. *Sand-filled Synthetic Sandbags*

Mulvihill et al. (1980) reported on the experimental use of sand-filled synthetic bags as breakwaters for shoreline erosion control in the Chesapeake Bay. They were used as alternatives to groins or in combination with them. Bulkheads, revetments, and groins have been used in the past to alleviate the problem, but they have not always been successful. Sandbag breakwaters are constructed of sand-filled, PVC-coated nylon bags measuring 13 X 5 X 2 ft. They are usually placed 50 ft channelward of the mean high waterline. Sandbag breakwaters are usually placed much farther inshore than most breakwaters, and are considerably smaller.

Nylon sandbag breakwaters have also been used successfully in rebuilding beaches in the Chesapeake Bay. One beach doubled in width in 3 weeks. Similar sandbag systems have been tried successfully as underwater breakwaters in Florida to protect residences (Ray 1977).

Sandbags of various dimensions have also been used in the construction of revetments and groins, as described in Chapters 5 and 6.

8.2.5. *Miscellaneous Fixed Breakwaters*

Other materials have been used to construct fixed breakwaters, but these materials have not been as popular as those previously discussed. Wood has been used for pilings, facing material, and cribs. Gabions are also potential structures for use as facing material. (For a detailed discussion of gabions, see Chapter 5.) Pillai and Verma (1977), who experimented with gabions as facing material on fixed rock breakwaters, found that the size of usable stones was only $^{1}/_{40}$th of that normally used in loose-stone placement, and that the amount of stone required was much reduced.

8.3. *IMPACTS ON THE ENVIRONMENT*

Offshore breakwaters have a tendency to form tombolos (a sand bar or spit connecting the shoreline with the breakwater) because they are so efficient at trapping littoral drift. Because they are usually placed in deeper water than jetties or groins, they control a wider part of the littoral zone. Some of the accretion of sand can be avoided by building offshore breakwaters in a series (U.S. Army Coastal Engineering Research Center 1977). If fixed breakwaters are connected with the shore, they have an even more severe effect on littoral drift (Mulvihill et al. 1980).

Mulvihill et al. (1980) reported that fixed breakwaters have biological impacts similar to those of jetties, groins, and revetments. Rough surfaces provide more habitat for aquatic organisms than do flat surfaces. Sloping faces provide a shallow-water zone. Water quality, temperature, and salinity can be adversely affected on the lee side of fixed breakwaters because of the reduced wave energy and changes in current patterns. Induced secondary waves may also change current patterns. Secondary waves often occur as a result of wave reflection. These changes in the environment can change the species composition of plants and animals in the area. If a sandbar or tombolo does develop, it may be used by beach-dwelling species of birds, provided that human disturbance in the area is limited. Fixed breakwaters can also affect migrating fish by altering their course or by creating areas of shallow water.

In a feasibility report on shore erosion control in the Chesapeake Bay near Smith Island, the U.S. Army Corps of Engineers, Baltimore District (1980) proposed several plans that involved the use of either one 1800-ft continuous rubble-mound breakwater or a series of five 200-ft-long offshore breakwaters. They predicted that the beneficial effects of both breakwaters would be shoreline erosion control and trapping of sand. Predicted adverse effects for the continuous breakwater were expected to be destruction of associated benthos and vegetation, closure of tidal cuts, and reduced tidal flushing and detritus output. Adverse effects of the series of breakwater structures were expected to be accelerated erosion of updrift and downdrift areas.

Fixed breakwaters can be a hazard to navigation unless they are properly marked to indicate their location.

Although no data are currently available on the environmental impacts of sandbag breakwaters, some inferences can be made. It is obvious that any habitat downstream from the sandbag breakwater would be lost or greatly altered. The U.S. Army Corps of Engineers has predicted that sandbag breakwaters will not increase flood height or erosion, or adversely affect the water quality, water supply, or aesthetics (Mulvihill et al. 1980). If shoreline erosion is prevented or slowed, the loss of upland vegetation will be reduced and the loss of habitat for wildlife prevented. How much sand will

be deposited around the structure cannot be estimated, so it is not possible to predict the effects on invertebrates. Fish can benefit because of the reduction of turbidity that results from erosion control.

Vertical wood pile, wood crib, low rubble mound, or sheet pile structures are useful in shallow areas not subjected to severe wave attack. They do not cause some of the adverse environmental impacts of other structures, and are less expensive (Mulvihill et al. 1980). Any wood used should be treated with chemical preservatives and should not be cut or drilled after treatment (U.S. Army Coastal Engineering Research Center 1977).

8.4. COSTS

Installed sandbags cost from $50 to $150 each, depending on whether professional help was obtained to determine how and where they should be placed (Mulvihill et al. 1980).

Information on the cost for constructing fixed breakwaters is meager. The zig-zag reinforced concrete breakwater described by Armstrong (1976) cost $70 per foot in 1973, but the system was not durable and required costly changes. Sanko (1975) commented in his guide for shoreline property owners along the Great Lakes or saltwater coastlines, that fixed breakwaters were too expensive for protection of private property. The U.S. Army Corps of Engineers, Washington, D.C. (1971) stated that offshore structures are always more costly than onshore structures.

Hanson et al. (1978) listed the costs of materials for groins and revetments, but did not include construction costs. Sheetpiling cost $4 to $6.90 per square foot; riprap, $3.40 to $8.10 per cubic yard; concrete, $30 to $35 per cubic yard; sand, $6 to $12 per cubic yard hauled up to 15 miles; and sandbags, $40 each.

The Great Lakes Basin Commission (1975) found that offshore breakwaters would cost $200 to $500 per foot of shore protection in the Great Lakes.

8.5. EVALUATION FOR USE ON UMRS

In general, fixed breakwaters are probably not appropriate structures for use on UMRS. They are designed to prevent wave action on the shoreline, but because they are (by definition) separated from the shoreline, currents can flow between the breakwater and shore. An L-shaped dike built as a fixed breakwater would provide more protection than a breakwater structure.

Inasmuch as floating breakwater structures would not create an obstacle to river flow, as fixed breakwaters would, sedimentation over and around the structures would not be likely to occur. In addition, there is no opportunity for scouring, as there is around the toe of fixed breakwaters, particularly if there is strong current.

Fixed breakwaters could be used to protect shorelines and islands in backwater areas where relatively long fetches are contributing to rapid erosion.

CHAPTER 9. FLOATING BREAKWATER STRUCTURES

9.1. SITUATION TO BE MITIGATED OR ENHANCED

Floating breakwaters are designed to reduce wave energy and wave height, particularly for short periods, in relatively steep waves generated by either wind or boats (see Chapter 3). The floating breakwaters are described here as possible shoreline protection structures. Any lessening of erosion would also reduce turbidity.

9.2. DESCRIPTION OF TECHNIQUES

Although floating structures have been used since 1905 to attenuate waves, the concept was not used much until World War II, when the Bombardon floating breakwater was constructed to form a harbor during the Normandy Invasion (Adee et al. 1976).

Steel, wood, plastic, tires, and reinforced concrete have been used in the construction of floating breakwaters. Although steel corrodes, it endures rough handling and is simple to repair in the field. Because reinforced concrete is difficult to repair in the field, care must be taken to ensure that the modules are not damaged in handling. Plastic flotation devices are subject to failure due to fatigue and must be properly connected to wooden decking (Adee 1976).

Various combination breakwaters were discussed by Katoh and Tsuchiya (1980) and Katoh and Sawaji (1980), and various floating breakwaters were compared by Bulson (1964), U.S. Army Corps of Engineers, Marine Division (1956), Johnston (1960), Griffin (1971, 1972), Brebner and Ofuya (1969), and Jones (1971).

Richey and Nece (1974) provided a classification system for the various designs of floating breakwaters known in 1974: (1) single prism, (2) rafts, (3) catamaran, (4) A-frame, (5) flexible assemblies, (6) tethered floats, and (7) miscellaneous (offset breakwaters, hydrofoil, pneumatic or hydraulic). Each of these designs are discussed here.

9.2.1. Single Prism Breakwaters

Various prism-like breakwaters of four basic shapes (inverse trapezoids, trapezoids, rectangles, and triangles) were tested by Kato et al. (1969) for protection of marine fish farms in Japan. The authors found that an inverse

trapezoid was highly susceptible to rolling but had a high damping effect on waves. Further tests are needed to evaluate the proper design, shape, and mooring systems for these types of breakwaters before they can be considered for use.

9.2.2. Raft Breakwaters

Various designs have been developed that involve use of the raft principle inspired by the Bombardon floating breakwater (Lochner et al. 1948). The Bombardon system failed because the breakwater was designed to withstand waves 8 ft high and 120 ft long, but was subjected to waves 15 ft high and 300 ft long. Failure of the system was related to the mooring system. The Harris floating breakwater was designed to present a thinner horizontal barrier to wave motion, thus causing less stress on the structure and its mooring. It consists of marine plywood units 31 X 33 ft held together by steel sections running the full length of the front and back booms. Overall dimensions of the five-unit test model were 483 X 33 ft (Fig. 22). Tests revealed that the design had great potential for use as a breakwater for marinas, harbors, and offshore activities (Harris and Thomas 1974), but its durability was not determined.

The "Seabreaker" floating breakwater was developed by Hasler (1974). Each unit is a long, rigid pontoon with a universal joint at each end attached to a series of tubular steel girders (Fig. 23). It can be used in four ways: permanently moored, temporarily moored, crawling, or fully mobile. "Advantages of the design include shallow draft, light weight, modest mooring loads even in strong currents, ease of towing or self-propulsion, ability to take to the ground or be winched up a beach, seaworthiness under overload conditions, and provision for catwalks, daymarks, lights, and refuge" (Hasler 1974). The system is effective for waves up to 5 ft high. To accommodate higher waves, the mooring forces are overly stressful and the whole installation becomes too expensive. A large, self-propelled unit could be designed to handle higher waves.

Kennedy and Marsalek (1969) used a box boom 0.2 ft deep with an open top and one porous side. If the breakwater extends over two or more wavelengths, it attenuates waves of moderate length. Such a device has two important advantages over other breakwaters: (1) its action is concentrated near the surface, where most of the wave energy exists, and (2) it tends to dissipate the energy of each wave over a time and space interval, thus avoiding the creation of large shock forces. The wood, however, is vulnerable to marine borers, loses flotation with time, and is difficult to hold in place. Such a system is limited to suppression of surface chop. Its usefulness centers on temporary harbors and summer recreational facilities.

Raft-type breakwaters were discussed in further detail by Stoker et al.

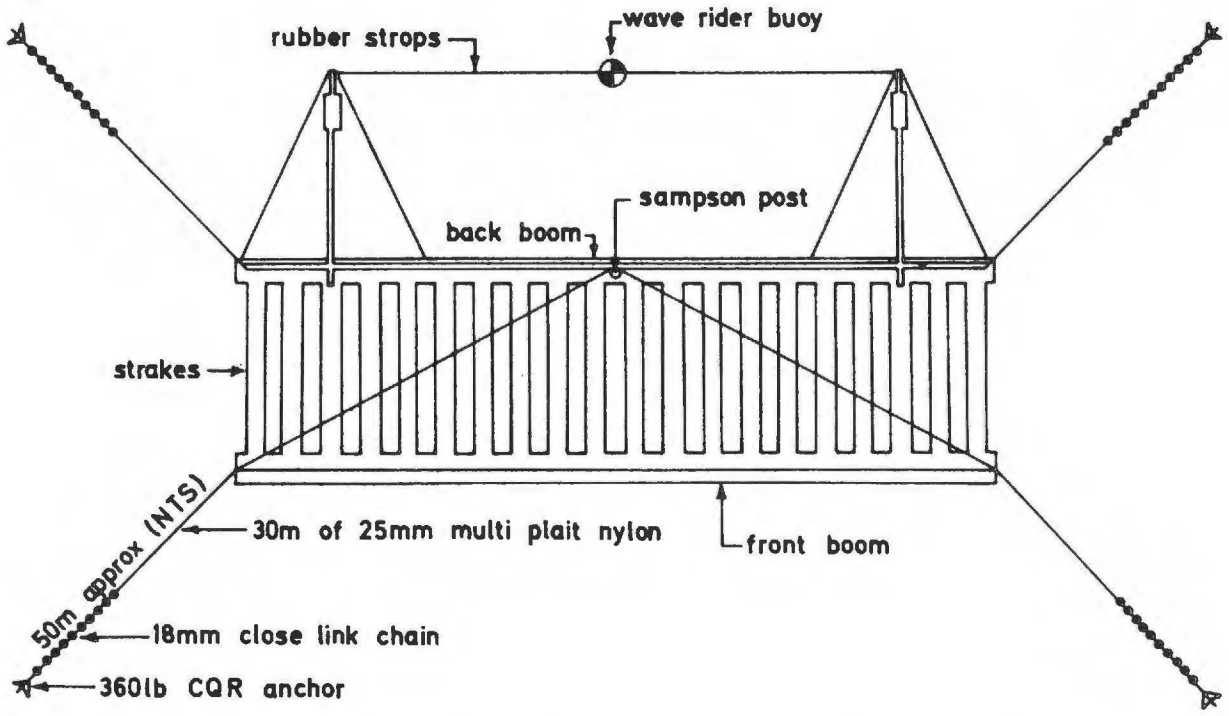


Fig. 22. Diagram of a Harris floating breakwater shown with the mooring arrangement and wave rider buoys (Harris and Thomas 1974).

(1953) and Ross (1957).

9.2.3. Catamaran Breakwaters

The catamaran breakwater is more stable than the single prism type and is used for limited protection of small boat harbors. This design allows for the addition of a wooden deck, and can then serve as a dock as well as a breakwater. Two designs were developed and tested in Alaskan harbors. One at Tenakee Springs consisted of reinforced precast concrete 3 X 5 X 15 ft pontoons, filled with Styrofoam, and joined together by galvanized steel bars to form 21- by 60-ft modules. The modules, described by Miller (1974), were coupled with chain links and rubber bumpers to form a breakwater 308 ft long, anchored with 26-ton concrete blocks (Fig. 24). A breakwater used at Sitka was a modification of this design. Both breakwaters performed well when subjected to wakes from large vessels. Disturbances due to choppy water were eliminated and larger waves were attenuated to some degree. In addition to providing protection for small boat harbors, such breakwaters could be used to

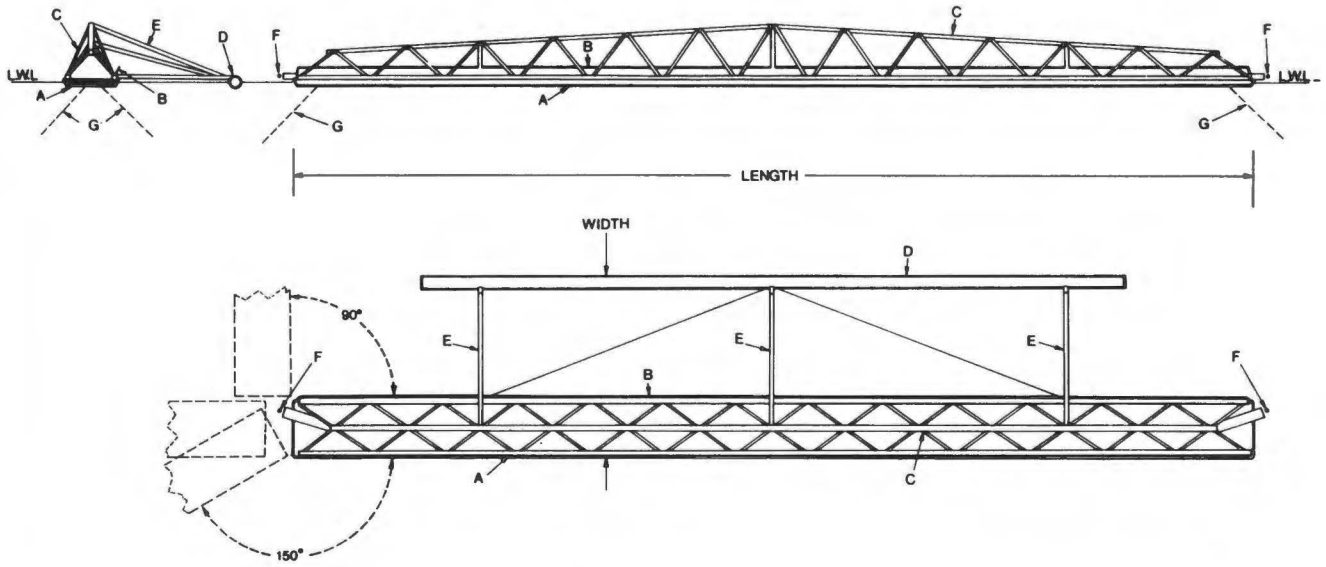


Fig. 23. Diagram of a "Seabreaker" floating breakwater (Hasler 1974).

protect salmon rearing pens on the Pacific Coast. Another catamaran structure installed in Friday Harbor, Washington, consisted of polyolefin flotation units linked together by large wooden timbers to form an L-shaped breakwater 25 ft wide and 904 ft long (Christensen and Richey 1976). That system was destroyed by failure of the plastic flotation units (Adee 1976).

9.2.4. A-Frame Breakwaters

A prototype of an A-frame breakwater made of steel and wood, installed at Lund, British Columbia, had been in place for 12 years by 1976. It performed well, but problems developed at the module connections (Adee 1976). Chen and Wiegel (1969) described an A-frame unit designed to incorporate all of the major mechanisms that reduce the transmission of wave energy. Its vertical wall serves as a reflecting surface. The sloping board causes run-up, possible wave breaking, and spilling into the inner chamber, from which water can flow through the bottom to further interfere with wave motion. The model consisted of two pontoons separated by a perforated bottom (Fig. 25). In

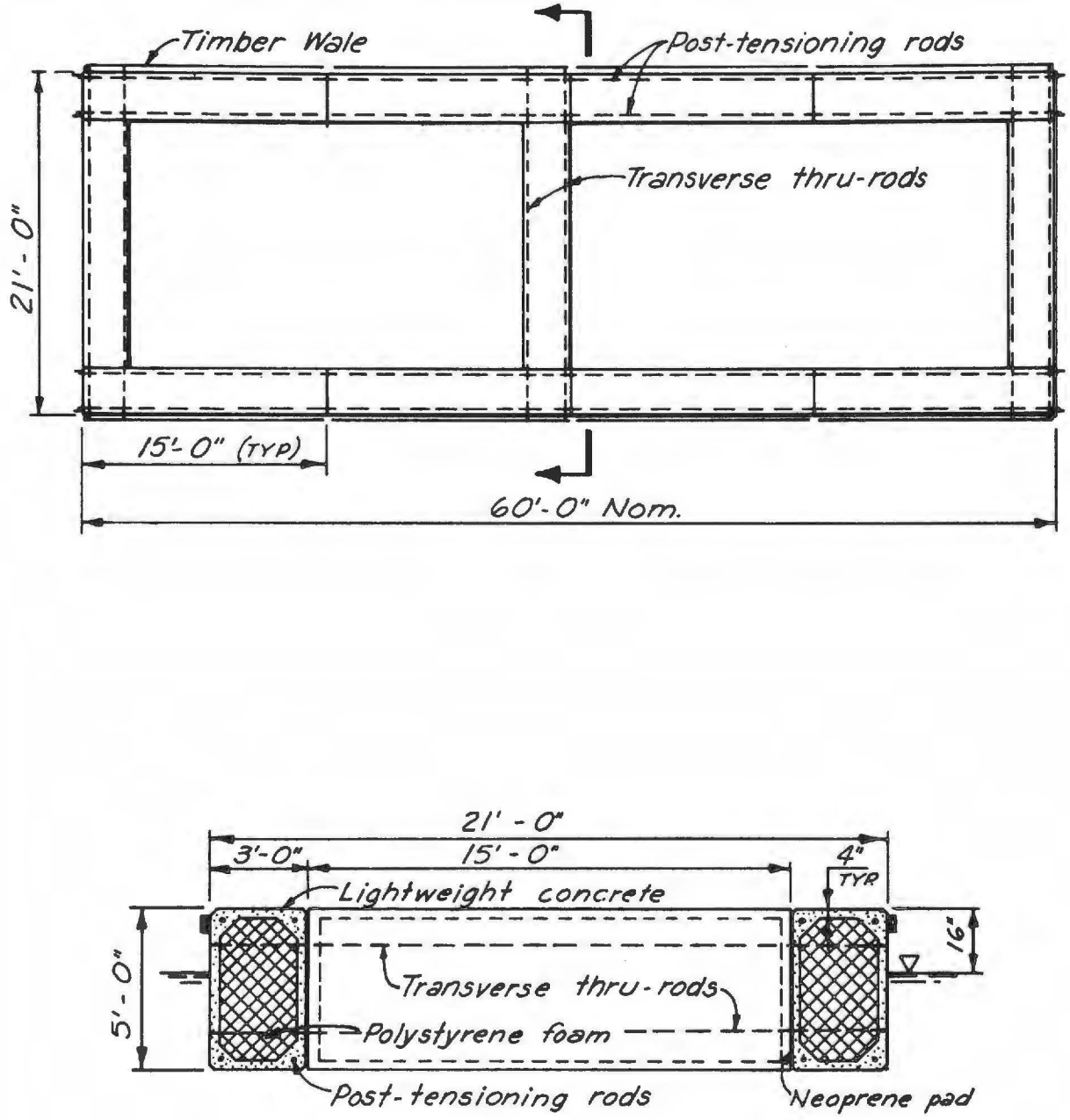


Fig. 24. Typical catamaran breakwater design with the basic plan (upper panel) and cross section (lower panel) (Miller 1974).

tests made by Chen and Wiegel (1969), the A-frame was more effective than other structures for controlling long waves.

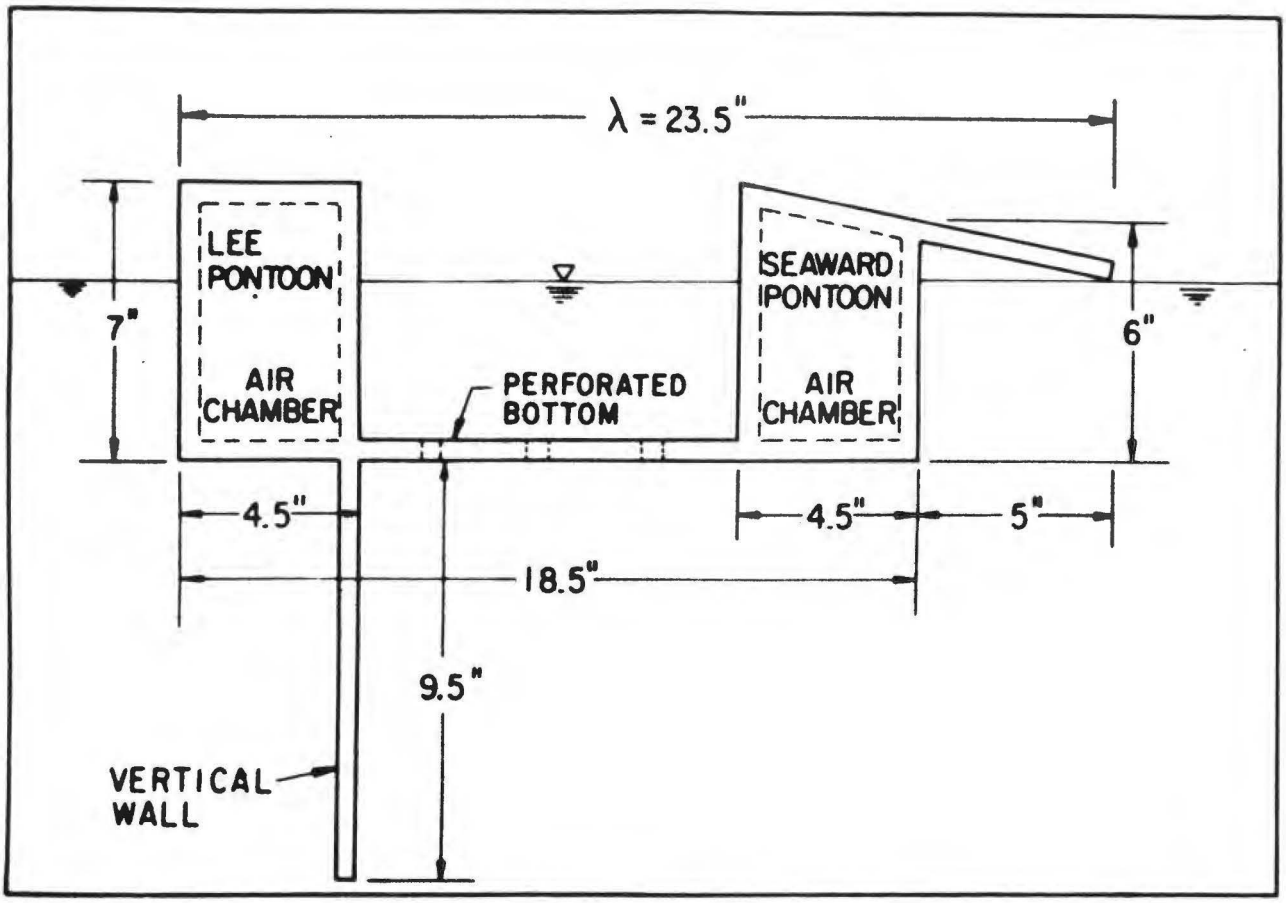


Fig. 25. Prototype of an A-frame breakwater structure (Chen and Wiegel 1969).

9.2.5. Flexible Breakwaters

Many different types of flexible breakwaters have been tested. Designers have used a variety of materials in the construction--plastic bags and sheets, rubber balls, plastic containers, and tires. Plastic sheet breakwaters, which are not considered here, were discussed by Ripken (1960b) and Watts (1960).

9.2.5.1. Hovering breakwaters

A hovering breakwater can be built of plastic bags filled with water. It can be transported in a collapsed form, lashed and moored, and then pumped full of water (Wiegel et al. 1962). Such a breakwater is effective if it is relatively long, compared with the incident wavelength. When this system was tested in San Francisco Bay and in the laboratory, it attenuated whitecaps in the Bay, but not swell-type waves generated in the laboratory (Wiegel et al. 1962). Breakwaters of this type can handle moderate mooring stresses (Ripken

1960a). The designer, who checked cylindrical, spherical, and flat bags, found that parallel, water-filled cylindrical bags, situated perpendicular to the wave crest and just below the surface of the water, are capable of attenuating waves to almost any degree desired. Further study may show that spherical bags attenuate waves even more effectively. Flat bags did not perform well. The author listed various conditions to be considered in placement of bag breakwaters. The design of a blanket depends on wavelength, wave height, direction of waves, and degree of protection desired. Fredericksen (1971) recommended the following criteria for placement of water-filled blankets used to attenuate waves in small bodies of water:

1. Bag length parallel to wave travel, 40 ft.

2. Individual bag widths, at least 30 ft.

3. Bag section rectangular, 36 in. thick.

4. Mooring load for seaward anchor (assuming wavelength of 50 ft with 4-ft wave height and a depth equal to 10 ft), 200 lb per front foot of the device.

5. Mooring load for shoreward anchor, 10 lb per front foot of the device.

Plastic bags can also be filled with other liquids, or with gases such as air. Submerged bags filled with air provide good attenuation of waves (90% attenuation of wave height), but a very substantial structural mooring system is required (Ripken 1960a).

Chen and Weigel (1971) found that breakwaters with large masses dissipate waves more effectively than do breakwaters made of floating bags. Griffin (1972) did not recommend further development of flexible bags, because the length needed to attenuate a wave is several times the wave length. As a result, the structures may become so large that they are not feasible.

The U.S. Army Engineer Waterways Experimental Station, Vicksburg, Mississippi, tested hollow rubber balls, 5 in. in diameter, for use as a floating breakwater. Balls of the top floating layer were attached together by metal bands and small hooks, and the top layer was attached to the lower layer with nylon cord. Holes were punched into the balls in the lower layer so that they would fill with water and remain submerged. In tank tests the response of spheres to wave action was similar to that of tires, except that the spheres flexed more with the waves, thus imparting a more jerky motion. To be effective, the length of sphere breakwaters must equal half or more of the wavelength and the wave steepness (H/L) must equal or exceed about 0.04. The authors believed that effectiveness would be improved if the porosity and flexibility of the balls were decreased, but such changes would cause an increase in mooring stresses and encourage drift (Kamel and Davidson 1968).

9.2.5.2. Floating tire breakwaters

The floating tire breakwater (FTB) is a flexible unit constructed almost entirely of scrap automobile tires and intended for areas where the fetch is short (<6.2 to 9.3 miles) or areas that are partly protected. The FTB is essentially a mat of tires floating near the surface and anchored to the bottom to provide a sheltered area of reduced wave activity. Mat designs rely on a modular construction concept in which relatively few tires are secured together to form a small, easily assembled, portable unit that serves as a building block for breakwater construction (Fig. 26 and 27). Binding materials include industrial conveyor belt edging, nylon bolts, stainless steel wire, open-link chains, and other items (De Young 1978; Shaw and Ross 1977). Davis (1977), who tested several binding materials in salt water, found that rubber conveyer belt edging with nylon fasteners withstood fatigue, abrasion, corrosion, ultraviolet degradation, and attack from aquatic organisms. Devices used to secure floating tire breakwaters include deadweights, embedments, screws, and pile anchors. Selection of the type of anchor depends on the maximum mooring stress, bottom conditions, and the available methods for placing the anchor (Giles and Eckert 1979). Added flotation is suggested, although air trapped in the crowns of vertical tires may provide adequate breakwater buoyancy (Ross 1977).

Unlike other breakwaters that function primarily as wave deflectors, a typical FTB is principally a dissipator of wave energy. Most of the incident wave energy is transformed into turbulence within and around the many components of the structure. Reflected wave energy is only 7 to 20% as large as the dissipated energy, depending on the relative wavelength (Harms 1979b).

The FTB acts as a wave-energy filter that discriminates not only according to relative wave length (length/berm = L/B), but also according to wave steepness or height/length (H/L). The effectiveness of the structure increases with the quotient of H/L and decreases with decreases in the quotient of L/B, if other variables are constant (Harms and Bender 1978; Gifford et al. 1977; Kamel and Davidson 1968). Hence, wave attenuation may be improved by either increasing the beam of the breakwater or restricting FTB installations to sites with relatively steep waves or waves with short wavelengths. The results of laboratory investigations by Kamel and Davidson (1968) and Harms (1979b) suggested that when wave steepness (H/L) equals or exceeds 0.04, a breakwater width between one-half and one full wavelength is required. As a rule, Ross (1977) advised that the beam must be greater than half the height of the significant wavelength and the draft must be greater than half the height of the significant wave.

The porosity of an FTB (defined as the ratio of the volume of breakwater to the volume of tires) is an important variable that influences the transmission coefficient C_T, and is determined by breakwater design (Harms

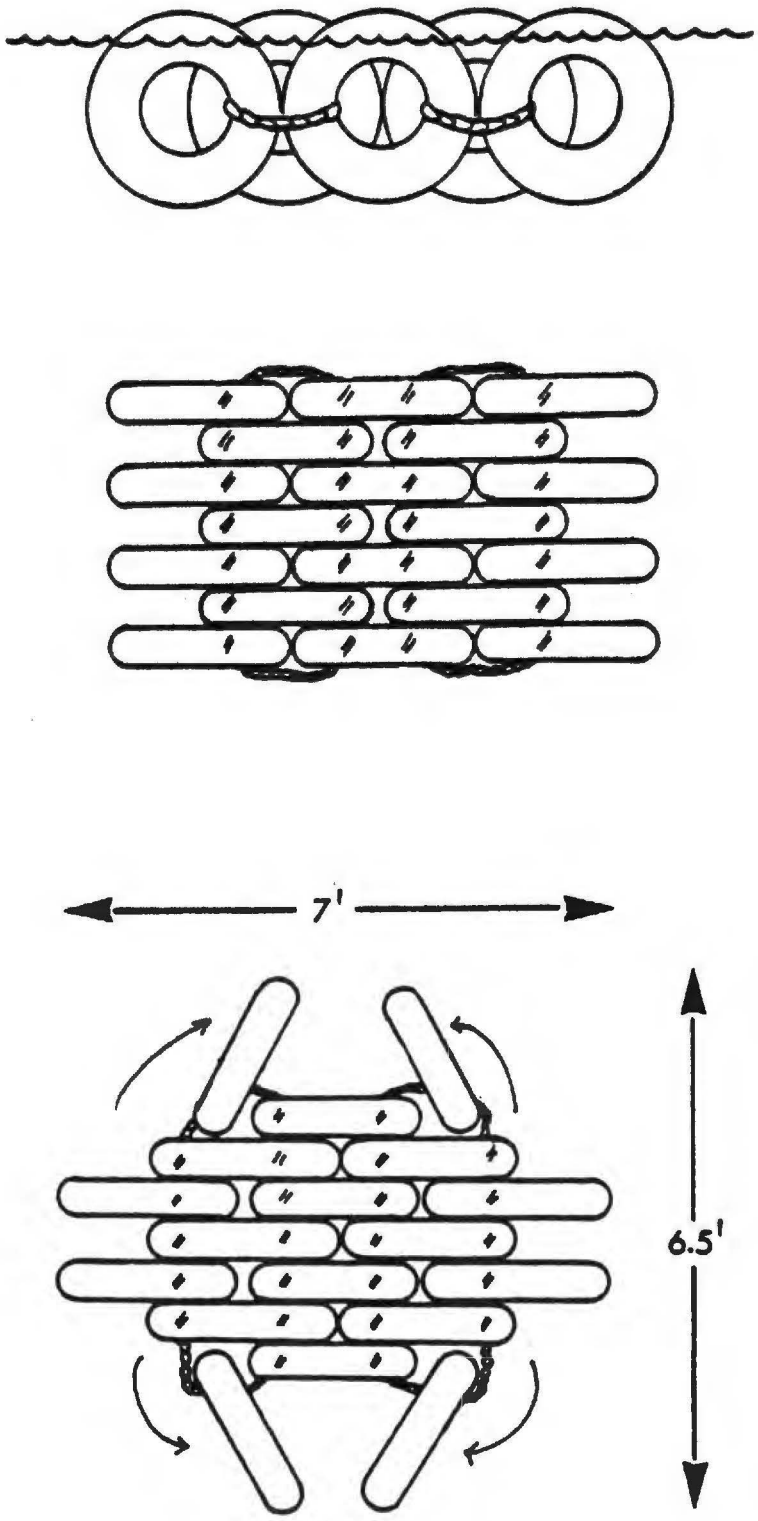


Fig. 26. Floating tire breakwater with side view of bun... ...in the water (upper panel), top view of same bundle as it is construct... land (center panel), and top view of the same bundle ready for attachment to other bundles (lower panel) (Kowalski and Ross 1975).

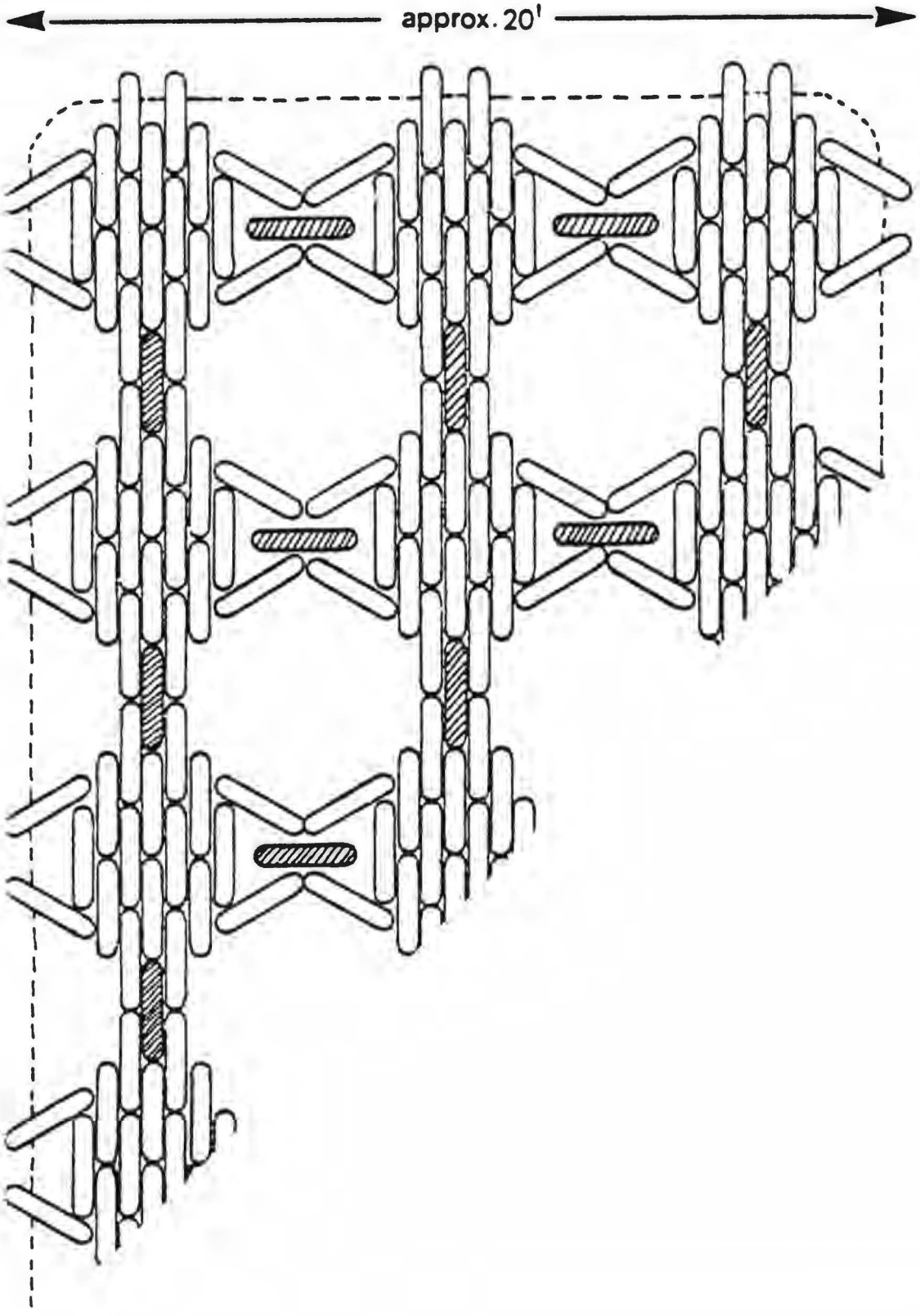


Fig. 27. Shore protection mat of used tires and connecting bridle (Kowalski and Ross 1975).

1979b). Three configurations of FTB's were described by Harms (1979a): the Wave-Maze (Kamel and Davidson 1968), the Goodyear (De Young 1978; Candle and Fischer 1977; Ross 1977; Harms and Bender 1978), and the Wave-Guard (Harms an Bender 1978). They differ principally in tire arrangement, spatial tire-density, and in binding materials used. For equal levels of wave attenuation, the various designs involve different beam sizes and peak mooring stress (force needed to anchor the float). Tests performed at the Hydraulics Laboratory of the Canada Centre for Inland Waters have shown that the Wave-Maze and Goodyear have similar wave-attenuation performances and differ principally only in cost, the Goodyear being more costly (Harms 1979b). The Wave-Guard requires a much higher peak mooring force, but provides more wave protection than a Goodyear of equal beam. However, for equal levels of wave attenuation, the difference in peak mooring force is generally not of practical significance. A more detailed comparison of FTB designs and construction was given by Harms (1979a).

The adequacy of FTB's for suppressing wave energy and height has been well documented, although their efficiency depends on the breakwater design. A Goodyear FTB 26 ft wide reduced 3- to 4-ft waves by 75% and half-foot waves by 100%. It almost entirely suppressed the wake from passing motor boats (Ross 1977). Gifford et al. (1977) investigated the use of a modified 22-ft wide Goodyear FTB for coastal erosion control in Florida. Waves 2 to 3 ft high, 10 to 20 ft long, and with periods of 1 to 2 s were "effectively attenuated." Kowalski (1974) found that a 25-ft wide Goodyear FTB in 15 ft of water reduced wave heights of 2 to 3 ft (wave periods = 2 s, H/L = 0.06) by 54 to 68% and wave energy by 79 to 89%. The Wave-Maze FTB performed similarly under about the same wave conditions (Kamel and Davidson 1968). Harms (1979a) found that a Wave-Guard FTB, of the same beam size and under the same conditions, may reduce height as much as 20% more effectively than a Goodyear FTB.

The floating tire breakwater is a recently developed innovation, designed to meet an increasing demand for low-cost wave protection structures. Although floating breakwaters date back to 1842 (Reid's Floating Breakwater, described by Harms 1979b), floating breakwaters constructed of scrap tires have been used for only the last 10 to 15 years. Increased demand for mooring space and the concurrent depletion of suitable natural harbor sites has created a need for artificial, low-cost protection of marinas and harbors (Richey and Nece 1974). Floating tire breakwaters have had little use for protection of inland waterways from wave-induced bank erosion. The Huntington District of the U.S. Army Corps of Engineers (U.S. Department of the Army, Chief of Engineers 1978) used FTB's on the Ohio and Kanawka rivers as part of a Section 32 Project of the Streambank Erosion Control Evaluation and Demonstration Act of 1974. A single line of FTB's anchored on pipe supports, was used with stone riprapping and tire mats to counteract bank instability on the Ohio River.

Gifford et al. (1977) investigated the use of a modified Goodyear FTB for erosion control in Florida. Waves 2 to 3 ft high were effectively attenuated, and shoreline accretion developed in the lee of the breakwater. Harms and Bender (1978) established a design procedure for determining site-specific FTB characteristics, using sample problems that included one proposal for the protection of a river marina that periodically suffers wave damage from the passage of large vessels. In addition, Candle and Fischer (1977) identified a number of FTB operations and projects, including two proposed field investigations to evaluate the use of tire stabilization mats to protect island marshland areas (Virginia Institute of Marine Science) and the use of tire mats to stabilize river banks (Skidaway Institute of Oceanography, Savannah, Georgia). This use concept is discussed in further detail in Chapter 5.

Floating tire breakwaters have also been used to mitigate other problems, such as protection of wave-swept spawning areas for largemouth bass (Clady et al. 1979), creation of artificial reefs (Alfieri 1975; Prince and Maughan 1978; Stone 1978), protection or creation of beaches, and protection of marine fish culture installations (Anonymous 1980).

Gifford et al. (1977) listed the following advantages of FTB's:

1. Effectively dissipate waves less than 3 ft high with short wavelengths.

2. Construction costs are low.

3. Can be easily built and repaired.

4. Can be moved from one site to another or easily disassembled if they are found to adversely affect the shore of adjacent property owners.

5. Cause relatively little damage if struck by a boat.

6. Create a floating biological reef.

7. Can be used for boat shelters (i.e., marinas).

8. Design and orientation can easily be modified if waves are not being damped sufficiently.

Gifford et al. (1979) also listed several disadvantages of FTB's:

1. Hazardous to navigation--navigation markers will be needed in some areas.

2. Debris that is collected must be cleaned out occasionally.

3. Long-period or shallow-steepness waves are not effectively damped.

4. Adverse shoreline effects (i.e., "downdrift" erosion) can result if longshore sand transport is a predominant sand motion in the area.

5. Aesthetic appeal is lacking.

9.2.6. Tethered float breakwaters

Tethered float breakwaters can be used to protect harbors, marinas, beaches, offshore activity areas, and offshore terminals because they can be installed at depths ranging from fairly shallow to very deep (Seymour and Isaacs 1974). A tethered float breakwater, as described by Hanes and Seymour (1976), consists of a large number of buoyant spherical floats situated just below the water surface and independently attached to a suspended ballast system, which in turn is moored to an anchor. The floats are usually made of seamless molded plastic, the tethers of synthetic material, and the ballast of reinforced concrete (Seymour 1976). (A cross-sectional view of a tethered floating breakwater as shown in Fig. 28.)

Seymour and Isaacs (1974) recommended tethered float breakwaters for beach erosion protection because they reduce the height of storm waves and thus reduce the transport of sand away from the beach. Moffatt and Nicol Engineers (1977) studied the economic feasibility of using them to protect activities such as ship discharge, offshore construction, dredging, pipe laying, or marina operation. The engineers found that the anchored system is not feasible for use at sites where the water is deep or the fetch is long. However, in sites where the protection needed is temporary and periodic movement is involved, a self-positioning tethered float breakwater may be useful.

Tethered float breakwaters have several advantages over other floating breakwaters:

1. Wave attenuation characteristics are broadband.

2. The performance is predictable.

3. The level of protection can be adjusted to meet the needs at a specific site.

4. Performance is independent of the mooring system and bottom characteristics.

5. Readily transportable.

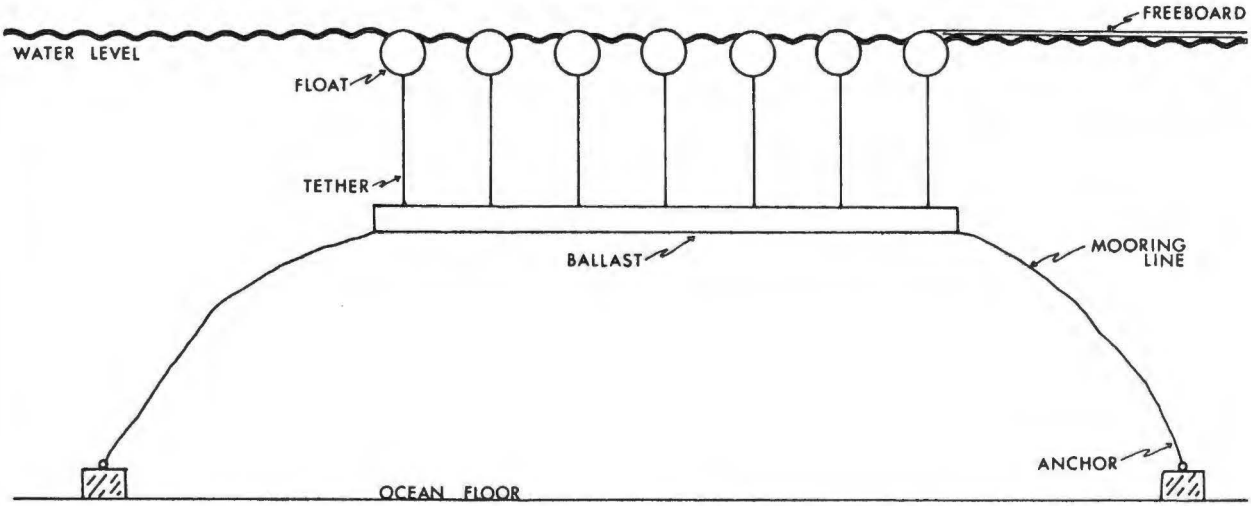


Fig. 28. Cross-sectional view of a tethered float breakwater (Mulvihill et al. 1980).

6. Durability is high and installation cost is low.

Design considerations for tethered float breakwaters were discussed by Hanes and Seymour (1976) and Seymour (1976).

9.2.7. Miscellaneous Floating Breakwaters

Several other types of devices that can function as floating breakwaters, do not fit into any of the other classifications. Magill (1953) published a general discussion of different geometric designs.

Sethness et al. (1974) developed a prototype design for a breakwater called an "Offset" breakwater. The model consisted of 20-gage aluminum sheeting and Styrofoam connected in a series of L-shaped pieces. The model was 6 in. high; in the water, 1.5 in. remained exposed. The assembled unit

was 70 in. long. Steel weights were used as anchors and were attached to the structure by wire, so the unit could pivot easily (Fig. 29). Placement of the anchor varied in each of two tests. One was tested with a free-floating anchoring structure and the other was tested with an anchoring structure attached to the bottom. The offset design allows less net force impact than a continuous wall. The design was found to be effective in attenuating the heights of both regular and wind waves.

Frey (1974), who studied the uses of airfoils or hydrofoils as breakwaters, determined that units combining discontinuous and continuous surfaces made of corrugated fiberglass were more effective than units composed of only discontinuous or only continuous surfaces (Fig. 30). A unit of continuous surface placed close to a beach would be useful in controlling oil spills or sand transport along a shoreline.

Pneumatic or hydraulic breakwaters are not true floating breakwaters, though they are competitors in a functional sense. Both devices consist of a submerged conduit, usually a circular pipe that contains a number of orifices or nozzles. Air is used in a pneumatic breakwater and water under pressure is used in a hydraulic breakwater. A curtain of air bubbles or water jets rises to the surface and spreads out more or less horizontally.

The pneumatic breakwater was developed in 1907 by Philip Brasher to attenuate waves. Bulson (1969) reviewed its use and design. The high cost of the apparatus is definitely a disadvantage. Green (1961) reported that pneumatic breakwaters were not able to protect dredges from long ocean swells off the New Jersey shore. Nece et al. (1969) found that hydraulic breakwaters were better adapted to controlling waves over deep water than over shallow water, but that they were generally not feasible for most practical applications because the power requirements were excessive. On the basis of results achieved with pneumatic breakwaters, Carr (1950) experimented with a hydraulic breakwater. His results were similar, but he recommended that neither type be considered further because of their requirements for critical velocity, excessive power, and anchoring devices, and their hazardousness to navigation. Colonell et al. (1974), after testing both pneumatic and hydraulic breakwaters, reported that the pneumatic breakwater was slightly more effective than the hydraulic breakwater in attenuating deep-water waves, and required less power.

Pneumatic breakwaters were discussed by Kobus (1969), Kurihara (1965), Bulson (1965, 1967), and Dock and Harbour Authority (1966), and hydraulic breakwaters by Dilley (1959) and Herbich et al. (1956).

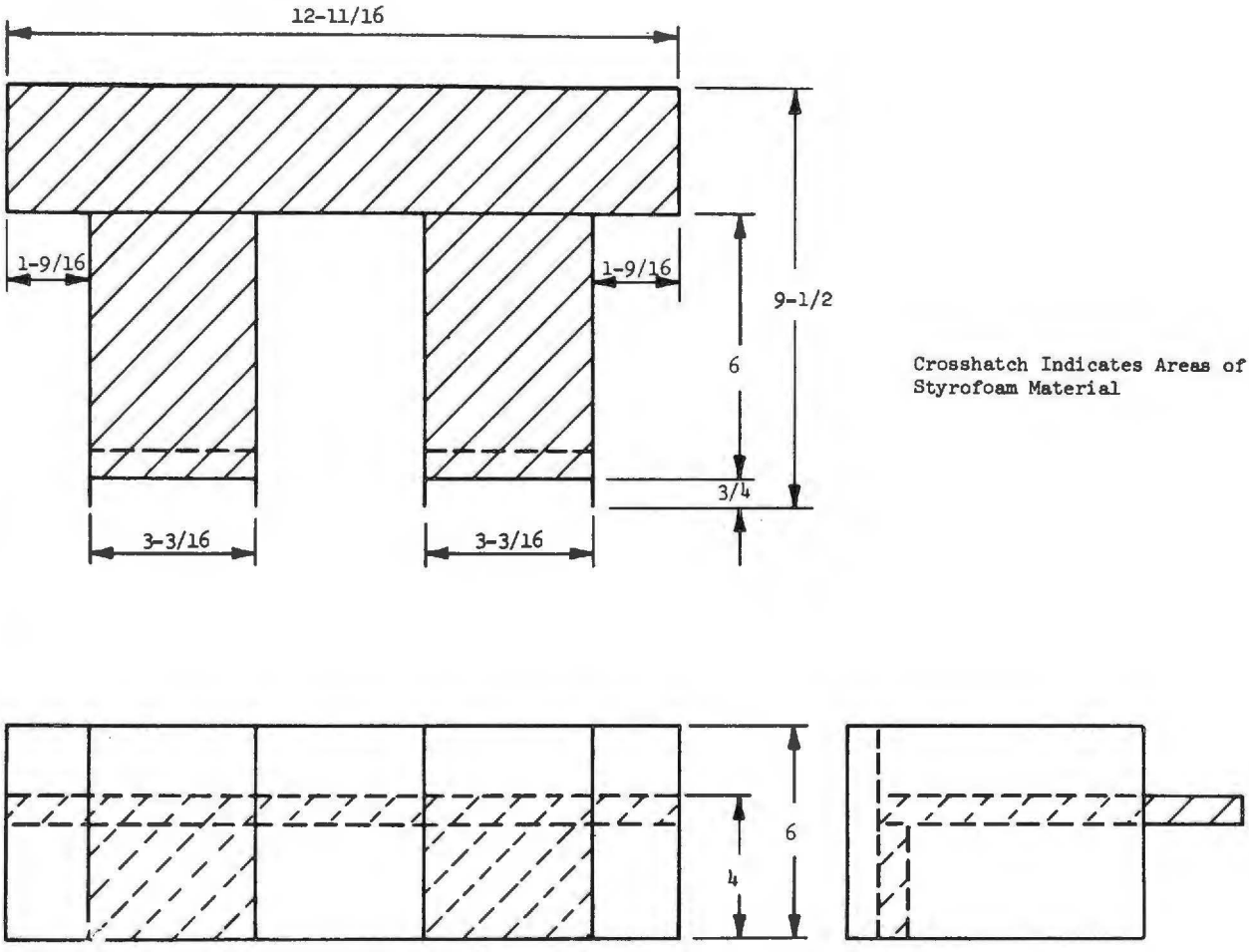


Fig. 29. Drawings of an offset breakwater structure showing top view (upper panel), front view (lower left), and side view (lower right). All dimensions are in inches (Sethness et al. 1974).

9.3. IMPACTS ON THE ENVIRONMENT

Floating breakwaters have less effect on the environment than fixed breakwaters because they do not obstruct water currents, littoral drift, or

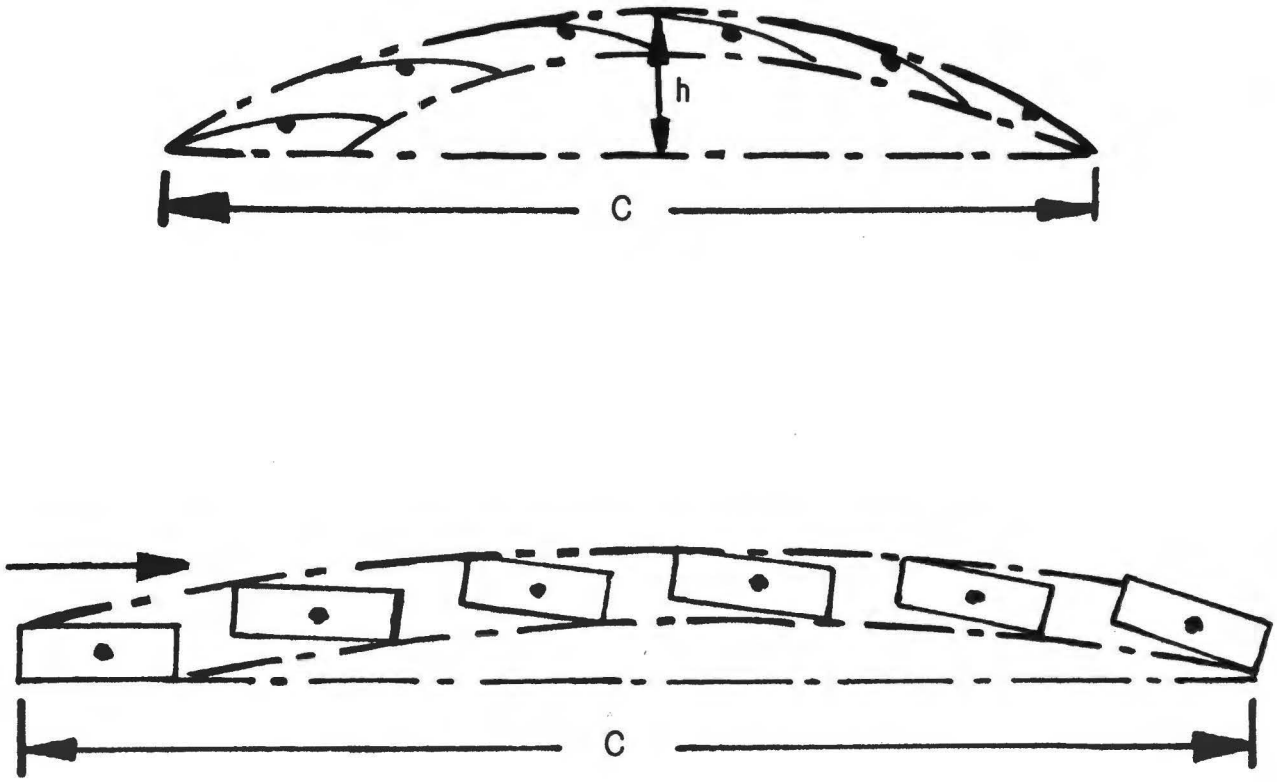


Fig. 30. Cross sections of airfoil or hydrofoil breakwater units. The h/c (height-to-chord or thickness) is 0.2 in the upper panel and 0.1 in the lower panel (Frey 1974).

fish movement or migration. Sediment may be deposited near such structures, depending on their functional design, and may have a positive or negative effect. A floating breakwater interferes with navigation if it is placed too near the main channel or in areas where pleasure boats normally travel. Some kinds of floating breakwaters can serve as artificial reefs for fish habitat. More habitat is provided for invertebrates and periphyton by rough surfaces than by flat surfaces (Mulvihill et al. 1980).

Beneficial and adverse impacts of floating tire breakwaters and tethered floating breakwaters merit further discussion here.

In general, floating tire breakwaters do not adversely affect the environment. In fact, they may be used to enhance water quality, reduce wave-induced bank erosion, enhance recreational potential of impoundments by protection or creation of harbors and marinas, and improve fishery habitat.

An important concept to note is that a properly designed FTB affects only wave energy because of its shallow draft (generally 2.5 ft), and does not significantly affect subsurface currents and turbulence. This means that, although FTB's do not obstruct littoral drift, water circulation, or river flow, they also do not inhibit bank erosion and scouring caused by underwater currents. The reduced wave action to the lee of the breakwater may reduce erosion but may also cause accretion of sediment.

Floating tire breakwaters may improve water quality or spawning conditions for certain fish species. In an Oklahoma reservoir, Summerfelt (1977) found a significant correlation between the population density of young-of-the-year largemouth bass and reduced wave height. He speculated that shoreline exposure to wind waves increased turbidity and turbulence, and resulted in poor spawning success. Clady et al. (1979, 1980) installed FTB's across the mouths of several coves to attempt to improve the spawning success of largemouth bass. The breakwaters reduced wave heights by 50% and may have slightly improved the physicochemical characteristics of the coves. FTB's did not adversely affect the environment and led to an increase in centrarchids.

Gifford et al. (1977) also observed biological changes on the leeward side of a marine FTB, including apparent bottom stabilization (the bottom color became darker, suggesting deposition of detritus); a "marked" increase in the density of burrowing worms and mollusks; incrustation of tires by oysters, barnacles, bryozoans within 2 weeks after installation; and the transitory appearance of rooted submerged grasses. The authors suggested the possible use of FTB's for protection or re-establishment of submerged grass flats, as well as for stabilization of the shoreline.

Other advantages may include the provision of increased boat mooring space, (if they are used for harbor or marina protection), and of artificial spawning substrate; they fluctuate with the water levels, are transportable, are made of nontoxic materials, and may be constructed on land. The modular units may then be floated into place, or the entire breakwater may be installed on ice and floated free in the spring (De Young 1978).

Disadvantages of FTB's, discussed previously, include their tendency to accumulate debris, the need for frequent maintenance, their vulnerability to vandalism, the requirement that they be removed in winter to avoid ice damage; and their hazard to navigation--particularly if anchoring is inadequate.

Tethered floating breakwaters differ from other floating breakwaters in that they do not reflect waves. The method of wave modification causes this breakwater to be effective in dissipating wave energy. It functions with equal efficiency against waves approaching from any direction (Seymour and Isaacs 1974).

Environmental impacts of tethered floating breakwaters are minor because their porousness allows normal hydrologic functions, such as flushing to occur, and allows nearly normal movement of plankton and nekton. Since only part of the wave energy is removed, sand remains in transport and is not deposited. As a result, silting does not occur in the area that the breakwater is protecting. Visual impacts of these breakwaters are minimal because they are nearly invisible from the shore (Seymour and Isaacs 1974). Heavy fouling that develops on the breakwaters in deep water increases the mass and decreases their response to wave driving forces (Seymour 1976).

9.4. COSTS

Little has been done to evaluate the economic feasibility of most breakwater designs (Griffin 1972). The limited information available is reviewed here.

The cost per foot at 1972 prices was $425 for the Alaska type of catamaran breakwater and $320 for the Friday Harbor, Washington, type. An A-frame breakwater cost an estimated $230 per foot at 1965 prices (Adee 1976).

The cost of a floating tire breakwater is low compared with that of more permanent breakwater structures; it is generally less than $50 per linear foot, compared with perhaps $200 to $500 per linear foot for conventional breakwaters (Ross 1977). De Young (1978) believed, however, that cost comparisons should be expressed in units of cost per square foot to allow for structures having variable widths, such as FTB's. In any event, the cost of an FTB is certainly very low, and generally within the target guidelines established by the Shoreline Erosion Advisory Panel ($50 per square foot) for low-cost erosion-control structures designed for inland and sheltered waters (Caldwell 1977).

The cost-effectiveness of a FTB depends on several factors. Although this type of structure has a relatively short life-span (5 to 15 years) and may require frequent maintenance, this factor may be offset by the reusability of the materials, for a bank stabilization mat, or an artificial reef for fishery enhancement, or for construction of a new breakwater. In addition, installation of an FTB does not require heavy machinery or much skilled labor.

The cost of an FTB is largely determined by the costs of binding material, labor, and the mooring system. Shaw and Ross (1977) reported that

the binding material can represent as much as one-third of the total cost of the breakwater. The binding material is particularly important because it affects the flexibility of the structure, its wave-attenuating efficiency, and its life-span. The main structural component, scrap tires, can often be obtained free or at little cost. Additional flotation, if needed, will add to the initial cost of an FTB, but may extend its life and increase its effectiveness (Giles and Sorensen 1978).

Candle and Fischer (1977) reported that a 26-ft wide Goodyear FTB may cost $15 to $40 per linear foot, and Shaw and Ross (1977) indicated that a Goodyear FTB with an expected life-span of 10 years could be built for less that $50 per linear foot. Dent (1980) reported that a marina in Lake St. Clair, Michigan, was protected for $5 per foot by an FTB; however, the owners did most of the work themselves. The largest FTB in the Great Lakes area was built on Lake Charlevoix at a cost of more than $100,000.

Harms (1979a) evaluated the costs of three different types of FTB's designed to provide the same level of wave attenuation. His assessment indicated that (1) a Wave-Guard FTB somewhat less costly and significantly smaller than a Goodyear FTB provides the same degree of wave protection; and (2) a Wave-Maze FTB is far more costly than either the Goodyear or Wave-Guard, but has a longer useful life and better capability to survive extreme storm events. A small royalty is charged for use of the Wave-Maze concept.

Seymour (1976) estimated that the cost for a tethered floating breakwater consisting of a single 5-ft diameter float with its proportionate ballast and mooring system, was $880. With 25 rows of floats per 10 ft of front, the cost per foot was about $2200. The estimated cost for a tethered floating breakwater used in San Diego Bay was $175 per foot in 1976 (Adee 1976).

Chen and Wiegel (1971) estimated that pneumatic breakwaters are too expensive for use in reservoir marinas because it would take about 25 horsepower per foot of wave height to suppress a 5-ft wave. Although 100% attenuation can be obtained with pneumatic and hydraulic breakwaters, the flow rate and power requirements are so high that they can be used only for short waves in rather shallow water (Jones 1971). Richey and Sollitt (1970) considered using hydraulic jets or a bubble curtain to absorb wave action on Lake Washington near Seattle, Washington, but rejected both because of the high power requirements and large physical dimensions of the systems.

9.5. EVALUATION FOR USE ON UMRS

Floating breakwaters are not necessarily viable alternatives to more conventional bank stabilization structures. Floating breakwaters might be

used in conjunction with riprap, gabions, revetments, or other structures in areas exposed to intensive wave action. Floating breakwaters could also be used by themselves to protect shorelines in certain unique situations along the river. In general, floating breakwaters are likely to be used only in major pools with relatively long fetches, small-boat traffic, or housing developments. Potential uses include protection of marinas and harbors, creation of artificial reefs, protection of beach areas, protection or creation of nursery coves, use in conjunction with mid-water spawning platforms, protection of barge fleeting areas, and protection below locks and dams.

The use of floating breakwaters to protect the shoreline from waves generated by towboats is questionable. Floating tire breakwaters are designed to attenuate wave height and energy, which is concentrated at the still-water level. Since the height of boat-generated waves is directly related to boat velocity (Karaki and Van Hoften 1974), slow-moving towboats and barges may not generate waves as large as smaller recreational vessels (Sparks 1975a). Because much of the energy generated by towboats seems to be dissipated underwater, floating breakwaters generally do not prevent the scouring and increased turbidity caused by barge traffic. Floating breakwaters, however, are being considered for use on UMRS. Lubinski and Reese (1980) prepared a proposal to investigate the use of an FTB for reducing the impact of waves and subsurface currents generated by commercial traffic on emergent aquatic macrophytes in Pool 26 of UMR.

CHAPTER 10. INTRODUCTION TO MEASURES FOR REDUCING SOIL INSTABILITY OR HYDROSTATIC PRESSURES

All of the methods mentioned thus far for stabilization of the banks of large rivers are mainly substantial, permanent structures (i.e., revetments, river training structures, and breakwaters). The measures discussed in this chapter and Chapters 11-16 are generally not considered structures, but are materials or measures used to reduce the effects of wave and current action on river bank material or on permanent bank stabilization structures that contribute to bank stability.

A natural method of bank stabilization is the planting of vegetation. Vegetation also reduces soil instability. Vegetation can be used alone to stabilize and protect the material constituting shorelines and banks, or it can be used with other bank stabilization structures to give additional protection, improve the aesthetic appearance, or create fish or wildlife habitat. Vegetation is considered in Chapter 11.

Newer man-made measures are also available. The Streambank Erosion Evaluation and Demonstration Act of 1974 advocated the development of newer, more effective, and economic bank protection measures (Caldwell 1977; Pickett and Brown 1977; Koppelman and Housley 1977). Keown et al. (1977) mentioned seven promising new structures, materials, or procedures for upper bank protection:

1. Membrane encapsulated soil systems (continuous bank paving and revetment of soil-filled bags).

2. Chemical stabilization (portland cement, lime, or asphalt) to form monolithic stabilization, stabilized soil blocks, stabilized soil, trenches parallel to the stream, chemically grouted soil piles, and continuous armor coating.

3. Rigid or collapsible honeycomb material backfilled with soil.

4. Reinforced soil systems in which membranes or fabrics are used.

5. Use of local waste products (without treatment, with minor processing, chemically treated, or membrane encapsulated).

6. Use of military surplus products such as lightweight pierced landing mat and antisubmarine net.

7. Special configurations of used-tire mattresses positioned perpendicular to the stream.

The first six methods relate directly to soil stabilization; however the

used-tire mattresses are essentially structural and are therefore not considered in the present chapter. The first four methods in the list are considered in Chapters 12 to 15.

CHAPTER 11. VEGETATION

11.1. SITUATION TO BE MITIGATED OR ENHANCED

The establishment of vegetation is described here as a means of stabilizing and protecting shorelines from erosive forces. Vegetation may attenuate wave action, reduce current velocities, buffer the bank against the impact of floating ice and debris, protect against surface erosion caused by piping and minor variations in river stage, add structural support to the bank, and act as a sediment trap. However, the principal function of vegetation, according to Parsons (1963), is to keep fast-moving water and transported coarse materials away from the soil surface. A well established stand of selected grass can reduce the velocity at the boundary layer between the water and the soil by as much as 90% (Keown et al. 1977). Parsons (1963) mentioned three characteristics of vegetation that most affect this attribute: area density (i.e., number of stems per unit area); length of stem; and the physical nature of the vegetation "tops" (i.e., blade of a grass, stem of a forb, or bole of a tree).

The number and distribution of stems per unit of area influence the level of protection provided by a given vegetation type. Dadkhah and Gifford (1980) investigated the effects of two species of grass (representing discrete and continuous distributions of vegetation) on infiltration rates and sediment production on loam soil. Study plots with sod-forming grass (continuous) infiltrated slightly more water than did plots with bunchgrass (discrete). Their results suggested that adequate watershed protection may be obtained by maintaining 50% protective ground cover.

The length of a stem or blade, relative to the depth of water, is also important. Kao (1980) found that the trapping efficiency of sediment by vegetation is inversely proportional to the depth and velocity of the flow. Shen (1973) noted that the average boundary shear acting on the channel bed is much more sensitive to changes in the size of vegetation and to changes in the slope than to variations in flow discharge and sediment size. As trees grow larger, the rate of reduction in boundary shear stress increases significantly.

The physical characteristics of a blade of grass include, for example, the width and relative density of the blade. These variables influence flexibility or stiffness. Kao (1980) stated that the effect of vegetation stiffness manifests itself in the resultant bending of the stem in flowing water. This bending, in turn, reduces the effective resistance to flow and the storage capacity for bed load among the vegetation stems. Increasing vegetation stiffness decreases the rate of downstream movement of the bed load.

As opposed to grasses, flexibility and resiliency in low-growing woody plants is a desirable property. Parsons (1963) reported that woody plants, such as small willows, act as skid surfaces for ice and transported debris because they are pliable and recovery quickly from severe mauling. Grasses, on the other hand, tend to be covered by deposited sediments and die, especially if they are too flexible (have low resilience) and have a tendency to mat.

Kouwen and Li (1980) evaluated vegetation stiffness as a function of the elasticity, cross-sectional area, and relative density. Inasmuch as vegetative stiffness values can vary by an order of magnitude or more for different grass species of roughly equal length, these values can be used as a criterion for classifying vegetation for its bank protection value. Kouwen and Li (1980) suggested that this measure of stiffness can be used to choose one vegetation type or species over another for a channel lining when the choice is not limited by other factors such as climate or soil.

11.2. DESCRIPTION OF TECHNIQUES

Vegetation can be used alone or in conjunction with a structural bank stabilization measure (e.g., riprap, gabions) to enhance the bank protection, aesthetic appearance, or wildlife and fishery value of the structure. In this respect, the establishment of vegetation could be regarded as either a mitigation or enhancement technique, depending on its application.

In general, vegetation is both an economical and highly desirable method of stabilizing banks for recreation and fish and wildlife management. Its use, however, is often limited by difficulties associated with the establishment of vegetation on steep, barren slopes. When one is designing and planning the revegetation of disturbed soils, Bennett and Donahue (1975) stated that consideration must be given to climate, soil type, seed and plant selection, fertilizer, seedbed preparation, timely seeding, mulching, and possibly irrigating. Simons et al. (1979) noted that one of the major problems in using vegetation as a bank protection measure is that of controlling bank erosion while the new vegetation becomes established. Parsons (1963) further stated that if vegetation is to be used to protect a bank, it must be established on the bank face between floods. The use of vegetation is also limited by its tolerance of innundation and fast currents. It generally cannot be used for toe protection. Logan et al. (1979) experimented with dividing the streambank into zones, based on frequency and duration of flooding, and planted each zone with native plant species with appropriate flood tolerance. Their work emphasizes the importance of appropriate site preparation.

Site preparation may include a variety of methods or approaches, depending on the soil characteristics, slope, and vegetation involved and on

the intensity, duration, and type of erosive forces acting on the bank. The site must be prepared by grading the bank to an acceptable slope (about 2H:1V), depending on the properties of the bank material (Simons et al. 1979). Logan et al. (1979) recommended adding topsoil to encourage the establishment of native species. However, topsoil is sometimes stripped from the bank if an exotic species is to be introduced (e.g., a turf of Bermuda grass), because it provides a fertile bed that encourages weed growth, which in turn tends to choke out deep-rooted grass. The soil that is exposed is usually rolled and scarified before planting (Keown et al. 1977).

Once the slope is graded, some form of temporary bank protection may be needed to curtail bank erosion while the vegetation grows to an effective size (Simons et al. 1979). Most of these temporary erosion control treatments can be categorized into three major types: mulches, blanket products, and chemical stabilizers. The following descriptions of these treatments were excerpted from Buxton and Caruccio (1979):

> Mulches. Mulch treatments absorb the erosive energy of rainfall impact (the primary mechanism for soil detachment) and reduce sheetwash (the primary agent of transport). Mulches are also used effectively to increase infiltration, reduce runoff, replenish deficient soil moisture, and insulate the soil surface from extremes in temperature. Recent studies showed that the application of a mulch to a soil results in the generation of a more thermally moderate and moist environment at the soil surface. This, in turn, encourages faster germination of seedlings.
>
> Many materials have been used as mulches, including straw, hay, leaves, sawdust, wood shavings, manure, bagasse, paper scraps, cotton refuse, and hardwood bark chips. Much work is being done to develop and refine suitable hydromulches from wood, paper fibers, and hardwood bark. Hydromulches are applied in a slurry with lime, fertilizer, seed, water, and a tackifier (if used). A major advantage of hydromulches is their ease of application. Modern hydroseeders with capacities of 3000 gallons can apply mulches and treatments to more than 5 acres in about 30 min.
>
> Blanket Products. Blanket products are surface materials or netting supplied in rolls and applied in overlapping strips down the slope face and stapled to the ground with 6-in. pegs. Most blanket products consist of a type of netting with a mulch of paper, wood shavings, or some other suitable material incorporated in the webbing. Blanket products afford the soil surface with all of the favorable attributes of a mulch treatment and, in addition, are more stable and resistant to disturbance if properly installed. Blanket products are expensive, however, and the method of application (rolling and stapling the material) requires considerable manpower.
>
> Chemical Stabilizers. The composition of chemical stabilizers varies from asphalt emulsions to a polymer latex or organic resin

derived from plant gums or seaweed. Many of the products have an appearance and action similar to that of household glue. Chemical stabilizers are used as soil binders in lieu of mulch treatments and as tackifiers in conjunction with mulch materials. As a soil binder, these treatments coat and penetrate the soil surface to increase cohesion between soil particles. This surface bond not only reduces erosion by rain-splash and sheetwash, but also retards dust and wind erosion. When used as a tackifier, these chemicals are used to hold mulch material in place by establishing contact points between mulch particles and between the mulch and the soil. In both methods of application, chemical stabilizers reduce moisture loss from the surface soil layers.

Because chemical stabilizers and blanket products have other uses, they are described in further detail in Chapters 12 and 13.

If erosion of the bank is so severe that the soil treatments mentioned would not adequately reduce erosion to the point of allowing vegetation to become established, more substantial structures can be used. Simons et al. (1979) noted that willow mattresses, combinations of filter fabric and wire mesh, and undersized riprap can also be used in rapidly eroding areas to promote vegetation establishment. Temporary wave-stilling devices constructed of either hay bales enclosed in chicken wire or of used tires threaded on steel cables have been used with limited success along the Gulf Coast to encourage the establishment of vegetation (Webb and Dodd 1976). Precast concrete blocks used in revetment construction (e.g., Monoslabs, Unigreen, or Grasscrete) and Enviroblox are designed to allow vegetation to grow through openings in the structures (see discussion in Chapter 5 on Cellular concrete grids and Enviroblox). Riprap and gabion revetments may also be considered a form of site preparation if the purpose of installing these structures is the eventual establishment of vegetation. A technique known as "root-rap" has been developed to promote the growth of vegetation on riprap. The waterway area should be shaped to carry a slow-water discharge (wide and flat) and should be subcut to receive a 1-ft layer of rock (8-in. sieve size). The rock should then be covered with 6-in. of topsoil and seeded with "Class 8" seed mix. The topsoil and seed fill voids in the rock and provide plant growth. The rock size and the thickness of stone and topsoil can be reduced if less severe erosion problems exist (J. Thomas and L. Kowalski, personal communication).

In addition to adequate site preparation, it is often neccessary to protect the lower bank to prevent undercutting of the vegetated upper bank (U.S. Soil Conservation Service 1979). On large rivers, such as UMR, the banks are often of such height that tree roots do not protect the lower bank areas. Undercutting of the bank by currents, coupled with the weight of the tree crown and with wind acting on the trees, may actually reduce bank stability (Simons et al. 1979). For this reason, White and Brynildson (1967) recommended that trees be removed from the bank at the outset of a

small-stream improvement program. Although this recommendation may not be applicable to the main channel border of UMR, it may apply to narrow side channels and chutes.

Simons et al. (1979), however, stated that the removal of bank line trees generally reduces bank stability unless the trees are replaced with some other form of bank protection, such as riprap. As an alternative to total bank protection, Simons et al. (1979) proposed placing riprap only on the lower bank of the Connecticut River. The lower bank protection would serve to prevent lateral channel migration. Waves, water level fluctuations, and high velocity flows at flood stage would erode the upper bank and help create a shallow berm wide enough to dissipate most of these erosive forces. The extent of this erosion landward would usually be limited to an average of 10 to 15 ft in a large river. Ideally, this new berm would eventually become revegetated, further stabilizing the bank and creating a wildlife corridor along the river. The U.S. Army Corps of Engineers successfully used this approach to bank stabilization on the Sacramento River in California. Kindel (1977) stated that this appears to be the most desirable method of bank protection from an environmental standpoint.

The type of vegetation used is an important determinant of the degree of bank protection that may be provided (Simons et al. 1979). Keown et al. (1977) reported that vegetation is generally divided into two broad categories--grasses and woody plants. This distinction is based on differences in height, development of the root system, and the ease with which these plants are established.

Grasses, small plants, and shrubs help prevent surface erosion by slowing the velocity of the flow, damping surface wave activity, and reinforcing the soil to the depth of the root system. Also, roots extending into the flow below the flow line retard velocity, and under some conditions encourage the deposition of fine sediments to strengthen the bank and reduce seepage losses. Tall vegetation, such as large shrubs and trees, has extensive root systems that extend through a greater mass of the bank and provide some reinforcement (Simons et al. 1979). In general, grasses require much less time than woody plants to become established, but offer less protection during periods of high velocity flows (Keown et al. 1977). For this reason, it is recommended that any long-term revegetation program include both grasses (for the initial stages of rehabilitation) and woody species (to promote long-term stability).

The actual selection of plant species for bank stabilization depends on a number of factors. Simons et al. (1979) established the following criteria for selecting species for bank stabilization:

1. Flood tolerance.

2. Life cycle (i.e., annuals or perennials).

3. Vigor of seedling habits.

4. Physical characteristics: stem length, number of stems per unit of area, root density, and stiffness.

5. Ability to spread naturally and readily by seed or vegetative means.

6. Availability: species selection is often limited by the commercial availability.

7. Ease of establishment (presumably this includes the ease with which a species will grow in disturbed soil and the ease with which this species can be seeded or planted over the area to be vegetated).

White and Franks (1978) offered three reasons for recommending reestablishment of native plants as an ideal revegetative approach for erosion control: (1) the method is aesthetically pleasing, blending in with the surrounding natural environment; (2) fertilizer requirements are lower for native than for most exotic species; and (3) native, drought tolerant species have relatively low water requirements.

Several difficulties may be encountered in attempting revegetation with some native species:

1. Plants or seeds are not generally available except by advance contracts with growers.

2. Plants are relatively expensive because difficulties of propagation and cultivation result in greater risks to growers.

3. Survival of small seedlings and cuttings is poor when they are given little attention and care.

4. Native species often provide less than adequate ground cover for effective soil stabilization and erosion control.

Plants that naturally invade disturbed sites in the area can be used as helpful indicators of the kinds of plants that are adaptable to adverse conditions. Simons et al. (1979) noted that transplanting species already growing in the area should be considered, but Keown et al. (1977) wrote that trees raised in nurseries are preferable over local plants because they are usually healthier, bushier, and have better developed root systems at maturity.

In addition, consideration should be given to selecting species that not

only provide suitable bank protection, but also provide food or cover for wildlife and fish, as indicated by Whitlow and Harris (1979):

> "The improvement of fish habitat is not necessarily inconsistent with waterfowl habitat improvement, but [it] is different in several respects. First, instead of concentrating on forage, it is largely directed at providing suitable cover for young fish. Submerged shoreline vegetation has been shown to significantly increase growth and survival in bass fry during the first three months of life, presumably by harboring food organisms and providing cover from predators. Because this requires that plants be flooded during the spring and summer, annual terrestrial plants generally are not suitable unless one is willing to replant annually. Either true aquatic macrophytes or flood-tolerant terrestrial perennials are required. Second, plants selected for fish cover often will not produce seed of value to waterfowl. Thus, if both fish and wildlife habitat improvement is desired, different species will have to serve in complementary roles. Finally, whereas waterfowl food can be provided by annual plants that do not need to be flood tolerant, plants providing cover for fish (or bank protection) must be able to withstand both flooding and drought, and ideally would be self-perpetuating."

Thought must also be given to selecting plants that are compatible with the needs of both wildlife managers and river engineers. For instance, legumes are often added to seed mixtures to provide nitrogen to soils that are deficient in nitrogen. However, Parsons (1963) stressed that legumes are not effective for streambank stabilization because they are generally weak in retarding flow. Therefore, Simons et al. (1979) suggested that applications of a good nitrogen fertilizer would be preferable. This would mean that nitrogen supplements would have to be added periodically in the absence of legumes. On the other hand, many legumes are important forage plants for wildlife. Thus it is desirable to fertilize initially and to seed the area with a mixture of legumes and grasses.

Tentative species lists of vegetation found in the UMR floodplain were given by Swanson (1978), Klein et al. (1975), and Terpening et al. (1974). A state-of-the-art review of flood tolerance in plants was offered by Whitlow and Harris (1979), and their species lists can be cross-checked with lists published by Teskey and Hinckley (1977a, 1977b, 1978a, 1978b). Ziegler and Sohmer (1977) evaluated the flora of dredged material sites in Pool 8 of UMR, and Lee et al. (1976) presented a species list of vegetation that might be introduced on dredge spoils. Klimas and Allen (1981) reported on 13 herbaceous and 6 woody species selected for an experiment to determine which species could withstand extended flooding. Survival of two woody species, persimmon and black willow, was good, even after 45 days of continuous flooding. The herbaceous species, except panicum and eastern gamagrass survived well after 5 weeks of flooding. We suggest that a listing of plant species be coordinated among various agencies, such as local U.S. Soil

Conservation Service offices, county foresters, and state fish and wildlife management divisions, so that the plants used will provide fishery and wildlife enhancement value, in addition to adequate bank protection.

The selection of planting or seeding techniques for banks and shorelines depends on the plant species used and on site-specific conditions, including accessibility of the area, the slope, soil characteristics, and the type of site preparation used. Essentially, there is no conceptual difference between the methods for planting in drawdown zones or on embankment slopes and the practices used by horticulturists, foresters, wildlife managers, and farmers (Whitlow and Harris 1979). Planting techniques used in riparian zones include hand seeding, tractor seeding, sodding, sprigging, use of mechanical planters, hand planting of seedlings, and mechanical broadcasting of mulches consisting of seed, fertilizer, and fibrous materials.

Willows have been planted extensively in the past for bank protection, particularly on small streams. They develop extensive root systems, are highly flood tolerant, and root easily from cuttings or shoots; however, they are of relatively little value for wildlife. Unlike most vegetation, the roots of established willows not only persist but thrive in water flowing at moderate speeds (Parsons 1963). Simons et al. (1979) reported that willows have also been used in a variety of other ways. Willow logs are often buried and anchored to the bank line. The logs eventually send up shoots, while providing a degree of bank protection during the initial growth period. When willow cuttings are used, the banks should be seeded with herbaceous ground cover just before or immediately after planting.

Another method used to revegetate areas is to remove only as much vegetation as necessary during construction or revetting activities. Selective cutting can be practiced, leaving only desirable species in the area to serve as seed trees. Species to be left can be chosen for qualities such as flood tolerance, lumber grade, or value as a mast crop. In addition, Shen (1973) found that the most effective pattern of tall vegetation (i.e., trees) for reducing flow velocities and sediment loads was a staggered distribution, and suggested that trees be planted with this distribution in mind. However, because it is difficult to harvest mature trees to form a staggered pattern, Shen (1973) recommended that trees be harvested in rows that are perpendicular to the direction of flow. These methods are useful in areas that are expected to be inundated frequently, such as areas between the bank line and flood control levees.

Fowler and Hammer (1976) described three unique methods of seed dispersal that are particularly applicable to large, inaccessible areas and that were used to establish Italian ryegrass on drawdown zones of Tennessee Valley Authority reservoirs: modified hydroseeding equipment mounted on a barge, a broadcast speader mounted on a hovercraft (air-cushion vehicle), and a hopper-spreader mounted on a helicopter. In an earlier project, hydroseeding

from a barge was used to establish common barnyardgrass, common buckwheat, and Italian ryegrass (Fowler and Maddox 1974).

Hydroseeding is commonly used by landscaping firms, and to some extent by state highway departments for vegetating roadsides. It is an effective technique because seed, fertilizer, mulch, and herbicides can be applied in one step. Hydroseeding trials on forest roadside slopes at two Vancouver Island sites showed that a single application of both seed and fertilizer was as effective as sequential applications of seed and fertilizer (Carr and Ballard 1980). This technique may prove to be an effective method for vegetating disposal sites for dredged materials.

Many of the revegetation techniques used along roadsides and on strip-mined land are directly applicable to dredged material sites. These areas are often exposed to erosive forces, surface runoff may be extensive, and the soils may be compacted and low in nutrients. Foote et al. (1978) described techniques for establishing vegetation on roadsides, and the U.S. Environmental Protection Agency (Bennett and Donahue 1975) published a manual on methods for vegetating soils of low productivity. Rafaill and Vogel (1978) prepared an excellent review of procedures for establishing vegetation on surface-mined lands. Sopper and Kerr (1979) provided information on the possible use of municipal sewage sludge for the nutrient enhancement of disturbed soils (i.e., dredged materials).

The use of aquatic or marsh vegetation for bank protection is noted but will not be discussed here. Marsh vegetation is a "prime candidate in designs for erosion control in areas of low and moderate wave energies" (Knutson 1977). The creation of marsh habitat is discussed in Chapter 36. Techniques for establishing marsh plants were reviewed by Wentz et al. (1974) and Knutson (1978).

11.3. IMPACTS ON THE ENVIRONMENT

In general, the establishment of vegetation is probably the least expensive, most visually attractive, and least complex method of combating bank erosion. Tree planting programs and other efforts to establish a protective cover of vegetation can also expand wildlife habitat and recreational opportunities, and improve water quality. Vegetation is the only self-renewable method of bank protection (U.S. Army Corps of Engineers, Rock Island District 1980; Tourbier and Westmacott 1974).

The corridor of riparian vegetation stretching along UMR is critical to its fish and wildlife resources. The riparian zone is the interface or ecotone between an aquatic and terrestrial community. The importance of the "edge effect" created by ecotones is widely recognized in wildlife management,

and recent research by Waldrip and Malespin (1979) has demonstrated that riparian habitats receive more use per unit area by wildlife than any other habitat type.

Care must be taken when selecting the species of plants to be used for revegetation efforts. A number of introduced weed species become established easily on disturbed soils but they often spread unchecked, to the detriment of native species. For example, 30 years ago the ASCE Subcommittee on Slope Protection recommended planting slopes with honeysuckle and kudzu for erosion control (Buzzell 1948). Since then, these plants have spread in epidemic proportions, inhibiting the growth of many native plants, or preventing their establishment.

The major disadvantage of vegetation is that its use as the sole method of bank protection is limited by high current velocities and high, steep banks. Vegetation is also at its low growth phase during the most pronounced erosive conditions in winter and early spring (Bache and Macaskill 1981). Vegetation does not provide adequate protection in large rivers with high shear velocities, particularly at bends, and vegetation on high, steep banks does not provide the lower bank protection needed to prevent undercutting. In such areas, vegetation must be used in conjunction with structural bank stabilization measures such as riprap, gabions, or concrete grids to provide the appropriate level of bank protection. Such combinations of vegetation and structure and intermittent structures are being tested on the Missouri River as part of the Section 32 Program associated with Streambank Erosion Control Evaluation and Demonstration Act of 1974 (U.S. Department of the Army, Chief of Engineers 1978).

11.4. COSTS

The cost of establishing vegetation on banks and along shorelines is highly variable and depends on such site-specific factors as soil conditions, water levels, current velocities, local wave climate, and slope. These conditions influence the site preparation, method of planting, and plant species used. Some attempts have been made to approximate the costs of a generalized planting scheme. Parsons (1963) reported that after the bank is shaped, it cost $0.20 per square yard of bank area to establish an herbaceous lining, and $0.50 per square yard for a combination of shrubs and grass. During the same time period a blanket of stone riprap 12 in. thick cost $4 to $5 per square yard. More recently, Keown et al. (1977) estimated that the 1976 cost of planting grass ranged from $500 to $650 per acre, including soil preparation and fertilizer. If woody vegetation is planted with the grass, the average cost is about three times that of the grass alone.

Woody plants generally have a greater initial cost than grass and require a longer time to become established, but they provide more effective long-term protection. Although trees raised in nurseries cost more than transplanted local vegetation, nursery trees are preferred because they are usually healthier, bushier, and have better developed root systems (Keown et al. 1977).

Many of the methods involved in plant establishment are highly labor intensive, and this use of labor is reflected in increased initial and maintenance costs. The St. Paul District of the Corps of Engineers reported that the initial cost of establishing grass on riprap could be 20 to 30% greater than that for riprap alone, because of the additional materials and labor needed. This estimate excludes expected increases in maintenance costs (L. Kowalski, personal communication). The Sacramento River Levee Revegetation Study concluded that the cost of manpower for the maintenance of levees with planted vegetation was increased by 64% over costs of similar levees without vegetation (Kindel 1977).

Cost estimates for different methods of site preparation differ widely, as evidenced by the material and construction costs (1977) given by Hanson et al. (1978) for some soil conditioning methods used along the Lake Michigan shoreline in Wisconsin (Table 3) and cost estimates for some erosion control-revegetation treatments (Table 4). Table 5 presents cost estimates of three seeding methods that are applicable to large, inaccessible areas. These costs were determined by prorating the application rates used in a study by Buxton and Caruccio (1979), and are presented here only for comparisons. Buxton and Caruccio (1979) noted that the cost of applying these treatments depends on such variables as crew experience with a product, labor rates, site locations, time and season of application, and the size of the job. It is expected, though, that treatments that can be applied most easily will also be the least expensive. Costs of application are also indexed in Table 4.

Table 3. Costs (1977) of some methods of site preparation (modified from Hanson et al. 1978).

Item	With construction
Topsoil, 4 in. deep, at $4.50-6.00 per cubic yard	$0.80-1.00 per square yard
Seed, with disking and fertilizer	$0.90 per square yard
Seed, with hydraulic equipment and mulch	$0.40 per square yard
Seed erosion blanket, jute with polyester fiber at $0.39-.42 per square yard	$0.60 per square yard
Regrading, on site only	$1.20 per cubic yard
Removal of excess soil (average)	$1.40 per cubic yard

Table 4. Cost analysis (1977) of revegetation treatments for erosion control (modified from Buxton and Caruccio 1979).

Type of product tested and trade names	Total cost of materials (per acre)	Relative cost of application[a]
Blanket		
Curlex	$1597	C
Hold/gro	2129	C
Jute	1228	C
Hydromulches		
Conwed	120	A
Silva	111	A
Turfiber	115	A
Pulch	84	A
Chemical Stabilizers (with 500 lb per acre at $50)		
Curasol AK	225	A
Genaqua 743	220	A
Aerospray 70	242	A
Dow Mulch Binder	157	A
Petroset SB	200	A
Terra Tack III	166	A
Tackifiers with straw (3000 lb of straw per acre at $120) with tackifiers		
Vexar net	604	C
Curasol AK	295	B
Terra tack II	231	B
Dow mulch binder	227	B

[a]Cost of application is presented as a relative degree of difficulty in installing treatment. A = easiest application technique (lime, seed, and fertilizer are applied simultaneously with a hydro-seeder); B = second easiest technique (requires the additional step of blowing the straw); and C = most difficult technique (requires very complex manual application of the treatment).

The following cost analysis is from Buxton and Carrucio (1979) and is based partly on Table 4:

The blanket treatments are the most effective in controlling erosion

and have much greater stability due to the staple method of tacking. Yet the expense makes utilization on a large-scale basis uneconomical in problem areas where slopes are very steep and unstable or where poor water management has resulted in confined flow.

The straw treatments are almost, if not fully as effective as blankets and are much more economical. Straw mulch can be applied to large areas on moderate slopes and needs no tackifier. A straw mulch, when tacked with a plastic net, such as Vexar, could be used in situations where a blanket product would otherwise be required for effectiveness, but for a much lower cost.

Hydromulches and chemical tackifiers have the lowest application cost per acre of treatment and are the easiest to apply. However, the results of tests showed that they were not as effective in controlling soil erosion as originally anticipated. Additional testing is needed for a variety of combinations of amounts of hydromulch and chemical stabilizers with the cost of materials ranging from $200 to $300 per acre. The formulation of an optimum blend of each component, which takes advantage of the merits of each treatment, would be a valuable and economical treatment for erosion control.

Table 5. A comparison of costs (dollars per acre) of inundation zone seeding techniques (modified from Fowler and Hammer 1976).

Seeding technique	Acres per day	Crew size	Cost item				
			Equipment	Labor[a]	Seed[b]	Fertilizer[c]	Total
Aquaseeder	90	3	$0.10[d]	$1.13	$5	$12	$18.13
Air Cushion Vehicle	90	2	0.13[d]	0.76	5	---	5.89
Helicopter	1000	3	0.52[e]	0.07	5	---	5.59

[a]Computed at $4.25 per hour.
[b]Ryegrass seeded at 20 lb per acre ($0.25 per pound).
[c]Application of 6-12-12 (N-P-K) at 200 lb per acre $0.06 per pound).
[d]Fuel and maintenance only.
[e]Estimated at 6 h actual seeding per day ($65 per hour plus $130 per day).

It is important that site preparation be adequate. Removal of bank vegetation and hydroseeding were ineffective in stabilizing the banks of the Connecticut River because needed studies were not made of species selection, site preparation, or maintenance of the plants (Simons et al. 1979). Even

with the additional costs of site preparation, the overall cost of bank and shoreline revegetation is small, when compared with the costs of installing bank protection structures.

11.5. EVALUATION FOR USE ON UMRS

Vegetation should be established whenever possible, as a bank protection measure on UMR. The use of vegetation, alone or in conjunction with structural bank protection measures, has important compensatory value for mitigation efforts there. Riparian vegetation along the UMRS corridor will almost certainly decrease as a result of current land use policies, and as channelization efforts, shoreline developments, and agriculture increase along this reach of the river. Although Olson and Meyer (1976) estimated that only 13,500 acres of terrestrial vegetation was lost in Pools 1 to 10 between 1929 and 1973, the possibility of severe changes in land use patterns is real. On the Missouri River, for example, floodplain forest coverage declined from 76% in 1826 to 13% in 1972; agricultural lands concomitantly increased (Bragg and Tatschl 1977).

Along much of UMR, structural forms of bank protection must be used, along with vegetation, to provide an appropriate level of bank protection, particularly at bends in the river. However, from the standpoint of fish and wildlife mitigation, it is not wise to assume that some structural method, such as riprap, is always needed in other areas of the river such as pools, backwaters, chutes, and islands. Such an assumption is costly and ignores the benefits that might be derived from using vegetation alone. Hehnke and Stone (1979), who compared the bird fauna of berms with riparian vegetation with that of riprapped berms that were vegetated with shrubs or grass on the Sacramento River, found that diversity was 71% less and density was 93% less on riprapped plots than on riparian plots. Furthermore, density and diversity were 95% and 32% less, respectively, on agricultural lands associated with riprapped berms than on agricultural lands associated with riparian berms. At the study site, the protected area was completely riprapped, as opposed to the recommended use of riprap on the lower bank and vegetation on the upper bank (C. H. Pennington, personal communication).

On the other hand, vegetation is sometimes removed from riprap revetments as part of routine maintenance. Vegetation can dislodge stones and create pathways for eroding currents to undermine a revetment. Large trees may be uprooted by flood flows, dislodging large sections of the revetment. Obviously, there are different schools of thought on the effects of vegetation on riprap. The Portland District of the U.S. Army Corps of Engineers is currently investigating this subject with field tests (C. H. Pennington, personal communication).

Hydroseeding from barges and other commonly used forestry practices

should be combined for use on UMR. These methods should be coordinated with bank stabilization efforts by the U.S. Army Corps of Engineers and goals of wildlife managers (provision of waterfowl habitat and mast crop production for wood ducks) on the river. Barge hydroseeding can be used in any inaccessible area, particularly along inundation zones (Fowler and Maddox 1974), and on dredged material disposal sites. Natural revegetation on these disposal sites is often limited to the area within about 3 ft above the waterline because moisture is maintained only to this height by capillary action (U.S. Army Corps of Engineers, St. Paul District 1974). Applications of mulch (with seed and fertilizer) by hydroseeding may help to retain moisture on the surface of the spoil pile, thereby alleviating this problem. The development of vegetation on dredge spoils is also prevented or retarded by repeated placement of material on sites. Revegetation efforts must be coordinated with maintenance dredging to prevent this occurrence.

CHAPTER 12. CHEMICAL SOIL STABILIZERS

12.1. SITUATION TO BE MITIGATED OR ENHANCED

Rain and the hydraulic and abrasive actions of moving surface water and wind exert forces on soil that cause erosion. Protection can be achieved by binding the soil particles together to form a mass that is less easily displaced by anchoring the soil in place (Mills and Clar 1976). Chemical soil stabilizers provide temporary erosion control until vegetation is established, act as tackifiers for organic mulches during revegetation, stabilize clay canal banks, and bind gravel for a riprap substitute. In the first two situations, chemical soil stabilizers aid in the establishment of vegetation on eroded, reworked, or newly shaped river banks. In the last two situations, chemical soil stabilizers act as a temporary revetment to a river bank. The basic purpose in all situations is increased stability of a river bank against erosive forces.

12.2. DESCRIPTION OF TECHNIQUES

Chemical soil stabilizers are used as temporary erosion control materials until vegetation is established, as tackifiers for organic mulches for revegetation, as stabilizers of clay canal banks, and as binders of gravel for riprap substitutes (Morrison and Simmons 1977). Lindner (1969) realized the potential of chemical soil stabilizers for bank stabilization applications, but stated that much research had to be done to determine their effectiveness. Kinter (1975) reported on a 20-year cooperative effort by the Federal Highway Administration and the chemical industry to develop and evaluate chemicals for soil stabilization. No single chemical or combination of chemicals had been found that was both effective and economic as a major stabilizer. Another program, this one a 30-year effort involving government agencies, universities, and private firms, was begun by the U.S. Army in 1946 to evaluate materials for use as chemical soil stabilizers. Cement, lime, and asphalt, alone or with certain additives, were the best materials for strength stabilization. Other useful materials included sodium silicate on silt, Powders A and B on loess, calcium oxide on clay, and Aropol 7110 on sand (Oldham et al. 1977). Other synthetic soil stabilizers were effective and could also be used. (For further information of chemical soil stabilizers in relation to vegetation, see Chapter 11.)

Morrison and Simmons (1977) tested several experimental chemical soil stabilizers in the laboratory and field for various applications. They found that (1) a polyvinyl acetate emulsion and an acrylic copolymer emulsion were effective in controlling erosion on spoil and canal banks until vegetation was established; (2) an asphalt emulsion and plastic emulsions were effective as tackifiers for organic mulches in revegetation work; (3) lime was an effective stabilizer of clay canal banks; and (4) an elastomeric emulsion and

a urethane product were effective in binding gravel for use as a riprap substitute or to stabilize gravel filters. Although the elastomeric emulsion had satisfactory strength properties and good resistance to wave action, the binder slowly deteriorated over a period of 4 years. Its use should therefore be limited to short-term applications such as temporary dikes or as temporary protection of beaches. The urethane product had the greatest strength and withstood continuous wave action in laboratory and field tests over a 2-year period without deterioration. It is very expensive, however--a factor that limits its use to special situations.

A polyvinyl acetate emulsion was tested for use as a stabilizer of backfill material at an aqueduct. Although it provided some erosion control, it softened with wetting and became susceptible to damage. It is not a good material for permanent erosion control (Morrison and Simmons 1977).

Lime effectively stabilized clay canal banks (Morrison and Simmons 1977). Townsend (1979) extended this use to levees. Slides due to sloughing often occur on clay levees in the Lower Mississippi River, increasing maintenance problems and causing vulnerability to scour from wave wash. The addition of 4% lime was enough to stabilize the banks.

Chemical soil stabilizers were tested for their ability to control erosion before vegetation was reestablished on river banks stripped of their natural vegetation during construction or repair in studies performed under the Section 32 Program for the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Oldham 1979). Oldham (1979) tested five materials and found that two, Aerospray 70 (a polyvinyl acetate and latex water emulsion) and Soil Seal (a copolymer emulsion of acrylate and methacrylates), were effective in helping to reestablish vegetation on denuded slopes. Both products cure into a durable surface film. Other materials, which were not effective, included an acrylic, a cutback asphalt, and a resin derived from semichoking of fuel shale and caustobioliths.

Buxton and Caruccio (1979), after testing both erosion-control mattings and chemical soil stabilizers for erosion control effectiveness, reported that erosion-control mattings were more effective in controlling erosion and were more stable than chemical soil stabilizers, but that matting products were too expensive to use on a large scale. Chemical stabilizers used with hydromulches did not preserve soil moisture at the surface. The authors recommended further testing to determine the amounts of hydromulch and chemical stabilizer needed to produce an optimum blend that would produce the most useful and economic treatment for erosion control. Mills and Clar (1976) found that chemical soil stabilizers work best on dry, highly permeable spoil or in-place soils subject to sheet flow rather than concentrated flow. The U.S. Environmental Protection Agency (1976) stated that the criteria to be followed for selecting the appropriate soil stabilizer included intended use, effectiveness, cost, availability, and success of field tests. The Agency

listed 12 commercially available chemical soil stabilizers that temporarily stabilize soil: Aerospray 52 Binder, Aerospray 70 Binder, Aerospray 72 Binder, Aquatain, Curasol AE, Curasol AH, DCA-70, Genequa 169, M-145, Petrose SB, Terra Tack, and XB-2386.

Johnson (1979), who searched for substances that could be used on silt and sand at low temperatures, found that Ashland urethane resin could be used at 32°F or below and recommended that the hydrophilic urethane "Mud Lock" be tested further for low-temperature application as a soil stabilizer.

12.3. IMPACTS ON THE ENVIRONMENT

Chemical soil stabilizers reduce sediment production, preserve top soil, and help achieve a more environmentally acceptable condition after construction is complete. Costs of preventing soil erosion and sediment runoff are less than those for removing silt from rivers and streams at a later time (Morrison and Simmons 1977).

Materials studied by Oldham (1979) did not have an adverse effect on the germination of seeds; some of the stabilizers even accelerated the emergence and propagation of the vegetation.

12.4. COSTS

Buxton and Caruccio (1979) reported that the costs of chemical soil stabilizers they tested ranged from $157 to $242 per acre for materials. Expenses for application should be minor because the stabilizers are easy to install.

Morrison and Simmons (1977) estimated the following costs (per square yard)for the materials they field tested:

Polyvinyl acetate emulsion	*$1.59*
Plastic emulsions	*$0.41*
Urethane	*$11 to $17.50*

The elastomeric polymer cost $300 to $750 per acre installed.

12.5. EVALUATION FOR USE ON UMRS

Chemical soil stabilizers have high potential for use on UMRS. The materials are fairly inexpensive and easy to apply in most situations. More

studies must be performed, however, to assess the durability and applicability of each potential substance--especially for use by itself to protect river banks.

CHAPTER 13. EROSION-CONTROL MATTINGS

13.1. SITUATION TO BE MITIGATED OR ENHANCED

Erosion-control mattings can be used to help establish and maintain vegetation on river banks and may also replace riprap in controlling surface erosion. These materials are particularly useful when a bank has been eroded, denuded, or newly formed.

13.2. DESCRIPTION OF TECHNIQUES

Keown et al. (1977) listed a variety of commercial matting materials that are widely used to protect streambanks. These materials are usually installed by hand and secured by staples or stakes. The matting sometimes biodegrades, thus assisting in the mulching process. The configuration of the material allows vegetation to become established on either eroded or prepared sites. (The use of matting is further discussed in Chapter 11.) The information we provide on these products was obtained from manufacturers.

Enkamat is a trade name for a three-dimensional matting made from heavy nylon monofilaments fused at their intersections. About 90% of the volume is filled with soil, gravel, or other materials after it is in place. Two thicknesses, 0.35 and 0.7 in., are available. According to the manufacturers, the matting can be used as a replacement for concrete, asphalt, and riprap rock to control surface erosion. It has been used on river banks, ocean and lake shorelines, drainage ditches, canals, bridge abutments, and dikes to establish or maintain vegetation where these areas are subjected to severe wind or water erosion. If secured, the matting stays in place on very steep slopes (i.e., slopes of 2H:IV).

Enkamat provides a stable environment for plant growth, functioning as a mulch by holding the grass seed in place. Its black color causes it to collect heat, hastening seed germination. The matting helps the soil to remain porous and helps stabilize the vegetation because the roots become entwined with the filaments. The material does not degrade from ultraviolet radiation because carbon black has been added to the matting coating. Enkamat comes in rolls 3.3 ft wide weighing 85 to 90 lb; it is easy to apply--supposedly one person can install it.

Buxton and Caruccio (1979) tested three netting products, four hydromulches, eight tackifiers, and straw mulch to determine their effectiveness in stabilizing soil and aiding in vegetation establishment. The

netting products (jute netting, Hold/gro, and Curlex) and straw mulches provided the best protection from erosion. The investigators determined that the most effective materials were also the most costly and were too expensive to apply over large areas.

Hold/gro is a patented combination of knitted synthetic netting interwoven with biodegradable paper strips. When installed, it is held in place by high-carbon iron staples. This product has been used to control erosion while vegetation was establishing itself on such areas as slopes, diversion ditches, dam facings, flood control dikes, canal embankments, and beaches. Hold/gro is about one-fourth the weight of jute, thus making installation by two people quick and easy. A roll of Hold/gro comes in 5- or 10-ft widths and weighs 25 to 58 lb.

American Excelsior Company produces a patented erosion-control blanket called Curlex that consists of curled and seasoned aspen wood excelsior in a biodegradable plastic mesh. Curlex blankets are installed horizontally or vertically on slopes and are held in place with staples. This product has been used to prevent erosion and to help establish vegetation on steep slopes, ditches, and dam sites. Curlex blankets come in rolls 4 ft wide and weigh about 80 lb.

Conwed erosion-control netting is a patented polypropylene extruded plastic net designed for use in areas that have been seeded and mulched. The netting is unrolled and stapled over locations susceptible to wind or water erosion. Typical applications are on highway medians, ditch bottoms, and slopes. The manufacturer stated that this material may have applications in pool and backwater areas of UMRS. Conwed comes in rolls 3.75 to 15 ft wide that weigh 35 to 140 lb.

Wilder and Rains (1976) reported on a stream channel stabilization project on the Yazoo and Little Tallahatchee rivers. They used Hold/gro, Conwed, and Curlex blankets to trap sediment and moisture to help establish vegetation. Hold/gro and Conwed blankets were best suited for sites characterized by smooth terrain or areas that have been previously shaped. Conwed was rated better than Hold/gro for stabilization of gully areas. Curlex was considered the best blanket for general stabilization. It could be used on sharp, exposed ridges, irregular shapes, and bottoms of eroding gully channels.

Soil Saver is a patented heavy woven jute mesh that holds seed and soil intact on slopes, dams, waterways, and other areas of concentrated water flow. The mat is held in place with staples and can be installed by two persons. Soil Saver was installed successfully in a dredged waterway with a 3:1 slope.

Advantages of erosion-control matting, according to Tourbier and Westmacott (1974), are as follows:

1. It is less expensive than most other stabilization techniques.

2. It is easily placed by unskilled labor.

3. It is not as subject to displacement by wind as are many organic mulches, though it must be well anchored to prevent slippage during rainstorms.

4. It permits the use of any seed mix, without the need to consider the decomposition period of an organic mulch.

A disadvantage of erosion-control matting is its nonretention of soil moisture.

13.3. IMPACTS ON THE ENVIRONMENT

Erosion-control matting can reduce soil erosion. As a result, less sediment enters waterways and less dredging is needed. Additional terrestrial habitat is formed and the total bank becomes aesthetically pleasing.

13.4. COSTS

Keown et al. (1977) reported that 1976 costs for in-place erosion-control matting ranged from $5.56 to $7.22 per square yard.

The estimated cost at 1981 prices for installation of an Enkamat revetment ranged from $4 to $5.45 per square yard for the 0.35-in. material, and from $5.55 to $7.25 per square yard for the 0.7-in. material. These amounts include the cost for Enkamat, labor, materials, equipment, and grass seed.

Buxton and Caruccio (1979) analyzed the per acre cost for three different matting systems: Jute matting, $1228; Hold/gro, $2129; and Excelsior blanket (Curlex), $1597. These prices did not include labor and site preparation involved in applying these materials.

Hold/gro was available to government agencies through a 1981 General Services Administration Contract for $0.46 to $0.49 per square yard. The 1981 prices for Curlex blankets ranged from $0.39 to $0.49 per square yard. Prices given by Wilder and Rains (1976) indicated approximate costs per square yard of $0.13 to $0.14 for Conwed plastic matting, $ 0.39 for Hold/gro, and $0.25

for Curlex. Morrison and Simmons (1977), reporting on tests of soil retention blankets, wrote that the cost of polypropylene netting interwoven with paper was $0.36 per square yard.

13.5. EVALUATION FOR USE ON UMRS

Erosion-control matting materials are more effective than chemical soil stabilizers in controlling erosion but the matting products are considered too expensive to use on a large scale to help establish vegetation. Applications in small areas might be reasonable and feasible.

Erosion-control mattings may not be viable alternatives to riprap or concrete, considering the magnitude of the erosive forces in UMRS. They may have practical application on slopes above the medium waterline. Enkamat, in particular, because it is more substantial than other matting, could provide protection to slopes subject to medium erosive forces. Representatives for Enkamat claim that Enkamat has been used successfully below the normal water level in the Ohio River where the river flow was 24,000 cfs. Enkamat, in combination with Curlex, can be used above normal water levels to establish vegetation. Cost is another factor to be considered. The manufacturers claim that the installed price for Enkamat is about one-third that of concrete.

CHAPTER 14. FILTER FABRICS

14.1. SITUATION TO BE MITIGATED OR ENHANCED

The major use of filter fabrics is to prevent water from washing away the underlying soil around bank or shore stabilization structures such as revetments, groins, jetties, and breakwaters. Uses of fabric filters have recently been extended to include the protection of drains, weep holes, and joints in various structures and the prevention of scouring around piers and bridge abutments (Dunham and Barrett 1974; Calhoun 1972; Bohan 1970a). The major cost for revetment repairs has been to correct settlement of the upper bank portion, caused by the loss of underlying material. Use of the proper filter can prevent the occurrence of flows or settling. (Further information is given in Chapters 4 and 5.)

14.2. DESCRIPTION OF TECHNIQUES

For some time, engineers have placed filters under bank or shore stabilization structures to prevent waves from washing away the underlying soil. Originally, these filters were usually some type of granular material such as graded sand, gravel, or stone in various thicknesses or combinations (Barrett 1966). These materials often proved to be very expensive or unavailable, and their installation was difficult and tedious because the material had to be properly placed to eliminate loss of the underlying soil (Dunham and Barrett 1974; Dallaire 1977). In general, engineers have had poor results with granular filters (Dallaire 1977; Murphy and Grace 1963).

These shortenings created a need for a more attractive filter material. Filter fabrics were first used in 1956 by Dutch engineers. The first use in the United States was in 1958. However, the use of filter fabrics did not gain wide acceptance until the 1970's. One of the problems lay in the distrust designers had for materials only 16 mils thick when they were accustomed to using layers of sand, gravel, or stone 1 to 2 ft thick (Dallaire 1977). As recently as 1967, only two domestic sources of filter fabric were known; by 1980, however, Keown and Dardeau (1980) reported that 17 companies supplied filter fabrics.

Filter fabrics can be woven or unwoven. Plastic and nonplastic materials have been used as filter fabrics, but they all allow water to pass, while retaining soil particles (Dallaire 1977). Certain fabrics must meet construction specifications for tensile strength, puncture strength, and abrasion resistance before they can be used in stressful situations (Keown and Dardeau 1980).

Keown and Dardeau (1980), who tested the various strengths of several types of fabrics, reached two principal conclusions:

1. In general, woven fabrics are considerably stronger in uniaxial tension than nonwoven fabrics; the general ranking in order of decreasing strength is (a) heavy to intermediate-weight woven fabrics; (b) intermediate to lightweight woven and heavy to intermediate-weight nonwoven fabrics; and (c) lightweight nonwoven fabrics.

2. Woven fabrics generally fail because localized strands break as a result of tension, or diagonal tearing occurs that suggests shear failure. Nonwoven fabrics fail primarily from diagonal tearing, excessive stretching, or a decrease in strength without outward signs of fabric rupture or tearing.

Filter fabrics should act as filters to the water, allowing waves to penetrate the armor of the revetment and flow through the filter and the underlying soil, producing an increase in hydrostatic pressure. As the waves recede, the water trapped in the sand reverses itself and flows out through the filter. If the filter becomes clogged, the fabric balloons because hydrostatic pressure builds up. If the filter were not there, sand beneath the revetment would quickly erode away (Dallaire 1977).

Fabric filters have also been used with wall drains installed in flood control works, bulkheads, and other impermeable structures, to release hydrostatic pressure in the soil behind the wall. In these applications, a perforated pipe is laid along the base of the wall, and gravel backfill is placed around it. Filter fabric is then placed over the gravel, and sand backfill is used to fill part of the trench. The sand acts as a filter to the surrounding soil, and the fabric prevents sand from migrating into the gravel but still allows the passage of water (Dallaire 1977). Filter fabrics have replaced grouting in the lining of retaining walls and vertical seawalls. The fabric retains the soil, yet permits water to drain through joints so that no hydrostatic pressure develops, as it would with grouting. If pressure is not allowed to build up and the backfill is retained, failure of the structure is averted, and maintenance is greatly reduced or eliminated (Calhoun 1972).

Filter fabrics have real benefit in protecting the banks of man-made barge canals in Europe. Granular filters have been unable to withstand the tremendous forces exerted by barges in these canals, and have failed repeatedly. Barges produce high energy waves, force water backwards at 7 fps and cause the water level between the barge and the bank to abruptly rise as much as 4 ft. Since the late 1960's, filter fabrics have replaced granular filters as the material of choice because of their high success rate in protecting the banks (Dallaire 1977).

Another unique use of filter fabrics is in the reinforcement of underwater surfaces of channels subjected to erosive forces caused by the churning action of passing vessels (Vos et al. 1979). The matting used consists of looped, continuous synthetic polymer filaments. The open structure allows sand, plant growth, and other particles to become entrapped, and to serve as anchors for the matting and cause it to blend into the underwater landscape. It is designed to be buoyant until it is towed into position for installation. The material becomes a substrate for aquatic plants and animals as it fills with detritus and sediments.

Fabric filters are more effective than gravel in retaining soil underlying revetments and bridges. However, Fairley et al. (1970) noticed that there was some downslope movement of material under their revetment test site. The failure occurred at the connection between the riprap and articulated concrete mattress. They observed that this problem could be remedied by the use of a more open-weave filter fabric, and concluded that filter fabrics could be used effectively in underwater areas if a means could be developed to place and anchor the fabric. In experiments conducted by the U.S. Army Corps of Engineers (Littlejohn 1977), filter fabric was successfully placed in underwater areas by bonding the filter to the bottom of armor material, such as articulated concrete mattresses. The 25% increase in cost was considered acceptable in areas where bank protection is crucial.

Keown and Dardeau (1980) recommended that filter fabrics be considered as a substitute for all or part of granular filters. If the armor material used in the revetment, groin, or jetty is heavy angular material, a thin layer of gravel should be placed between the filter fabric and the armor to protect the filter from tearing (Lindner 1969). In areas of turbulent flow, thicker armor material may be required to keep the fabric from being subjected to adverse and fluctuating pressures. Gravel filters will still be required in high-energy environments. Soils of a silty sand or a sandy silt composition are not stabilized by a filter fabric (Dallaire 1977). In the few situations where filter fabrics have failed, the main problem has been the improper matching of the fabric with the soil type. The fabric must always be more permeable than the soil. Where problems occurred, the fabric had ballooned but the revetments had not collapsed. The damage can be easily rectified by slitting the balloon, placing a granular filter in the area, and covering it with riprap (Dallaire 1977).

Further information on filter fabrics is given in Chapters 4 and 5.

14.3. IMPACTS ON THE ENVIRONMENT

We saw no reference in the literature to adverse environmental impacts associated with filter fabrics. Judging by the nature of their use, there is no reason to suspect that filter fabrics would pose environmental problems.

The fact that these filters reduce erosion of underlying soil makes their use a benefit because bank failure and turbidity are reduced.

If filter fabrics are selected that are not permeable enough for site-specific conditions, hydrostatic pressures may develop in localized areas (Calhoun 1972; Dallaire 1977). Properly used filters generally reduce hydrostatic pressure rather than increase it. Case histories of the use of filter fabrics have shown that the fabrics have been durable and have not deteriorated over periods of up to 14 years (Dallaire 1977).

14.4. COSTS

Material costs (1978 estimate) for woven filter fabrics range from $0.10 to $0.25 and for nonwoven material from $0.04 to $0.55 per square foot (Keown and Dardeau 1980). Fairley et al. (1970) found the cost of filter fabrics to be comparable to that of gravel, if repairs needed on gravel filters were considered in the total cost of a project.

14.5. EVALUATION FOR USE ON UMRS

The U.S. Army Corps of Engineers has increasingly used filter fabrics in place of gravel filters under riprap and other armor for bank erosion in the lower and upper Mississippi River System (Littlejohn 1977). Although more research is needed on the ability of filter fabrics to withstand turbulence, waves, and rapid drawdown (Keown and Dardeau 1980), the success that Europeans have had with fabric filters in their barge canals would indicate that these materials can perform satisfactorily under extremely difficult situations.

CHAPTER 15. HYDRAULIC WELLS OR DRAINS

15.1. SITUATION TO BE MITIGATED OR ENHANCED

Hydraulic wells or drain tiles, weep holes, or drain pipes relieve hydrostatic pressures under and behind bank stabilization structures. Hydrostatic pressure develops when water is trapped behind or beneath impermeable structures, with no way of escaping. This pressure can cause the failure of a bank stabilization structure by forcing the structure to lift or bulge, and may cause the soil to be eroded beneath or behind the structure.

15.2. DESCRIPTION OF TECHNIQUES

Hydraulic wells, drain tiles or pipes, or weep holes are placed in retaining walls, seawalls, bulkheads, dams, and locks where hydrostatic pressure may build up. A buildup of pressure could create an imbalance that would lead to failure of the structure.

Relief well systems have been installed along Mississippi River levees from Alton to Gale, Illinois, at Trotters, Mississippi, and in an overbank structure near Natchez, Mississippi (Trahan and Mitronovas 1968; Trahan 1970; Kaufman and Perrine 1957; Montgomery 1972). The system between Alton and Gale, Illinois, consists of 2346 wells (Montgomery 1972) designed to provide seepage control. The wells are 70 to 100 ft deep and are spaced at 75- to 300-ft intervals parallel to the levee system. Each well has a check valve, a metal well guard, and screens 50 to 80 ft in length. The wells consist of wood stave pipe risers 8 in. in inside diameter and slotted wood stave screens wound with galvanized or stainless steel wire. A graded gravel filter 6 in. thick surrounds the screens. Because it is important that these wells function properly during high water, test wells have been selected to monitor their pumping abilities. Montgomery (1972) concluded that a loss of efficiency in some of the wells was due to clogging of the gravel filter and the well screens. The U.S. Army Corps of Engineers, after checking the wells at Trotters, Mississippi (Kaufman and Perrine 1957; Trahan 1970), and at Natchez, Mississippi (Trahan and Mitronovas 1968), found them to be functioning adequately for the intended purposes.

In an erosion control project on Cayuga Creek, New York, Svensson and Sweeney (1979) used a single layer of used automobile tires to form a mat on a slope of 2H:1V. Before the mat was installed, drain tiles were placed in the bank to reduce the hydraulic pressure that could build up in the alluvial soil. Cambefort (1976) also used drains equiped with filters to reduce hydrostatic pressures at earth or rockfill dams.

Gantt (1975) reported that small drainage pipe holes or weep holes are installed in bulkheads to release hydrostatic pressure. Weep holes should be protected with filter fabric to prevent soil from washing away (Mulvihill et al. 1980).

15.3. IMPACTS ON THE ENVIRONMENT

Hydraulic wells and drain tiles or pipes have no adverse environmental impacts.

15.4. COSTS

No estimates of costs have been published, to the best of our knowledge.

15.5. EVALUATION FOR USE ON UMRS

If bulkheads, seawalls, and other impermeable structures are built on the UMRS, it will be necessary to install some type of system to relieve hydrostatic pressures. Drain holes, pipes, and tiles would be preferable to wells because they are probably less expensive to install and maintain.

CHAPTER 16. MISCELLANEOUS SOIL STABILIZERS OR HYDROSTATIC PRESSURE RELIEF DEVICES

Many of the measures being considered for reducing soil instability or hydrostatic pressure for upper and lower bank protection are still in the developmental stage. Little or no information is available on possible methods, such as the use of new configurations of used-tire structures, local waste products, artificial clay plugs, military surplus products, or root piles (an array of slender piles driven into the streambank).

Grouting has been used with some success to protect and stabilize streambanks. Grouting is used on riprap when rocks of sufficient size or quality are not available, or when it is desirable to reduce the quantity of rock used for bank protection. The grout is composed of portland cement and aggregates having a maximum diameter of $^3/_4$ in. (Simons et al. 1979). Bank slopes should not be too steep; a 1.5H:1V slope is suitable. Grouted riprap is especially suitable for paving banks of high-velocity channels (Buzzell 1948). Murphy and Grace (1963) rejected grouting as a method to protect overflow embankments from scouring. They chose thick riprap as a more satisfactory and economical method of protecting against the anticipated wave heights and velocity. Lindner (1969) stated that grouted, hand-placed riprap was a possible revetment for riverbanks; however, the armor would rupture unless provision is made for relieving any water pressure. Holes or joints should be left ungrouted to relieve hydrostatic pressure (Buzzell 1948). Grouted riprap is used little in the United States because of the high cost of labor. Underscouring and back pressures can easily lead to the failure of the revetment if the filter material used is improperly installed or unsuitable (Simons et al. 1979). However, when a low sill structure on the Mississippi River collapsed as a result of scouring, and grouting was used to repair the damage, assessments 4 years later indicated that the grouting was effective (Wilson 1978). Peterson et al. (1978) developed a bibliography on the use of grouting around dams and bridges, and for soils.

The potential use of grouting to provide additional protection for riprap revetments is limited in UMRS. Inclusion of adequate drainage to reduce hydrostatic pressure is critical. Filter fabrics are proving effective and economical and have replaced grouting in the lining of many revetments and seawalls.

Another method for stabilizing soil is a soil-cement revetment. Soil-cement is defined as a mixture of natural soils, portland cement, and water; a typical mixture contains 10% cement, by weight, of the dry soil. These revetments have been used since 1947 as slope protection for earthen dams, especially in areas where rock suitable for riprap was not available. Recently they were used successfully to protect 6000 ft of shoreline on the St. Lawrence River and 1500 ft of embankment on the Welland Canal. Considerable savings have resulted from the use of soil-cement rather than

more expensive slope protection and lining materials. Performance to date has ranged from satisfactory to exceptional. Consideration should be given to certain design concepts to prevent damage to the embankment due to leakage through the facing (Dinchak 1980):

1. The weight and strength of the facing is considered to be sufficient to resist any uplift pressures that may develop, particularly since outward drainage through cracks in the soil-cement serves to relieve such uplift pressures.

2. The embankment should be designed so that its least permeable zone is immediately adjacent to the soil-cement facing. This method ensures that any seepage through the facing will not build up sufficient water to produce damaging uplift pressures or to erode the body of the embankment.

3. Free drainage should be provided behind and through or under the facing to prevent uplift.

Soil-cement revetments may be a potential substitute for riprapping where rock suitable for riprap is not available on UMRS. More information is needed, however, on impacts of this type of revetment on the environment and natural resources.

CHAPTER 17. ISLAND CREATION

17.1. SITUATION TO BE MITIGATED OR ENHANCED

River banks that are exposed to long wind fetches (as on some of the larger pools and backwater areas of UMRS) are susceptible to erosion due to wave impact, runup, and backwash. Artificial islands are probably the only method available to reduce fetch in pools and backwater areas of UMRS. In large, open water areas created by the lock and dam system, wind and wave action suspends bottom materials and causes shoreline erosion, resulting in turbidity and the accumulation of sediment. This situation reduces the diversity of aquatic organisms because vegetation cannot grow in unstable areas lacking good light penetration. Vegetation supports increased populations of invertebrates, fish, and wildlife. In addition, the wave-stilling effect of vegetation is not available unless plants are present in sufficient numbers (Kennedy et al. 1979).

Further information on island creation or development is given in Chapter 35.

17.2. DESCRIPTION OF TECHNIQUES

Islands created to reduce wind fetch in pools and backwater areas can be constructed from dredged material obtained directly from maintenance operations in the navigation channel, from a nearby stockpile, from the adjacent bottom area, or from other material shipped to the selected site. A discussion of the use of dredged materials for this purpose is given in Chapter 35. The options discussed in this chapter are limited to oil drilling platforms, industrial islands, and ice containment islands.

Keith and Skjei (1974) described how islands can be constructed in offshore areas. The core of Rincon Island, California, was constructed from quarry stone and the seaward side was protected with tetrapods because they are more stable than quarried stone against wave action.

Garratt and Kry (1978) and Croasdale and Marcellus (1978) reported on the construction of islands for drilling platforms in the Beaufort Sea. Three different construction techniques were used to construct the 15 islands in water depths of 5 to 28 ft. Islands created in summer were built with dredged material and some were protected with synthetic sand-filled bags. In winter, ice was cut on the island site and sand and gravel were moved to the site with front-end loaders. When adequate sand and gravel were in place, the material was pushed into the ice-free hole.

Some of the difficulties encountered in constructing islands in areas with extreme temperatures ranges (+80° to -60°F) include ice action, violent summer storms, scarcity of construction materials, and mobilization of equipment (Riley 1976; Croasdale and Marcellus 1978). Consideration must be given to protect the islands from erosion under these conditions. The use of conventional protection devices (monolithic breakwaters, block revetments, and caissons) is often too costly and time consuming. Instead, shallow, naturally sloping sand beaches (for shallow islands) and synthetic sand-filled bags (3-ton units) or gabions (6-ton units) can be used to protect islands in water 15 to 25 ft deep. The use of gabions or sand-filled bags reduces the amount of fill material required (Croasdale and Marcellus 1978). The islands in the Beaufort Sea were protected from 15- to 25-ft design waves and extreme ice conditions. By 1977 none of the islands had yet suffered major damage (Croasdale and Marcellus 1978).

Bonasia (1975) developed certain criteria for choosing sites for industrial ports on the Atlantic and Gulf Coasts of the United States. The criteria of interest to inland applications include suitable foundation conditions, known nearby sources of sand, moderate tides, and little current. It was believed that slopes of 30 to 1 were more suitable than steeper slopes, which require armor protection.

Danys (1979) reported on the construction of islands in the St. Lawrence River to control ice movement and to reduce the cost of continuous icebreaking for winter navigation. Originally, no armor was placed on any of the islands; however, due to erosion and damage by ice and waves, heavier quarry-run rock was added and berms were installed. In addition, the soft bottom caused substantial settling and instability of the structures. More attention to design and construction would have resulted in fewer repairs and less maintenance work.

The design characteristics of islands built to reduce wind fetch differ from islands created solely for wildlife or fishery uses. For various reasons, the elevation of an island for wildlife uses should not be more than 2 to 4 ft above maximum water levels (Soots and Landin 1978; Keith 1961; Uhler 1956; Johnson et al. 1978). This elevation may not be high enough to reduce the fetch of wind to any meaningful degree. According to Simons and Chen (1977), a structure affects a downwind area 11 to 12 times its height. Thus an island 30 ft high (including tree height) protects an area only 330 to 360 ft long. Spacing between islands should also be considered to further reduce amplitude of waves. Simons and Chen (1977) recommended that islands be placed 3000 ft apart, edge to edge. Islands for wildlife use should be long and narrow, about 0.05 acre in area, and parallel to prevailing winds to avoid damage by wave action (Jones 1975). Fetch-reducing islands would probably not be long and narrow, but crescent-shaped, wider, and larger. These islands would be constructed perpendicular to the prevailing wind to affect the greatest wind area. Islands constructed perpendicular to the prevailing wind require armor protection to prevent severe erosion in high energy regimes.

Generally, islands for wildlife can be designed to allow for use by desirable aquatic and terrestrial species. A silty sand or muddy substrate around the island should be encouraged to promote a more diverse habitat for invertebrates and fish. Stump fields should be left undisturbed because they provide good habitat for centrarchids (Kennedy et al. 1979).

Kennedy et al. (1979) provided several design criteria for the creation of an artificial island for enhancement of fishery habitat:

1. It should be placed in open water areas exposed to significant wind action.

2. Containment and stabilization should be provided with riprap or vegetation.

3. A shallow-water area should be established on the protected side of the island.

4. A deep-water area should be adjacent to the island.

17.3. IMPACTS ON THE ENVIRONMENT

Islands created to reduce fetch result in a more stable area, decreased turbidity, reduced shoreline erosion, increased production of invertebrates and vegetation, and beneficial use of dredged material for wildlife and recreational uses. One minor negative effect is a short-term increase in turbidity during construction (Kennedy et al. 1979; Robinson 1970).

The islands affect a fishery in several ways. With proper substrate, riprap, vegetation, and possible creation of deep holes, an increased food supply and excellent habitat for various species of fish are established. On the other hand, rooted aquatic vegetation accelerates sedimentation, decreases depth of the water, contributes to lower dissolved oxygen concentrations in winter due to decomposition, and creates a high biochemical oxygen demand in the summer. (Further beneficial and adverse impacts of artificial islands created for wildlife are given in Chapter 35.)

Lepetit and Mareau (1976) studied the impacts that artificial islands constructed for industrial purposes have on waves, currents, and shorelines. Using computer calculations they ascertained that a tombolo would be created. For an island 3828 yards, long and 3828 yards from shore, the section of shoreline protected by the island would advance 1.5 ft per year and other sections not protected by the island would recede 0.8 ft per year. An island 2406 yards long, and 2406 yards from shore would cause as yearly advance of the protected shore of 1 ft and a recession of the unprotected shoreline of 0.3 ft. Groins on either side of the island would reduce the volume of

deposited sand. Velocity of the current can be changed by up to 25%, depending on the island's length, width, shape, and distance from shore.

De Groot (1979) reported on the potential environmental effects of building a planned industrial island off the coast of the Netherlands. The time required to build the island by large-scale dredging was estimated to be 8 years. Turbidity created by the dredging would lower primary productivity, and contaminants could be suspended, producing potentially toxic effects. Larvae of sea animals might be severely affected by suspended matter, by lowered oxygen, and by the elimination of food (phytoplankton and zooplankton). In general, however, the adverse effects were expected to be temporary and the environment would be expected to return to preconstruction conditions after 12 years.

Keith and Skjei (1974) observed the ecological effects of the construction of Rincon Island, 0.5 mile off the shore of California. They found 14 species of biota before construction and 298 (divided among 10 phyla) after construction. The new community of fauna included 27 species of algae, but the greatest increase was in mollusks--from no species before construction to 61 after construction. They felt that the effect of Rincon Island on shoreline accretion would be minor because of the distance of the island from the shore and its relatively small maximum width (500 ft). Johnson and Dewit (1978) later found an additional 200 species of animals associated with the island. The island established a new environment with many hard surfaces for attachment by various organisms. The tetrapods that were used provided shelter and habitat for pelagic organisms and mussels that were not present over the adjacent sedimentary bottom area. Also, terrestrial habitat provided roosting areas for a variety of marine birds.

Noble and Dornhelm (1975) found that offshore islands can withstand wave action if properly designed and that proper placement can closely control the environmental impacts of islands on the coastal ecosystem and on the shoreline. They found some scouring and accretion around the islands, but not enough to affect the structural integrity of the islands. In the lee of one of the islands, the diffracted waves of a height of 3 to 5 ft decreased to 2 to 3 ft at the shoreline.

17.4. COSTS

Construction and planning costs for islands made of dredged material are given in Chapter 35. Additional costs would probably be encountered beyond those listed because extensive armor protection would be needed. Costs for riprap and other revetments are given in Chapters 4 and 5.

The construction of artificial islands for oil drilling platforms in the

Beaufort Sea by dredging or onshore stockpiling cost $2.5 to $3 million in 1974. These islands were constructed in water less than 10 ft deep. One of the platforms created measured 225 by 375 ft, and had 10 ft of freeboard; 80,000 cubic yards of gravel were required to construct it (Riley 1976).

17.5. EVALUATION FOR USE ON UMRS

Simons and Chen (1977), who studied the Weaver Bottoms (River Miles 742.5 to 747.5) on UMR near Winona, Minnesota, observed that wind-generated waves exerted tremendous shear stresses on the bottom, resulting in high concentrations of suspended particulate matter. When the fetch length is 4 miles, the depth at high flow is 10 ft, and the wind speed is 15 mph, the resultant wave height is about 1 ft. Such waves have the power to resuspend fine material, increase bed erosion, and interrupt fish and plant life. Simons and Chen (1977), Nielson et al. (1978), and Kennedy et al. (1979) believed that properly designed, constructed, and placed islands would result in improved habitat for fish and wildlife in Weaver Bottoms. Simons and Chen (1977) suggested the possible placement of five man-made islands in Weaver Bottoms (Fig. 31) to significantly reduce wind fetch.

Other pools and backwater areas in UMRS that have wind fetches similar to that at Weaver Bottoms are good candidates for island creation. Simons and Chen (1977) recommended developing physical models to evaluate the merits of certain characteristics (numbers, sizes, spacing, heights, and vegetation) for reducing fetch. Kennedy et al. (1979) cautioned that island creation should only be an enhancement method, and must be site specific.

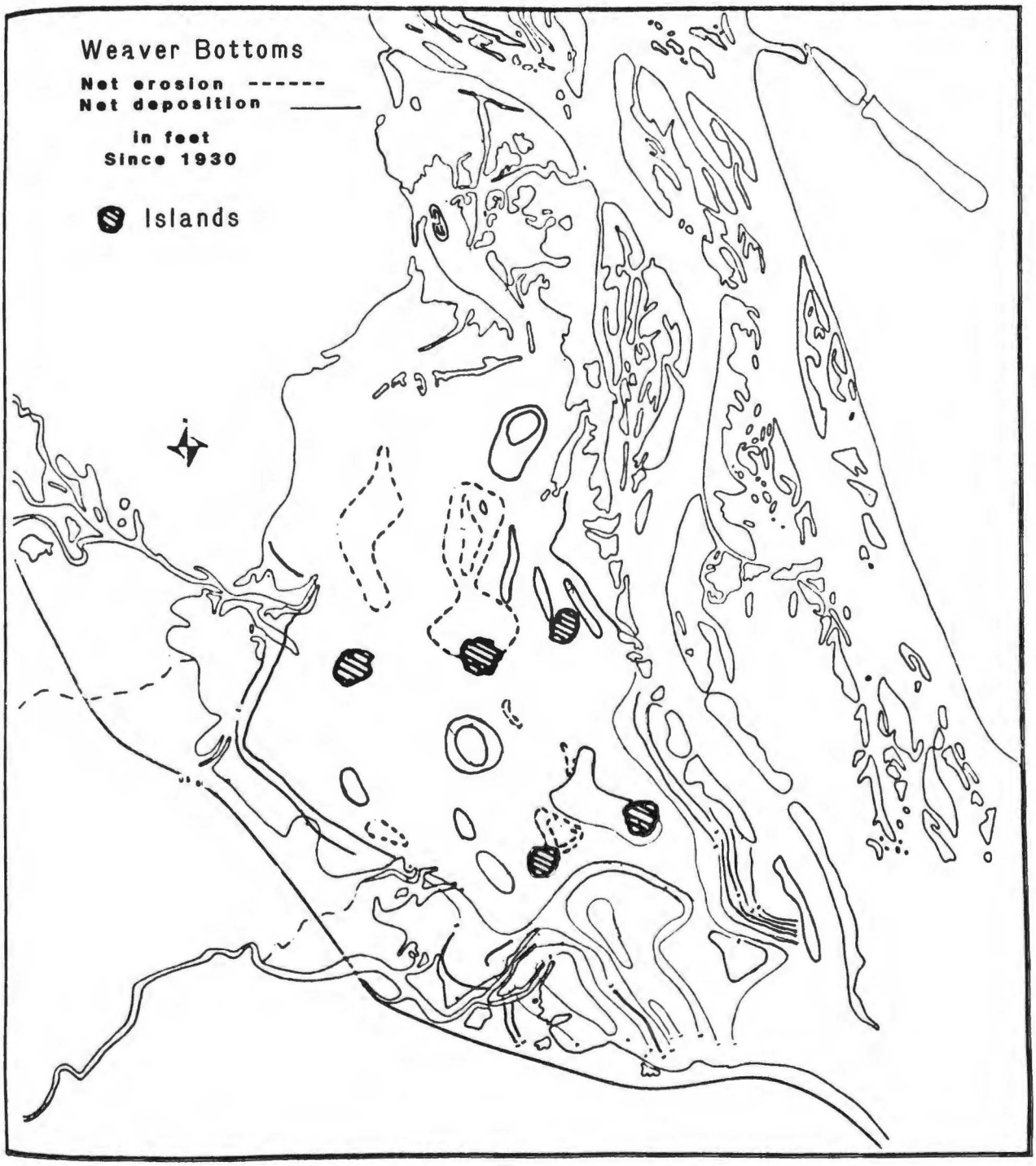


Fig. 31. Example of possible placement for wave-control islands in Weaver Bottoms, UMR (Simons and Chen 1977).

CHAPTER 18. BERM CREATION AND BEACH ENRICHMENT

18.1. SITUATION TO BE MITIGATED OR ENHANCED

The creation of berms and enrichment of beaches are two ways of dissipating wave energy and preventing wave action from reaching the river bank or backshore (Great Lakes Basin Commission 1975; U.S. Army Coastal Engineering Research Center 1966). This process has been used to protect shorelines and bluffs around the Great Lakes and along the coastal United States. Beaches can also enhance recreational potential. In the past, groins have been used to create or restore beaches, but they are successful only if littoral drift or current parallels the existing or proposed beach. However, groins reduce drift to downstream sites and are not effective against direct attack by waves. Berms, sills, or perched beaches are terms for structures at or just in the water parallel to the shoreline. When used in this way, berms are neither a revetment nor a breakwater (Payne 1980).

18.2. DESCRIPTION OF TECHNIQUES

Beaches can be considered a shore protection structure because they dissipate wave energy before it reaches the adjoining backshore (U.S. Army Coastal Engineering Research Center 1966, 1977). To insure that beaches perform this function, they must be formed, restored, or maintained. Beach material can be obtained by dredging sand out of a navigation channel. The material can be deposited directly on the beach or stockpiled for later placement. When material is stockpiled upstream from a beach, it can drift naturally downshore to replenish the beach. Stockpiled material can also be mechanically transported to the beach; this operation is called sand bypassing and is usually used where littoral barriers, such as breakwaters or jetties, have been installed near inlets that need to remain open (U.S. Army Coastal Engineering Research Center 1977). The basic types of sand-bypassing plants are fixed, floating, and land-based. Such devices have been used extensively along United States coastal areas and by other countries where eroding beaches and inlets must be kept open (Anonymous 1978; Nishimura and Lau 1978, 1979; U.S. Army Coastal Engineering Research Center 1977).

Construction of an adequate artificial beach requires that a number of determinations be made (Great Lakes Basin Commission 1975):

1. Determination of the predominant direction of littoral transport, and of whether the supply of material is deficient in the problem area.

2. Determination of the composite average characteristics of existing beach material or native sand.

3. Evaluation and selection of borrow material for initial beach fill and periodic nourishment.

4. Determination of the needed beach elevation and width and of the wave-adjusted foreshore slope.

5. Determination of whether structures such as groins are needed to maintain a stable beach at a reasonable cost.

Having made these determinations, an engineer can design a beach of proper height, width, slope, and sand size to meet the requirements of the area (Sanko 1975; Shuisky and Schwartz 1979).

Since many bank stabilization structures interfere with the recreational use of beaches, artificial nourishment of beaches in the Great Lakes has been promoted (Hanson et al. 1978; Sanko 1975; Armstrong 1976). Armstrong (1976) cautioned that artificial nourishment should not be used in areas with strong littoral currents that rapidly remove the sand.

Armstrong (1976) reported on two beach nourishment projects on the Great Lakes. One project, with a groin, was stable, long-lasting, and required little maintenance. The other project, without a groin, remained stable for only 1 year. Much of the sand then dispersed, leading Armstrong to conclude that a groin system was necessary if a beach was to be maintained for a longer time. Roelling and Hiipakka (1978) also reported on mitigation of shore erosion in the Great Lakes by beach enrichment. Erosion of beaches occurs at an annual rate of as much as 3.9 ft at several sites along the Upper Great Lakes. Beaches can be enriched by transferring sand pumped during normal maintenance dredging of harbors. In addition, a portable sand-bypassing method developed by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, would allow the bypassing of sand at harbors. Roelling and Hiipakka believed that, in the future, permanent sand bypassing plants with buried pipelines could be installed to correct the problem.

A stable beach provides good protection against land erosion, but the methods used to build or maintain a beach are usually costly and temporary (Payne 1980). Beach stabilizers in the form of berms have been used for many years. "Perched beaches," berms, or sills constructed of sand- or grout-filled fabric bags, concrete blocks, or gabions have been tested in the Chesapeake Bay and along the Massachusetts shoreline as low-cost erosion control structures (Fig. 32). These structures allow sand to accumulate on both sides and provide protection of the backshore (Gutman 1979).

Only interconnected structures can apparently withstand the force of breaking waves; even concrete blocks fastened together with bars are not stable enough to withstand the forces of breaking waves (Payne 1980). A Beach

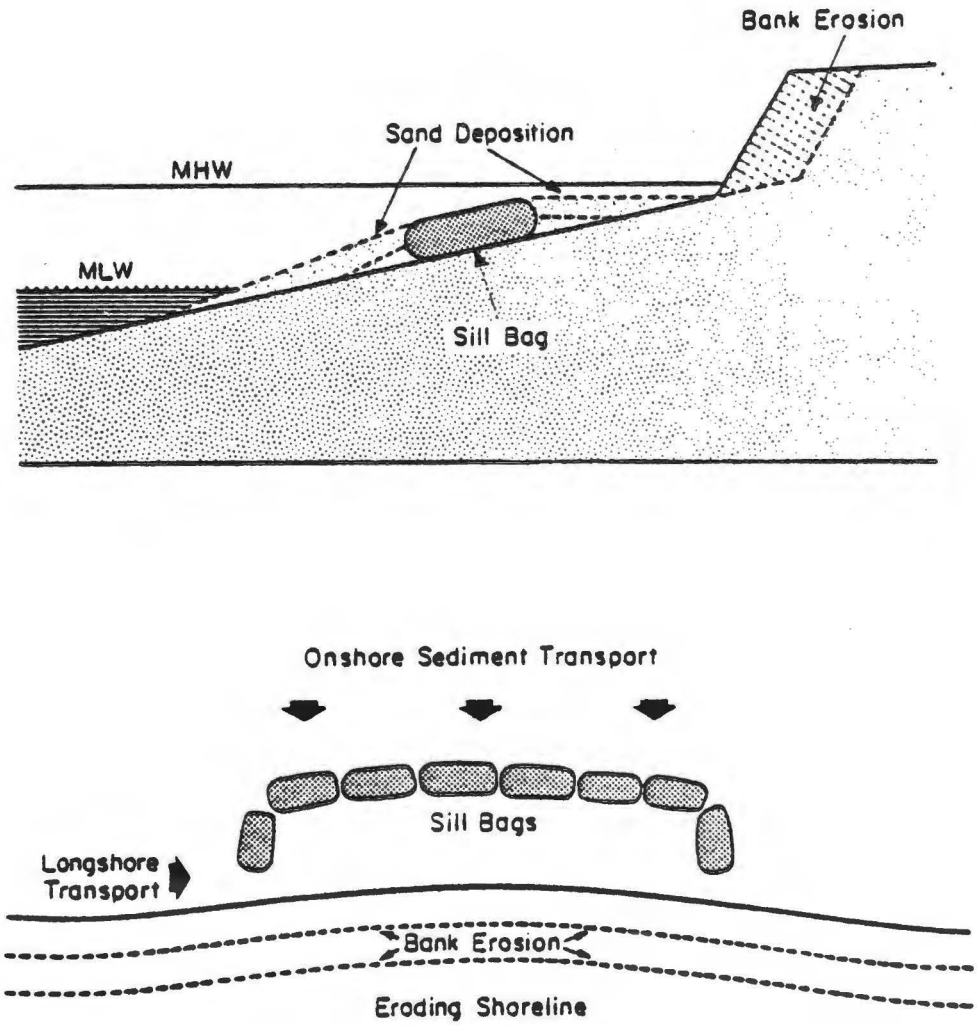


Fig. 32. Schematic section (upper panel) and plan view (lower panel) of a perched beach, constructed of sand-filled bags (Gutman 1979).

Prism has been developed, which consists of a series of triangular prisms made of concrete, reinforced with steel or glass fibers, and held together by three stainless steel cables (Fig. 33; Payne 1980; Wilder and Koller 1971). These prisms are available in heights of 1.7 to 5 ft. A major advantage is that the assembled prisms can be transported to the installation site by many different methods.

Berms can also be used to protect river banks. Thomson and Townsend (1979) reported on efforts to stabilize the banks of the North Saskatchewan River, Edmonton, Alberta. Low-level erosion protection berms were used to stabilize the toes of banks where lateral erosion had occurred. The berms were constructed of river gravels and cobbles with 2 to 1 slopes. The berms were protected with armor stones (2.0 to 5.9 in. in greatest dimension); the size of the stone used depended on flow velocities.

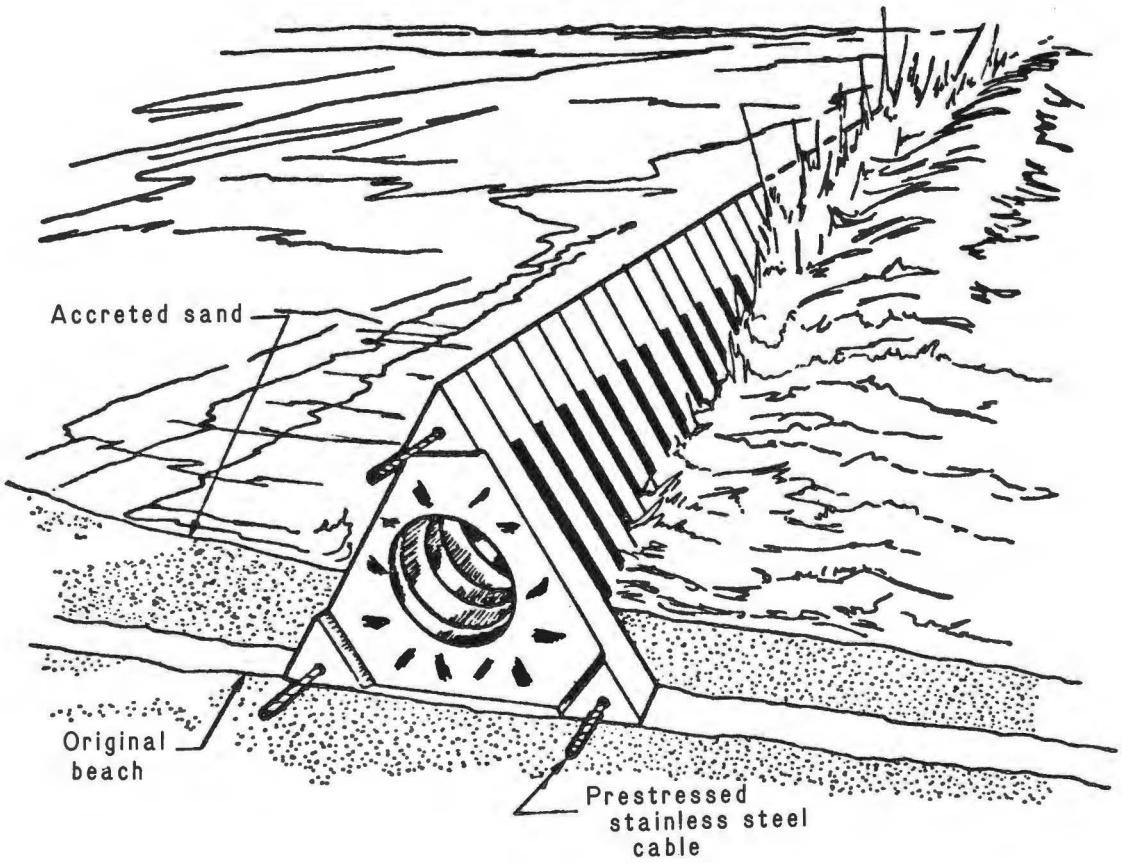


Fig. 33. Schematic section of a Beach Prism installation which has just started to accrete sand (Payne 1980).

18.3. IMPACTS ON THE ENVIRONMENT

There are at least three advantages of berm creation or beach enrichment (Great Lakes Basin Commission 1975; U.S. Army Coastal Engineering Research Center 1977; Armstrong 1976):

1. Beaches have considerable recreational value and may be aesthetically pleasing.

2. Beach enrichment remedies the basic cause of most erosion problems--that is, a deficiency in the natural sand supply--and therefore benefits rather than damages downdrift shorelines.

3. Beaches are a fine protective device against erosion of a backshore.

If beaches are to protect a backshore, they must be stable and the rates of supply and loss of material must remain the same over a significant period of time. If the rate of loss exceeds the rate of supply, the beach erodes and thus offers only temporary protection (U.S. Army Corps of Engineers, Washington, D.C. 1971; Payne 1980). Protective measures are sometimes used that accelerate erosion of adjacent shorelines. Shoreline protection of beaches calls for comprehensive planning that considers erosive processes over the total shoreline.

Groins and other protective devices that have been used to protect beaches have sometimes resulted in the starving of other areas that need sand nourishment: the protective structures may themselves cause additional problems. Marks (1977) found that beaches in the Great Lakes not protected by groins failed because the fill could not be held. Maintenance of beaches in Hawaii and Georgia required several groins and breakwaters to protect the sand placement (U.S. Army Corps of Engineers, Honolulu, Hawaii 1973; U.S. Army Corps of Engineers, Savannah District 1973; Oertel et al. 1977).

Another problem sometimes associated with artificial beach construction is the lack of an inexpensive supply of suitable beach material (Great Lakes Basin Commission 1975). This is not a general problem on UMRS, but may be a problem in certain localized areas.

Synthetic sand- or grout-filled bags usually withstand breaking waves up to 6 ft and survive 3 months of ice cover. They do not perform well if storms do not permit accretion of sand to occur (Gutman 1979). Bags do not settle and they are durable, but they are subject to vandalism, and foot or vehicular traffic can cause damage.

In some sections of the country, regulations prohibit the use of any structures that interfere with littoral drift or starve downdrift beaches of sand. In some localities only short structures, less than 500 ft long, are allowed because they rapidly fill to capacity and allow further littoral drift to continue down the shoreline (Gutman 1979).

When berms were built along the Sacramento River to protect flood levees from erosion (Mifkovic and Petersen 1975), much of the riparian vegetation was lost during construction or through erosion of unprotected berms and levees.

Recommendations were made that the berms be restored by protecting the toe with stone and filling in the eroded area. In addition, revegetation was recommended for the areas where vegetation was lost during construction.

18.4. COSTS

Sanko (1975) advocated the use of beaches to protect Great Lakes shorelines because he believed that they were the most economical structures available. The costs vary widely, depending on conditions, location of material, length of the shoreline, and the amount of periodic maintenance required. Armstrong (1976) reported on two sites used for beach enrichment projects under a demonstration and research program for low-cost shore protection on the Great Lakes. In Tawas City Park on Lake Huron, 4350 cubic yards of sand fill were used to protect 400 ft of shoreline, at a cost of $20 per foot. If the cost of a timber groin built to protect the project is added, the cost was $80 per foot (1974 prices). East Tawas, also on Lake Huron, received 3000 cubic yards of fill for 400 ft of shoreline. The fill cost $15 per foot.

Others have estimated that beach enrichment costs ranged from $50 to $400 per foot of shoreline for the initial fill. Costs depended on wave exposure, proximity of suitable fill, length of beach, and degree of restoration desired. (Great Lakes Basin Commission 1975; U.S. Army Corps of Engineers, Washington, D.C. 1971). Maintenance of the new beach may be required every 1 to 5 years; maintenance costs range from $5 to $15 per foot per year for beaches at least 2000 ft long. The U.S. Army Corps of Engineers, Washington, D.C. (1971) determined that it was impractical and uneconomical to enrich small beaches without providing other protective structures, such as groins or retaining walls.

The cost for UMRS applications depends on the proximity of the beach to the main channel and whether there is dredging in the area.

Payne (1980) reported costs for beach nourishment and for the Beach Prisms. The cost of dredging (at 1977 prices) was $88 per foot for beach nourishment and $88 per foot for 50 years of maintenance--a total of $176 per foot. The 1979 costs of the Beach Prisms of different heights were as follows: 1.73 ft, $20; 2 ft, $30; 3 ft, $45; 4 ft, $65; and 5 ft, $80.

Gutman (1979) wrote that sand- or grout-filled fabric bags installed in the Chesapeake Bay and along the coast of Massachusetts cost $10 to $15 per linear foot.

Thomson and Townsend (1979) found that gravel berms constructed on the

North Saskatchewan River cost about $48 per foot in one area at 1972 prices and $96 per foot in another area at 1977 prices. The increased price in 1977 was largely due to costs for transporting fill material over long distances.

18.5. EVALUATION FOR USE ON UMRS

The use of beach nourishment or berms on UMRS to protect river banks has merit, particularly along areas where beaches are used extensively for recreational purposes and where beaches have historically protected public and private shorelines from bank erosion. Careful consideration is needed in maintaining beaches because the beaches affect downdrift shorelines. This is particularly true of beaches on enriched barrier islands adjacent to the main channels. Side channel openings fill in quickly from eroding beaches, and thus may cut off sources of fresh water to the backwater areas.

Fremling et al. (1976) recommended that a berm be constructed on the marsh side of dikes placed in cuts at the Weaver Bottoms (near Winona, Minnesota) to protect that area from the impact of erosive processes of the Mississippi River (e.g., wave action, sedimentation, etc.). They recommended that the berm be adjacent to the fringe of willows and other shrubs that borders the marsh, that both the dike and berm be smoothed and shaped with a bulldozer, and that the berm be planted with a mixture of shrubs and trees.

CHAPTER 19. WATER LEVEL CONTROL

19.1. SITUATION TO BE MITIGATED OR ENHANCED

Water level fluctuations can cause river banks, bluffs, and shorelines to become unstable and erode. This erosion contributes to turbidity, loss of fish and wildlife habitat, and a reduction of aesthetic quality (Klimas and Allen 1981). The banks along UMRS are stratified and consist of layers of noncohesive materials subject to surface erosion. Failures of this type of bank may be induced by the presence or absence of water. Changes in the river stage as a result of the storage and release of water for hydroelectric and navigation purposes, even though relatively small, can cause adverse flow conditions within the banks.

19.2. DESCRIPTION OF TECHNIQUE

Franco (1965) analyzed the effects that changes in river stages have had on five revetted riverbanks and on an eroding bank on the Lower Mississippi River near Vicksburg, Mississippi. The study was conducted to develop data that would help predict flow failures along revetted riverbanks. A number of general conclusions were reached after evaluation and analysis of the data:

1. Either scouring or filling could occur along a given riverbank during high flow, depending on the alignment and configuration of the river channel.

2. The amount of scouring or filling along a given riverbank during high water appears to be more a function of river stage and its duration than of the rate of change in stage.

3. Conditions are less favorable for stability of a riverbank when scouring occurs during the higher river stages.

4. The tendency for scouring landward of the end of a revetment is generally greater when the end of the revetment does not extend to the thalweg.

5. There is less tendency for scouring landward at the end of a revetment when deposition occurs during high-water periods.

6. A definite pattern for conditions leading to bank caving could not be established from the information available. It appears that caving of the upper bank can occur during a rising river stage without erosion of the lower bank.

7. As judged by scouring and shoaling patterns, it appears that if the ends of the revetments are to be placed as deeply as

possible without dredging, construction should be scheduled during the early part of the low-water season along banks where scouring occurs during high water, and during the latter part of the low-water season where shoaling occurs during high water.

8. Conditions affecting the stability of the banks and revetment were more severe at False Point, Reid-Bedford, and Marshall-Browns Point, in that order, than at the other locations surveyed, as judged on the basis of (1) scouring of the channel bed during high stages, (2) the height of the top of the bank above the maximum thalweg depth, (3) the amount of scouring under the revetment, and (4) the amount of scouring landward of the ends of the revetment.

9. The stability of any revetments placed at Kings Point should not be severely affected by river currents.

10. In general, the effects of river currents on the stability of a riverbank are more a function of the alignment of the channel upstream (which affects the direction of currents toward the bank) than of the curvature of alignment of the bank.

11. The relative effects of river currents on the stability of a riverbank can be determined from a study of the alignment of currents approaching the bank from upstream during low and high water stages, or by spot surveys to determine maximum depths along the bank during the period just preceding the start of the high-water season and by one or two surveys during the high-water period.

In the Great Lakes, extreme erosion of shorelines and bluffs has been associated with water level fluctuations. The average distance of bank recession is 12.5 ft per year. The average recession rate increased along with the lake level and decreased in 1974 when the lake level stabilized and no major storms occurred (Birkemeier 1980). The International Great Lakes Levels Board concluded that only limited control can be exercised over Great Lakes water levels and that only limited information was available on the impacts of various water level plans on shorelines, wetlands, fisheries, and water quality (University of Wisconsin-Madison 1976). This lack of control is also a problem on UMRS.

More details and general descriptive information on water control structures and management of water levels and flows are given in Chapters 27, 28, and 39.

19.3. IMPACTS ON THE ENVIRONMENT

Born and Stephenson (1973) listed the following environmental impacts of water level fluctuations associated with management practices for hydropower and flood control in the Chippewa Flowage, Wisconsin: degradation of water quality, decline in fisheries, shoreline erosion, decline in littoral zone fauna and flora, and impairment of shoreline aesthetics. To prevent excessive shoreline erosion, the authors advocated a drawdown of the reservoir by 3 ft in November and rapid filling in the spring to limit the amount of littoral zone subject to erosion from snowmelt and rainfall. The reservoirs should remain nearly full to provide optimal recreation and to allow wave energy to be dissipated lakeward.

Simons et al. (1979) evaluated the forces that cause bank erosion in the Connecticut River. The relative magnitude of the forces causing bank erosion was qualitatively assessed and rated on a scale from one to nine in ascending order of their estimated effect. Pool fluctuations were rated from three to five for noncohesive banks and three to four for stratified banks. Conditions evaluated included natural rivers with low banks (<15 ft) and high banks ($\geq$15 ft) and pools with low and high banks, with or without vegetation. The greatest impact was associated with high banks with or without vegetation. Simons et al. (1979) estimated that the stability of the banks on the Connecticut River and in the pools would increase 15 to 18% if hydro-pool fluctuations could be completely eliminated or maintained at selected static pool levels for 30 days or more. This management of fluctuation would reduce bank erosion by 7 to 9% but the gain in erosion control would be offset by losses in power generation. Born and Stephenson (1973) also found that management of a reservoir to control erosion may conflict with power production and flood control needs. Winter drawdowns that limit power production and reduce storage capacity could increase the likelihood of spring flooding. On the other hand, good spawning and nursery habitat for fish is often provided if a reservoir is filled in spring.

Bhowmik et al. (1980) found that "pool level fluctuation within a normal range of water surface elevations will have little physical effect unless the rate of change is rapid enough to cause sloughing of banks."

Further details on adverse or beneficial impacts on the environment are given in Chapters 27, 28, and 39.

19.4. COSTS

Cost details and information are given in Chapters 27, 28, and 39.

19.5. EVALUATION FOR USE ON UMRS

Along UMRS, stratified banks consisting of layers of noncohesive materials are subject to erosion. Failures of this type of bank may be induced by the presence or absence of water. Changes in the river stage as a result of the storage and release of water for hydroelectric and navigational purposes, even though relatively small, can cause adverse flow conditions within the banks. Any gain in erosion control by water level manipulation may not be enough to offset losses to navigational and hydroelectric operations. In some reservoirs, only a 7 to 9% reduction in erosion would result from regulation of water level fluctuations. Further study is needed to determine if any regulation of water levels on UMRS would result in significant erosion abatement. Water level management would significantly benefit fish and wildlife resources of UMRS.

CHAPTER 20. REGULATION OF BOAT TRAFFIC

20.1. SITUATION TO BE MITIGATED OR ENHANCED

The environmental effects of boat traffic in river systems have not been evaluated in detail. Although the physical hydraulic effects have been determined to estimate the biological impacts at a specific location, no systematic or accumulative analyses have been completed to take into account the vast ecological differences among river systems. Both recreational and commercial boat traffic produce complex interrelations of physical, chemical, and biological factors that result in adverse impacts on the river system. Commercial barge traffic can cause increased shoreline erosion, turbidity, resuspended sediments, and changes in waves and water velocity (UMRBC Environmental Work Team 1981d).

Bank erosion occurs throughout UMRS. About 15% of that along the Illinois River is caused by wind- and boat-generated waves. Similar types of problems exist along the Mississippi and Ohio rivers. Demissie et al. (1981) noted that "Erosion of stream banks attracts public attention, reduces property values, results in permanent losses of real estate, increases turbidity, and accelerates the silting of reservoirs or backwater lakes along the stream course."

About 8% of the 7 million miles of streambanks in the United States have been damaged by erosion (Lubinski et al. 1981). Resource managers and engineers recognize that commercial and recreational boat traffic reduces streambank stability. Both types of traffic can generate waves high enough to erode river banks or shorelines. The height of waves generated by boats depends on a number of factors: draft, speed, length of boat, distance between boat and wave gage, and depth of water (Bhowmik 1975; Camfield et al. 1980). Subsurface energy generated by larger vessels causes drawdowns and changes in pressure and velocity that disturb substrates by suspending bed material and adversely affecting water quality and aquatic organisms (Camfield et al. 1980; Bumm et al. 1973; Lubinski et al. 1981; Herricks and Gantzer 1980; Sparc s 1975a). The amount of material resuspended and the degree of change in velocity and pressure depend on the size, speed, horsepower, and propellers of boats; space between boat and river bottom; frequency of boat traffic; characteristics of bed material; and the location of breaking waves (Bhowmik et al. 1980; Johnson 1976b; Karaki and Van Hoften 1974; Liou and Herbich 1976; Lubinski et al. 1981; Yousef et al. 1980).

Sediment movement into backwater areas is a major problem on UMRS. Barges resuspend and redistribute sediment particles in a river and transport them in a lateral direction. Studies on UMR have demonstrated that the concentration of suspended sediments sometimes increases twofold to threefold after the passage of tows, and the ambient sediment concentration remains

elevated for a short period after a number of barges pass (Bhowmik et al. 1981d). During one such passage, suspended sediment increased twofold for about 15 to 20 min after a barge passed. Other study results indicate that flow velocity drops immediately before barge passage and fluctuates before returning to normal levels (Lee et al. 1981).

Increased bank erosion, turbidity, and sedimentation have significant adverse impacts on the biota of UMRS. Impacts to be mitigated were discussed in Chapter 2.

2 0.2. *DESCRIPTION OF TECHNIQUES*

The magnitude of the effect that boat traffic has on bank stability, turbidity, resuspension of sediments, and drawdown depends on the factors listed in the preceding section, some of which could be regulated. To mitigate the erosive forces and other adverse environmental conditions generated by boat traffic, regulatory measures could (1) restrict speed or horsepower; (2) decrease permissible draft of vessels; (3) restrict the volume or frequency of boat traffic; (4) restrict seasonal navigation; (5) require improved maneuvering devices and techniques; or (6) maintain off-limit zones between boats and river banks.

Simons et al. (1979) recommended two measures to reduce the impact of boat waves on bank stability of the Connecticut River, in an effort to reduce bank erosion by 5%: (1) set maximum speed allowed for power boats at 5 mph, and (2) restrict an area 25 to 50 ft from the shoreline as a "no traffic zone."

The most critical time for biota occurs from late spring through early fall when the organisms are reproducing and growing (Lubinski et al. 1981). Commercial and recreational traffic increases in intensity and frequency during these seasons, causing wave action and turbidity.

The Academy of Natural Sciences of Philadelphia (1980) reported on the possible impacts associated with increased barge traffic on the Ohio River:

> "It is expected that barge traffic will increase from 1976 levels of 8 upbound, loaded tows/day to 12 and 20 upbound, loaded tows/day in 1990 and 2040, respectively. Approximately 10% of the these will, in later years, be in excess of 4500 horsepower. Of the ten test transects located on the Ohio River, only one will experience turbidity related impacts 2 kg/m^3 after passage of a maximum hp tow (upbound, loaded) during normal flow conditions. Duration of turbidity levels above ambient would persist for less than 35 min and generally for less than 15 min (with only 5 exceptions being recorded out of 30 test situations). The zone of impact is expected

to extend to a 60-ft wide band in the channel area centered around the tow operating in a river which is generally wider than 1000 ft. Thus turbidity effects are minimal.

"Other impacts from wave wash and back flow velocities are considered even less significant as wave heights are normally less than 4 in. and backwater flow velocities are usually well under 1 ft/sec. According to Louis Berger and Associates, Inc. (1980) it would take 50 tows to deliver as much energy to the river banks as a 4-h storm with wind velocities of 40.0 ft/s. However, propeller jet flow velocity may cause direct physical damage to benthic organisms and propeller entrainment may kill pelagic or drifting animals."

Lubinski et al. (1981) pointed out that the study by the Academy of Natural Sciences of Philadelphia did not address "impacts of littoral phytoplanktonic production in fine-grained sediment areas if the material was continually winnowed from wave-caressed river banks." In addition, no actual field measurements were taken to verify their conclusions. Bhowmik et al. (1980) stated that all effects associated with boat traffic occur along the entire UMRS and that the amount of traffic, especially by commercial barges, and the channel geometry, determine the magnitude of the effect on sediment movement and deposition. They recommended further study of each class of vessel in each season of the year to help predict the actual effect in any particular stretch of river. Comparisons should also be made with data on wind-generated waves to determine the relative impact these two types of waves have on bank erosion and sedimentation. In fact, before any changes in the regulation of boat traffic occurs, information must be developed to fill the following data gaps identified by Bhowmik et al. (1980):

1. Amount of resuspension of sediment by vessel propeller jets and velocity and pressure fields.
2. Lateral movement of resuspended sediment.
3. Extent of pulse inputs into side channels and backwater lakes.
4. Spectra of waves generated by wind and vessels.
5. Velocity and pressure fields caused by vessels in the main channel and channel borders.
6. Histories and projections of wind and of vessel traffic.
7. Extent of bank erosion by waves caused by winds and boats.
8. Seasonal considerations for waves, traffic, and bank erosion.
9. Accidents.
10. Vessel wastes and pollution.

Blaauw and Van de Kaa (1978) developed a method to determine what types of bottom protection materials are needed, given a barge's horsepower and the diameter of its propeller. Propeller wash can move channel sediments and create turbidity, and the level of effect is related to the draft, speed, frequency of traffic, size and type of propeller, horsepower, and channel configuration (UMRBC Environmental Work Team 1981b, 1981c).

The potential for accidents could be reduced if certain devices and techniques were used to improve maneuvering and stopping abilities of large vessels (Card et al. 1979). Devices and techniques that might be used include bow thrusters, twin screws and twin rudders, steerable Kort nozzles, slower approach speeds, and turning in lieu of stopping when space permits. Most barges on inland waterways have flanking rudders that are used to negotiate sharp bends, approaches to locks, and critical reaches (Franco 1976). Bow steerers, for various reasons, are not in general use. Rudder angle measurements indicate that centerline stops for the steering rudders would improve underway efficiency (Schulz 1978). Louis Berger and Associates, Inc. (1980) studied potential structural and nonstructural alternatives for increasing navigation capacity to increase efficiency of operation. Bow thrusters promote safety and reduce transit times by improving the maneuverability of barges.

The U.S. Coast Guard (1977) and the U.S. Department of the Army, Chief of Engineers (1975) have authority over navigation and have developed rules and regulations that vessels must follow. For example, the U.S. Coast Guard enforces regulations on special equipment, machinery, hull requirements, operations, special construction, arrangement of barges, provisions for carrying certain dangerous flammable or combustible cargoes in bulk, and pollution prevention. The U.S. Army Corps of Engineers has developed navigation rules and regulations for the Ohio River and the Mississippi River above Cairo, Illinois, and for their tributaries. These rules concern authority of lockmasters, safety of vessels using navigation locks, reporting of navigation incidents, precedence at locks, unnecessary delays at locks, lockage of recreational craft, simultaneous lockage of towboats with dangerous cargoes, stations while awaiting lockage, stations while awaiting access through navigable passes, signals, rafts, entrance to and exit from locks, mooring, draft of vessels, handling machinery, refuse in locks, damage to locks or other structures, restricted areas at locks and dams, operations during high water and floods in designated vulnerable areas. Thus both agencies have the authority to implement regulations that might reduce erosion or turbidity.

Anklam (1971) surveyed potential nonstructural, low-cost waterway system improvements that could be used to solve a number of problems associated with near-capacity traffic conditions on the Mississippi, Ohio, and Missouri rivers instead of investing in major construction activities. Possible improvements

included changes in operating procedures of the locks, revisions of the operating rules for towboats approaching and using locks, and provision of adequate staff for operation and supervision of the locks.

20.3. IMPACTS ON THE ENVIRONMENT

Simons et al. (1979) estimated that bank erosion on the Connecticut River could be reduced by 5% if boat speed and zoning were regulated.

It is difficult to quantify the causes of erosion at a particular location, even though barges may be suspected of causing some of the erosion. Sorenson (1973) and Karaki and Van Hoften (1974) considered the various factors involved in wave energy from boat traffic and the resultant impact on shorelines. (For a detailed discussion of this topic see Chapter 3.)

Sparks and Thomas (1978) sampled areas in the upper Illinois River to determine the effects of barge traffic on suspended particulate matter and turbidity. They collected samples before, during, and after locks were closed and barge traffic was stopped. The suspended particulate matter was highest during the period before lock closure, declined to a minimum 4 to 8 weeks after closure, and increased sharply 4 to 5 weeks after the locks were reopened. Concentrations of suspended solids increased by an average of 30 to 40%. Similar results were noted on the Kaskaskia River (UMRBC Environmental Work Team 1981c).

If off-limit zones were enforced for barge traffic, the effects on backwaters and shorelines could be lessened. In studies on Pools 9 and 26 of UMR, tows were observed outside the normal navigation channel about 30% of the time. The velocity increase observed in the backwater areas, along with the associated resuspension and deposition of sediment, would have been reduced if the barges had been farther from the affected areas (UMRBC Environmental Work Team 1981d).

GREAT I (1980c) and GREAT II (1980d) reported the volume and limitations of commercial navigation on UMRS. The Rock Island District had 30 million tons of cargo and the St. Paul District 20 million tons. Both Districts claimed that commercial traffic was far less than what the river can support. Nonmarket regulatory constraints that limit commercial traffic (GREAT I 1980c) and adversely affect the economy include restrictive bridges, governmental regulation, user charges, and predesignated closing and opening shipping dates.

Other authors have listed various effects of barge regulation that may

adversely affect the economic operation of barges: Anonymous (1977), Binkley et al. (1978, 1979), A. T. Kearney, Inc. (1980), Christianson (1974, 1975), Hill et al. (1978), U.S. Army Corps of Engineers, North Central Division (1981), and U.S. Department of Transportation (1975).

On the other hand, the Environmental Work Team of UMRBC recommended in their final report that "No increase in commercial traffic should be considered until extensive mitigation and enhancement measures are instituted to correct existing problems, and an adequate data base is available to make decisions regarding the extent of future impacts" (Rasmussen 1981).

The UMRBC also recommended in their Comprehensive Master Plan for the Management of the Upper Mississippi River System that certain measures be taken to regulate barge traffic (UMRBC 1982):

1. As part of a total navigation improvement plan, steps are to be undertaken to increase the capacity of specific locks throughout the system by employing certain non-structural measures and making minor structural improvements.

2. Traffic movements on the navigation system should be monitored to update traffic projections, verify lock capacities, and refine economic justifications and implementation dates for future expansion of capacity.

The measures that are selected should be the most environmentally acceptable, cost-effective, and efficient techniques available. The measures recommended include kevels, switchboats, helper boats, and relief of air entrainment in culverts.

20.4. COSTS

Costs have not been developed for the regulation of commercial or recreational boat traffic.

20.5. EVALUATION FOR USE ON UMRS

Possible techniques for mitigating adverse impacts of boat traffic on enviromental resources include restricting speed or horsepower (or both), decreasing the draft of vessels, restricting the volume or frequency of boat traffic, restricting seasonal navigation, using improved maneuvering devices and techniques, and maintaining certain off-limit zones between boats and river banks. All of these measures could be used in UMRS but they may have an adverse economic impact on the navigation industry. The regulation of boat

traffic on UMRS has some merit, but systemic and accumulative analyses are necessary before an adequate understanding is reached on the direct effects of boat traffic on the environmental resources of UMRS and other large river systems. When scientists have determined the qualitative and quantitative effects of navigation in different situations, improvements to be gained by regulating boat traffic can be determined.

PART VI. DREDGING AND DISPOSAL OF DREDGED MATERIAL

Dredging is defined as a process by which sediments are removed from the bottom of streams, lakes, and coastal waters; transported by ship, barge, or pipeline; and discharged in open water or on land (Lagasse 1975). The principal purpose of dredging is the creation and maintenance of waterways for commerce, recreation, and defense. Rapid siltation from urban, industrial, and agricultural sources often compels continual dredging to maintain navigable channels. On UMR, dredged material resulting from channel maintenance is primarily sand originating from upland and streambank erosion (GREAT II 1980a). Waterborne commerce is vital to the economic viability of the United States and the only alternative to dredging to maintain waterways is to control the influx of sediments from the watershed (Brady 1976; Saucier 1978).

The capacity of moving water to erode, transport, and deposit sediments is largely a function of its velocity and degree of turbulence, and the physical characteristics of the sediment (Morton 1977). In large river systems, alluvial sediments settle out and clog harbors and navigation channels. The act of dredging alleviates the problem caused by filling-in of waterways by removing the sediment and thus allowing waterborne commerce to continue. Maintenance dredging is essential to keep channels navigable because they are rapidly filled in by natural and man-induced sediment loads. The problem of how to dispose of dredged material is a side effect of dredging.

Most of the recent information about research on dredged material has come from the 5-year U.S. Army Corps of Engineers Dredged Material Research Program (DMRP). An index containing abstracts of over 200 DMRP reports is available as a reference for the specific projects covered within the program (Herner and Co. 1980). A literature review by Morton (1977) on dredging and dredged material disposal included a discussion of environmental impacts on freshwater habitats. A more recent literature review on the effects of navigational dredging on fish and wildlife was compiled by Allen and Hardy (1980). The authors included the DMRP reports, as well as other recent significant studies, and provided information on dredging equipment, characteristics of dredged material, and the assessment of dredging and disposal in coastal waters, rivers, and the Great Lakes.

CHAPTER 21. DREDGES, DREDGING METHODS, AND DISPOSAL OF DREDGED MATERIAL

21.1. SITUATION TO BE MITIGATED OR ENHANCED

The effects of dredging on the environment are influenced by conditions at the dredging site, by the composition of the dredged materials, and by the different types of equipment used to remove and dispose of the material. The operation of dredges causes the removal of benthos, resuspension of sediments, and change in water quality (GREAT II 1980g). Depending on the nature of the sediment, aquatic organisms may be adversely affected by heavy metal uptake, fluff coverage, oxygen depletion, and reduced photosynthesis.

Turbidity caused by dredging can adversely affect (1) life functions of fishes; (2) photosynthetic processes, nutrient uptake, dissolved gas exchange, abrasion and direct coverage of plant communities in channel border areas; (3) susceptibility of invertebrates within main channel and main channel border areas to localized exterminations, turbidity effects, and coverage; and (4) flora and fauna, by release of contaminants from polluted sediment (UMRBC Environmental Work Team 1980d).

Most of the concern associated with the disposal of dredged material involves the effects of open-water disposal on water quality and aquatic organisms and the closure of side channels. The short-term effects associated with disposal operations include the following situations (Colbert et al. 1975):

1. Increased turbidity can interfere with primary production, flocculate plankton, decrease food availability, and produce effects that are aesthetically displeasing.

2. Increased sedimentation can result in the smothering of benthic organisms, destruction of spawning areas for fish, reduced habitat diversity, and reduced vegetation cover.

3. Reduction of dissolved oxygen can suffocate or stress organisms in the immediate vicinity and release noxious materials into the water column.

Unlike short-term effects, which usually can be detected during or immediately after the disposal operation, long-term effects are more subtle and thus more difficult to detect and evaluate. The possiblility of long-term effects resulting from disposal operations is attributed to the presence of nutrients and chemical toxins in the sediment and their release and subsequent effect on the extent, rate, and diversity of the recolonization of benthic populations (Colbert et al. 1975).

Location and habitat type of the disposal site poses the most significant potential environmental effects from dredging and disposal operations. Direct coverage of aquatic habitats has buried aquatic organisms and sterilized biologically productive acreage (GREAT II 1980g). Increased sediment suspension can affect survival of developing fish eggs through physiological changes, morphological changes, and behavioral modifications. Dredging effects on adult and juvenile fishes can include alteration of movement patterns, reduction of visibility, and loss of food organisms. Dispersion of disposed dredged material, particularly during periods of high flow, has closed side channels and sloughs that provide flow to backwater areas (GREAT II 1980g). The result is isolation of valuable backwater areas, causing decreased dissolved oxygen levels and increased sedimentation. This effect has displaced desired productivity and has generally caused accelerated ecological succession in aquatic habitats. Over 1800 acres of aquatic habitat were adversely affected by disposal of dredged materials between 1956 and 1975 in Pools 11 to 22 of UMR (GREAT II 1980j).

For further discussion of impacts to be mitigated see Chapter 1 (Section 1.2, "Channel enlargement, dredging, and disposal of dredged material").

21.2. DESCRIPTION OF TECHNIQUES

21.2.1. Dredges and Dredging Methods

Weck and Crossan (1981) recommended the use of new equipment designs, appropriate equipment, better operation, and proper maintenance techniques to improve dredging operations. Dredge operators should also take advantage of timing, weather, and water velocity to reduce adverse impacts.

Two basic types of dredges--hydraulic and mechanical--are used on navigable waters. Pequegnat et al. (1978) noted that about 99% (by volume) of the dredging in the United States is done with hydraulic dredges. Such dredges operate by mixing sediments with water to form a slurry, which is then pumped to the discharge point (Allen and Hardy 1980). Mechanical dredges involve the movement of material with some type of bucket and their use is usually confined to small projects. Dredged material is usually removed by barges.

Hydraulic pipeline dredges (with cutter, suction, and dust pan heads) remove a variety of material through a pipeline to land or to open water. They are limited to protected areas because of problems with unstable pipeline units. The dustpan dredge, used extensively on the Mississippi River, is efficient in removing sandbars. The hydraulic hopper dredges work mostly in coastal areas and the Great Lakes. The hopper dredge has the advantage of being highly mobile, and less disruptive to vessel traffic, and it can operate in very rough water (Allen and Hardy 1980).

Mechanical bucket dredges are used extensively for removing relatively small volumes of material. Although the dredging depth is practically unlimited, the deeper the depth, the lower is their production rate (Weck and Crossan 1981). A ladder dredge is a special type of bucket dredge that is used extensively in Europe and is being advocated for use in the United States. Dipper dredges are particularly useful for excavating hard bottom material in shallow water of 30 ft or less (Allen and Hardy 1980).

Further information on various designs, advantages, and disadvantages of different types of dredges was given by Allen and Hardy (1980), GREAT I (1980b), Lagasse (1975), Morton (1977), Pequegnat et al. (1978), and Pierce (1970).

Weck and Crossan (1981) summarized the proper engineering devices or measures that could be used to control turbidity from dredging and disposal of dredged material: (1) pipeline discharge configurations, (2) submerged diffuser system, (3) silt curtains, and (4) flocculant injection. The U.S. Army Engineer Waterways Experiment Station (1982) prepared an annotated bibliography dealing with excavation and transportation of dredged material, equipment, physical processes, and planning and execution of dredging projects.

21.2.2. Disposal of Dredged Material

Disposal of dredged material can be improved by selecting proper equipment and procedures. Planning measures, such as timing and location, can reduce the impact of disposal. Beneficial use of dredged material can greatly lessen the impacts of the disposal of dredged material (Weck and Crossan 1981).

Traditional disposal of dredged material has been either terrestrial or aquatic. In the present review, terrestrial disposal refers to all placement on land masses above mean high tide, on nonwetlands, or in confined disposal areas in shallow water that will become land masses when filled. Aquatic disposal covers any disposal site in open water or on wetlands, including the creation of islands in open-water sites. The use of productive upland has recently been investigated as a viable alternative to traditional disposal methods.

Terrestrial disposal may occur on either confined or unconfined sites, depending on sediment characteristics and subsequent land use. Confined disposal areas are often used to store contaminated dredged material. In constructing such disposal sites, earthen dikes are usually built as containment structures, and are equipped with weirs to release the carrier water. Confined disposal in shallow water was once a common alternative,

especially for contaminated material. However, these areas are no longer considered suitable disposal sites and "contained upland sites" are now used. Nevertheless, suitable locations are becoming increasingly difficult to find due to land acquisition problems, and the concept of reusing existing disposal sites has become increasingly important. An initial disposal area can become a transfer station for future removal for other productive uses or for other inland disposal. Such redisposal restores the storage capacity of the initial site. Montgomery et al. (1978) offered reuse management guidelines, for disposal areas and Palermo et al. (1978) provided guidelines for designing, operating, and managing dredged material containment areas. The process of dewatering dredge spoils to reduce their volume and make them more acceptable as fill was described by Morton (1977) and Herner and Co. (1980).

Problems associated with past dredged material disposal practices have created the need for alternate disposal methods. Methods of productive use on uplands have developed because of that need. Information on possible productive uses of dredged material was provided by many studies (Herner and Co. 1980; GREAT I 1980b; GREAT II 1980e; Morton 1977). The transportation of dredged material to locations for upland use was discussed by Souder et al. (1978) and Spaine et al. (1978). We compiled a list of references related to each type of productive upland use:

1. Sanitary landfill (Bartos 1977; Spaine et al. 1978).
2. Agricultural (Arthur D. Little, Inc. 1975; Gupta et al. 1978; Spaine et al. 1978).
3. Surface mine reclamation (Spaine et al. 1978).
4. Construction material or landfill (Boyd et al. 1972; Collins 1980; Mallory and Nawrock 1974; Reikenis et al. 1974).
5. Upland habitat development (Ocean Data Systems, Inc. 1978; Hunt et al. 1978).
6. Recreational site enhancement and maintenance (Coursolle 1978).

The GREAT I Dredged Material Users Work Group identified and studied many potential uses for dredged material along UMRS; they concluded there was a large demand for the dredged material for ice control, landfills, and flood protection levees (GREAT I 1980b).

Allen and Hardy (1980) reviewed the merits of a variety of potential aquatic disposal sites, including areas adjacent to navigational channels, estuaries, the ocean, and the thalweg of streams. Lagasse (1975) noted that the disposal of dredged material in the main channel or thalweg region of UMR can offer an alternative based on the morphology and hydraulics of the river system. This method avoids the direct biologic impacts of bankline or island disposal and is generally well within the capabilities of existing dredging equipment.

An aquatic disposal method that has been used to develop wildlife habitat

is the use of dredged material to create islands and marshes. This technique is described in Chapters 35 and 36. The creation of aquatic habitat does not have great potential in river environments, but proper modification of cuts to backwater areas can rejuvenate them (Allen and Hardy 1980). These techniques are described in Chapter 30.

Other methods of channel maintenance that would result in reduced volumes of dredged materials include (1) moving the navigation channel to take advantage of existing deep sections of the natural channel, (2) reducing the depth of dredging, and (3) increasing the heights of submerged wing dams (Brady 1976).

Planning measures should take into account proper timing and location. Dredging and disposal of dredged material should be completed when the biota potentially affected are at low ebb in their productivity or reproductive cycles (Weck and Crossan 1981).

Habitat disruption can be reduced by locating disposal sites in the least sensitive or critical habitats. This can often be done on a seasonal basis. Known fish spawning or nursery areas should be avoided just before and during use, but might be acceptable for disposal during other periods of the year. However, care must be taken to ensure that the physical substrate and biological community in spawning or nursery areas return to their original condition before the next use of the areas by the fish. Clam or oyster beds, municipal or industrial water intakes, and highly productive backwater areas should be avoided in selecting disposal sites (Weck and Crossan 1981).

Habitat disruption can be further reduced by matching the physical characteristics of the dredged material to the substrate found at the disposal site. The ability of fauna to migrate is heavily dependent on the physical characteristics of the dredged material overburden. Overburdens of mud placed on sand not only produce maximum immediate impact, but they also change the substrate at the disposal site sufficiently to make it unsuitable for the species originally found there (Weck and Crossan 1981).

21.3. IMPACTS ON THE ENVIRONMENT

Dredging operations disturb bottom sediments, cause resuspension of fine sediments and associated pollutants throughout areas affected by local currents, and reduce light penetration needed for plant growth. The major disadvantage of mechanical dredges is the excessive turbidity they develop; the major advantage of mechanical dredging over hydraulic dredging is that less water is incorporated into the material. Hydraulic dredges are advantageous because the material can be disposed of through a pipeline while the dredging operation continues; however, if the slurry is not contained, the

water returning to the river will retain suspended sediment.

Hydraulic (cutter head or pipeline) dredges create suspended solids levels in excess of only a few parts per million in the water column, whereas mechanical (ladder, bucket, or dipper) dredges create plumes in which the levels reach 500 ppm. The use of hydraulic hopper dredges brings solids into suspension only intermittently, and in smaller areas (Weck and Crossan 1981).

Turbidity caused by mechanical bucket dredges can be reduced 30 to 70% by using watertight buckets. Another effect of these dredges is that they usually leave irregular, cratered bottoms. Ladder dredges use less energy and create less turbidity than do hydraulic dredges.

Adjacent riparian zones on many large river systems are common terrestrial disposal sites. Dredged material is hydraulically placed above the normal water level across substrates in the riparian zone. Plants vary in their response to deposition according to the fill depth and characteristics of the sediments. Riparian disposal atop early successional stages of vegetation is environmentally less damaging than disposal over later stages because revegetation occurs more quickly (Brady 1976).

Aquatic disposal has been used primarily because it is the least expensive disposal method. However, adverse environmental effects of aquatic disposal have resulted in changes in disposal practices. The filling of wetland areas, marshes, sloughs, and side channels has been one of the most damaging aspects of dredged spoil placement (Brady 1976). The pollution potential of dredged material constitutes another environmentally damaging feature of aquatic disposal. After studying dredged material from 10 sites on UMR to determine its chemical characteristics and possible toxic effects on aquatic organisms, Marking et al. (1981) reported that sites with large proportions of silt and clay often produce toxic effects on aquatic organisms and usually show higher concentrations of contaminants than do sandy materials.

Additional information on the effects of dredging methods and the disposal of dredged material is given in Chapter 1.

21.4. COSTS

In the St. Paul District of the U.S. Army Corps of Engineers, a hydraulic cutter-head dredge can move material at a cost of about $0.33 per cubic yard, versus $1.57 per yard for a mechanical clamshell dredge (U.S. Army Corps of Engineers, St. Paul District 1974). The farther the dredged material is transported from the dredging point, the higher the cost of dredging (Table

6). The GREAT I Channel Maintenance Reports provided costs for dredging of specific cuts on UMRS and for delivering the dredged material to a recommended placement site (GREAT I 1980f).

Table 6. Costs of moving dredged material (from Brady 1976).

Method	Cost per cubic yard
Pipeline transport (hydraulic)	
1600 ft	$0.36
2600 ft	0.51
1 mile	0.75
2 miles (with booster)	1.40
Barge transport and pump out 10 miles over water	1.53
Rail and barge transport 10 water miles + 25 land miles	4.03

21.5. EVALUATION FOR USE ON UMRS

Two reports by GREAT provided recommendations for evaluating dredging and the disposal of dredged material on UMRS (GREAT I 1980a; GREAT II 1980c). The GREAT I and II plans developed detailed site-specific channel maintenance plans and recommendations for management of UMRS and its interrelated components within the river corridor.

A major recommendation of the GREAT I study concerning types of dredging equipment was that "the Corps of Engineers should request the necessary appropriations to purchase efficient dredging equipment to best accomplish all objectives of the GREAT I Channel Maintenance Plan. Until this equipment is available the Corps should emphasize contract dredging to meet those objectives" (GREAT I 1980a). This statement also applies to GREAT II.

The GREAT I study concerning dredged material placement included the following information:

> "The damaging effects of dredged material placement were one of the chief public and agency concerns promoting the GREAT study. The most extensive and detailed product of GREAT I is a site-specific

dredged material placement plan. On the basis of Corps of Engineers records and projections through the year 2025, GREAT I identified probable dredge cuts and annual volumes for each cut. For each cut, GREAT I identified potential sites available for placement of dredged material. Sites were identified on the basis of location; potential beneficial use; impacts on flood flows; potential for site erosion; impacts on water quality, fish and wildlife resources, and recreation; costs of use; and public opinion" (Great I 1980a).

PART VII. FISHERY MANAGEMENT TECHNIQUES

Bennett (1970) defined fishery management as "the art and science of producing sustained annual crops of wild fish for recreational and commercial uses." The objective of all fishery management techniques is the elimination of physical and physiological barriers that affect the well-being of the fish species selected for management.

The process of altering river systems for navigation, hydropower, irrigation, and recreation has imposed physical barriers (e.g., dams) and physiological barriers (e.g., various pollutants) on the well-being of desirable indigenous fish species. The mitigation and enhancement measures described in this Part are designed to offset, ameliorate, or overcome such barriers. Some techniques facilitate reproduction, early-life survival, and migration of fishes; others are designed to increase living space and to enhance or insure good water quality; and still others are designed to protect fish from direct destruction.

The variety of the techniques reflects the complexity of fish management problems in large river systems--problems that will only intensify as human demands on river systems increase.

CHAPTER 22. FISH ATTRACTORS

22.1. SITUATION TO BE MITIGATED OR ENHANCED

Structure is an important feature of aquatic ecosystems. Prince et al. (1977) defined structure as "irregularities of substrate or relief, either artificial or natural, living or nonliving, which are concave or convex on the lake bottom or floating on the surface ...." Structural complexity mediates ecological interactions between littoral fish and their prey (Crowder and Cooper 1979).

Crowder and Cooper (1977) argued that prey capture rates decline as a function of increased structural complexity, and Hall et al. (1970) noted that prey density (diversity and abundance) increases with structural complexity. Because these two relations vary inversely, predator feeding rates are highest at intermediate levels of structural complexity.

It follows that, in those lakes and streams deficient in structure, prey densities are likely to be low and predator feeding rates sub-optimal. Consequently, the carrying capacity and growth rates for predator fishes (i.e., the product of interest) will also be suboptimal.

Lakes that are deficient in structural complexity can be improved by installing man-made structures. Such structures should not only increase the system's carrying capacity and improve predator fish growth rates, but may also facilitate the capture of fish by anglers. Prince et al. (1977) presented the following rationale for using artificial reefs (fish attractors) as a fishery management technique:

1. In structure-deficient nonflowing waters, artificial reefs effectively concentrate warmwater sport fishes--primarily black basses, sunfishes, and catfishes.

2. Firm reef substrate serves as a surface of attachment for plants and animals, thus increasing biological productivity. Attached aquatic organisms are eaten by reef fishes.

3. Many warmwater sport fishes (black basses, sunfishes, and catfishes) often spawn on or near artificial reefs. Young fish occupy the reefs through the growing season. Eggs and young of reef fishes also are seasonally important in the diets of reef sport fishes.

4. At temperate latitudes, sport fishes use reef areas only seasonally. Warmwater sport fishes move to reef areas as temperatures exceed 50°F in the spring. The numbers of species

and individuals increase through the spring, remain at high levels through the summer and early fall, and decline when water temperature decreases in late fall.

5. Depending on the species present in individual watersheds, the geographical location, and the season, small sport fishes are often most abundant on reefs in shallow water (5 ft or less), and larger ones are often found on reefs in deeper water (15 to 20 ft). However, reefs in temperate latitudes at depths of 20 ft or less are generally devoid of fish in winter.

6. Fishing quality for warmwater sport fishes is usually better on artificial reefs than on nonreef areas.

Fish attractors are installed for two principal reasons: to create habitat features that promote fish production and survival, and to encourage desirable fish populations to congregate near installations, thereby facilitating angler harvest. Fish attractors are primarily enhancement devices, but may be used to mitigate structural losses resulting from clearing and snagging, sedimentation, dredging, detrimental water level fluctuations, and decay of flooded timber.

22.2. DESCRIPTION OF TECHNIQUES

Man-made structures, collectively named fish attractors, have been called by a variety of names--e.g., fish concentrators, fish hides, fish havens, fish shelters, brush shelters, fish cribs, and artificial reefs. Attractors have been constructed in many forms and from a wide variety of materials (Prince et al. 1977; Petit 1972; Jones 1970; Stone et al. 1974; Hiscox 1976; Wilbur 1974; and others). The type of structure, and the material used, depends on the intended purpose of the structures and the availability of materials and labor.

The effectiveness of fish attractors can be severely limited if they are not placed in appropriate locations. They should not be placed at depths subject to oxygen depletion, and should be on firm bottom (to prevent sinkage) and in areas where structure is insignificant or lacking. Structures should not be placed where they impose a hazard to navigation.

Materials that have been used in freshwater attractors include such varied materials as used tires, brush, trees, vitrified clay pipes, cement blocks, bricks, rubble, stake beds, clumps of plastic strips, automobile bodies, and old boats.

Scrap tires, for several reasons, have become one of the most popular materials for the construction of fish attractors (Edmond 1967; Prince et al. 1975; Stone et al. 1974; Wilbur 1974; Wilbur and Crumpton 1974). They are often available in large quantities at no charge. They are easy to manipulate and are readily assembled into various configurations. Further, tires are inert, they do not decompose nor leach harmful compounds, and they last indefinitely (Stone et al. 1974; Tolley 1981).

Several structural designs have been developed in which tires are used, but modifications and improvements may be desirable (Prince et al. 1977). The attractors should be bulky and have many cavities and several entrances. They should have a high profile and should rise as close to the surface as legally permissible, because high-profile structures concentrate fishes more efficiently than do smaller structures. Synthetic rope may be used as a binder. Concrete-filled cans and tires can be used for ballast. Holes punched in the tires allow trapped gases to escape. In addition, the stability of tire structures placed in aggregate can be improved if the individual units are strung together with synthetic rope (Prince et al. 1977).

Brush is widely used in the construction of fish attractors. Structural configurations range from stacked brush frames, bundled brush, anchored trees, the "Wisconsin log crib," and felled shoreline timbers to brush combined with other materials. Green oak is prefered for construction material, but other green hardwoods may be substituted. Dry wood is undesirable because it is too buoyant and therefore requires too much ballast.

Rodeheffer (1945) and May (1968) each described a variation of framed brush structures. In each design, brush is bundled and secured to a frame by wire. Rodeheffer formed a circle of brush 18 ft in diameter; May stacked brush bundles to a height of 6 ft on a 5- by 10-ft frame.

The Wisconsin log crib is the only fish attractor recommended and approved for installation in Wisconsin waters (Jones 1970). Green oak is recommended for logs, poles, and brush. The following materials are required for construction of one shelter:

18 logs 8 ft long and 6 in. in diameter at the top; if logs of smaller diameter are used, more are required

90 ft of No. 9 galvanized wire

10 ft of No. 12 galvanized wire

36 fence staples, $1^3/4$ in. long

4 sapling poles, 8 ft long

1 white, plastic, 1-gallon jug

The completed structure looks like a brush-filled, roofless log cabin (Fig. 34). The logs are secured with No. 9 wire. An 8- to 12-in. overhang of logs is allowed at the corners. A sapling floor is constructed on the second tier of logs to allow a space for fish that prefer to live underneath the structure. The "cabin" is then filled with loose bundles of brush and boxed in with a grate of four saplings fastened over the top. A plastic jug or other float is secured to the top as a navigational marker and an aid to anglers. If the finished structure is too buoyant, concrete blocks may be attached as ballast.

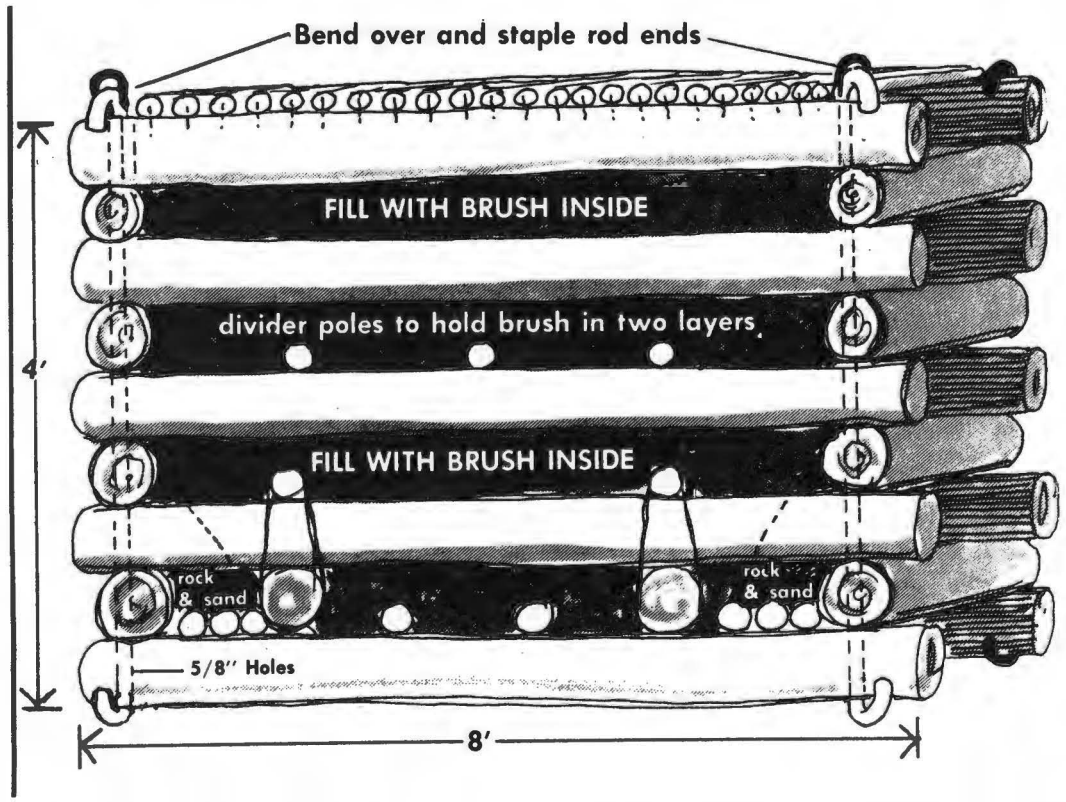


Fig. 34. Diagram of a Wisconsin log crib for use as a fish attractor (Drawing by the Wisconsin Department of Natural Resources, La Crosse).

The Wisconsin log crib can be installed by building it on ice-covered water over a selected location. The crib may also be constructed on a ramp over the water and towed by boat to the selected location.

The simplest brush attractor is merely bundled brush, but it is not very

durable. The bundles are weighted with ballast and placed at appropriate locations.

Cedar trees, orange trees, and discarded Christmas trees have been used to construct attractors (Wilbur 1974; Prince et al. 1977). Single units are constructed by inserting a 12-in. piece of steel bar stock at right angles at the base of the trunk. The trunk is then placed in a 5-gallon can and concrete is poured around it to three-quarters capacity. Maughan et al. (1976) reported that single units are very unstable; Prince et al. (1977) recommended that three trees be cabled together and held in place by a single anchor. The three-tree design readily maintains its upright position.

One of the easiest ways to create shoreline attractors is to fell large trees into the water. In northern latitudes the trees can be dropped on the ice, trimmed if necessary, and weighted with ballast. The trees sink into place as the ice melts. In reservoirs with large water level fluctuations, trees may be felled, positioned, and weighted with ballast during drawdown periods.

Damaged vitrified clay pipes can also be used to construct quality fish attractors (Wilbur 1974). The pipes are bundled with plastic binding material to form a pyramid or irregular shape. Pipes of different diameters (4 in. and larger and 2 to 5 ft long) are incorporated to create habitat diversity. Several units are generally placed in aggregate. The inclusion of several solitary, short, large-diameter pipes in the grouping may be desirable. In one study (Wilbur 1978), vitrified clay pipes attracted more fish (bluegills, largemouth bass, white catfish, and brown bullheads) than were present in control areas, but fewer than were attracted by brush sites.

Block-brush structures are constructed by piling up as many as 700 damaged concrete blocks. The resultant pile is then fringed with weighted brush to form a reeflike attractor (Prince et al. 1977).

Stake beds were first used by the Tennessee Game and Fish Commission to concentrate crappies (Petit 1972). Two construction methods were described: The driven-stake bed is constructed by driving 15 stakes (4 to 7 ft long) to form a 4- X 8-ft bed. Construction is usually done in reservoirs during drawdowns. The prefabricated stake bed is of the same dimension as the driven bed, but the upright stakes are nailed to a base frame. The bed can be floated into position and sunk by placing concrete blocks over the corner stakes.

Junk cars have been used for fish attractors in deep water. The car bodies must be stripped of upholstery and steam cleaned to remove petroleum residues before installation. Significant drawbacks to the use of cars are

the difficulties of transporting and handling them (Prince et al. 1977).

Old boats, as well, can be a convenient source of structural material. After the hulls are cleaned and floatable materials removed, the boats can be towed to the appropriate location and sunk (Prince et al. 1977).

Plastics have been used to create "artificial seaweed" (Brashears and Dartnell 1967) and "kelp clumps" (Hiscox 1976). The artificial seaweed concept was developed to reduce shoreline erosion, but the kelp clump was developed as artificial cover for centrarchid fishes.

The kelp clumps are constructed of buoyant black polyethylene plastic strips that are cut 2 in. wide and 8 to 12 ft long. Clumps of 25 to 30 strips are held together by a base weight. The clumps are strung together to facilitate placement, maintenance, and recovery of the structures. Singular or multiple strings can be used.

Hiscox (1976) listed the following advantages of kelp clumps over more elaborate systems.

1. The entire system is movable.
2. As water level recedes, the artificial cover collapses to a low profile. It also presents little hazard for boats, water skiers, etc.
3. The lack of tangible materials discourages vandalism.

A disadvantage of the plastic seaweed concept is that sediment deposits and attachment organisms can cause the units to collapse (Prince et al. 1977).

Various concrete products make good shallow-water fish attractors. Ryder (1981) listed the advantages of concrete:

1. Concrete provides protection, food, spawning, and longevity.
2. Low and high profile structures may be developed.
3. Concrete products ae readily available and inexpensive to acquire and prepare; however, transportation can be costly.

Midwater fish attractors may merit consideration for use in freshwater systems, even though they were originally designed to attract commercially harvestable quantities of coastal pelagic fishes (Klima and Wickman 1971;

Reeves et al. 1977). The structures are composed of buoyant objects of variable design that are held suspended some distance below the water surface by a mooring system. The structures may be placed singly or in groups, and may be suspended at uniform or different depths. Structural shapes that have been used are tents, inverted cones, and horizontal platforms.

Artificial midwater structures constructed primarily with fiberglass panels and scrap tires attracted six species of game fish--spotted bass, bluegills, white crappies, white bass, redear sunfish, and largemouth bass (Smith et al. 1981). Spotted bass and bluegills were the dominant species observed. More harvestable fish were associated with these midwater units than with previously designed midwater structures (Smith et al. 1981).

22.3. IMPACTS ON THE ENVIRONMENT

A number of adverse effects can result when fish attractors are installed improperly or without proper planning. Improperly installed fish attractors may negate the intended effect.

It is important to avoid promoting potential or existing imbalances in fish populations (Prince et al. 1977). To prevent stunting, which results from overprotection of prey species, the number of fish attractors installed should not be too large nor should they be placed in habitat where cover is already abundant. If overharvest potential exists in the target populations, the installation of fish attractors may accentuate the problem by increasing angling success.

Navigational needs and aesthetic requirements must be considered. Fish attractors must be placed at sufficient depth and marked with buoys to prevent them from being a hazard to navigation. If the attractors are visible to fishermen or others, aesthetically pleasing construction materials (e.g., brush, logs, trees) are preferred.

When a fish attractor is installed, a localized ecological complex develops that promotes increased production at each trophic level, and can ultimately lead to increased angler harvest. The structures provide stable substrate for the development of periphyton (Alfieri 1975; Pardue 1973; Prince et al. 1976). The structures stabilize local conditions and sometimes promote development of aquatic macrophytes (Thomas and Bromley 1968; Thomas et al. 1968). Colonization by macroinvertebrates provides a larger food base, which can improve condition and increase production of the species of fish that use the structures (Prince 1976; Swingle 1968).

Fish attractors also provide cover that attracts forage species seeking

shelter and predators seeking prey (Pierce and Hooper 1979; Prince et al. 1975; Wilbur and Crumpton 1974). Fish attractors are also used for escape cover by spawning centrarchids (Prince et al. 1975; Vogele and Rainwater 1975). It is the concentrating effect of introduced cover that can result in a fish population's increased susceptibility to angler harvest.

22.4. COSTS

The costs and availability of manpower, materials, and equipment are important limiting factors for fish attractor construction (Prince and Maughan 1978). By using durable materials and by involving the local community in project development, however, the financial burden can be reduced (Prince et al. 1977).

Scrap tires are durable and inexpensive. They are easily obtained and dealers sometimes pay to have them removed (Stone et al. 1974). Prince et al. (1977) presented the following materials cost analyses (1974 dollars) for the pyramid and high-profile designs:

Pyramid unit

	Estimated cost
Materials	
Scrap tires (9 per unit)	0
No. 10 can (6 per unit)	0
Concrete (amount needed to fill 6 No. 10 cans, at $0.07 per can)	$0.42
Polypropylene line, (40 ft, 1/4-in. diameter, at $0.02 per ft)	0.80
Total per unit	$1.22

High-profile unit

	Estimated Cost
Materials	
Scrap tires (13 per unit)	0
Concrete (about 40 gallons necessary to fill base tire, at $0.11 per gallon)	$4.40
Reinforcing bar (40 ft, 1/2-in. diameter, at $0.10 per ft)	4.00
Total per unit	$8.40

Prince and Maughan (1978) presented a construction cost analysis for an artificial reef project in Smith Mountain Lake, Virginia (Table 7). The estimate, which included the cost of donated materials and labor, was $7998 for reefs that covered an area of about 2.4 acres.

Table 7. Construction costs for artificial reefs in Smith Mountain Lake, Virginia (from Prince and Maughan 1978).[a]

Materials and equipment	
Estimated total of donated materials and equipment	$2202
Cost to project of materials and equipment	1271
Subtotal	$3473
Labor	
Donated labor, Virginia B.A.S.S. Federation (325 man-hours)[b]	$ 650
Labor from project personnel (325 man-hours)	875
Subtotal	$1525
Total estimated costs of reef construction	
Donations	$2852
Actual costs to project	2146
Total	$4998

[a]Nine reef sites covered an area of 2.4 acres.
[b]Costs of donated labor were computed on the basis of the 1974 minimum pay scale of $2.00 per hour.

Hiscox (1976), who made an extensive cost analysis of "kelp clump" construction, reported that the total retail cost (1976 dollars) for one system of clumps, containing 20 units on 75 ft of cable, was about $52.

Cost considerations vary among the other types of attractors; those for brush-type attractors should focus on fuel and binding materials because brush and logs can usually be obtained without cost near the installation sites. Damaged vitrified clay pipes and concrete blocks may be obtained at little or no cost. Stake bed construction cost can be reduced by using slab lumber, which is usually inexpensive (Wilbur 1974).

22.5. EVALUATION FOR USE ON UMRS

Some of the fish attractors discussed may have only limited use in UMRS. Though brush and tire fish attractors may be stable in lentic waters or last a long time in reservoirs, they may be dislocated or destroyed by powerful currents during floods in UMRS. Concrete block-brush reefs and vitrified clay pipe bundles are very dense, however, and thus, would remain functional under

a variety of current conditions.

The vitrified pipe and concrete block-brush attractors supply stable hollows and overhead cover preferred by some members of the catfish family which are an important component of the UMRS fishery (Davis 1959; Hickman 1975). However, the structures should be placed where current will prevent damage from sedimentation.

Because midwater attractors primarily attract fish such as crappies that have a habit of "suspending" in open water (Reeves et al. 1977), such attractors may improve angling in pelagic areas in UMR impoundments. The devices can be easily installed and removed; they could be installed after flood danger has subsided and removed before the river freezes over.

Properly constructed and anchored fish attractors made of small groups of scrap tires may be the least expensive, most durable, and most easily installed replacement structure for a stump field. Their use has received wide acceptance and their value to fishery resources has been demonstrated.

CHAPTER 23. SPAWNING STRUCTURES

23.1. SITUATION TO BE MITIGATED OR ENHANCED

Spawning behavior among freshwater fishes is very diverse. Some fishes build nests and provide parental care; others build nests and desert them after spawning; and still others build no nests, but broadcast sinking eggs over the bottom or buoyant eggs near the surface (Lagler et al. 1977).

Fishes that do not have buoyant eggs often require very specific substrate types. Some centrarchids build circular depressions in mud, silt, and sand, often among the roots of aquatic plants; others build nests in gravel. Channel catfish and yellow bullheads nest in tunnels. The pikes scatter eggs over aquatic or flooded terrestrial vegetation. Whitefishes, lake trout, suckers, and walleyes scatter eggs over shoals of sand, gravel, or boulders.

If appropriate spawning habitat is not available, the construction of spawning reefs may be a successful management measure. Spawning structures can be used to mitigate the destruction of pristine spawning shoals resulting from construction projects or catastrophic climatological and geological events, and to mitigate the degradation of spawning shoals by gradual siltation that often results from poor land use practices and dredging activities. Spawning structures for catfish can be used to offset the depletion of catfish spawning habitat caused by the gradual loss of the original stumps, logs, and timbers that occurs in most impoundments. Spawning reefs may provide a stable substrate that will reduce egg mortality due to siltation and predation, and reefs may also provide a more secure spawning habitat for adult fishes that give parental care for eggs and fry--e.g., black basses and catfishes.

23.2. DESCRIPTION OF TECHNIQUES

Spawning structures have been developed to increase spawning success of a variety of fishes. Successful spawning reef applications have been documented for walleyes (Johnson 1961; Newburg 1975; Sprague 1963; Weber and Imler 1974); black basses (Prince 1976; U.S. Forest Service 1969; Vogele and Rainwater 1975); catfishes (Bennett 1970; Prince 1976); and brook trout (Carline and Brynildson 1977), among others.

Spawning structure designs vary depending on the fishes' needs. Rock shoals (Carline and Brynildson 1977; Hacker 1956; Johnson 1961; McKnight 1975; Newburg 1975; Prevost 1956), gravel filled boxes (Hubbs and Eschmeyer 1938; U.S. Forest Service 1969), suspended platforms (Brouha and von Geldern 1979),

and several of the fish shelters described in Chapter 22 have been used (Bennett 1970; Prince et al. 1977).

The placement of spawning reefs and the structural components incorporated into reefs are a function of spawning behavior, water movement and depth, substrate requirements, potential predators, and potential deleterious environmental effects. In the placement of spawning reefs, advantage should be taken of spawning behavior; the reefs should be placed either in the path of a known spawning run or in an area of previous spawning activity, even if it was only marginal (Newburg 1975). Behavior patterns may also require that escape cover be incorporated into the reef (Prince 1976; Vogele and Rainwater 1975). Fishes that do not attend their eggs may require running water, wave action, or upwellings to keep the eggs supplied with oxygen and free of silt (Carline and Brynildson 1977; Johnson 1961; Newburg 1975). Some species will not spawn in water lacking sufficient depth, and minimum depths may be necessary to ensure egg and fry survival (Priegel 1970; Schneberger 1972). Some species are dependent on appropriate substrate for spawning sites; in reef construction, substrate type and size must be carefully selected to induce use by the desired species (Bennett 1970; Johnson 1961; Priegel 1970; Threinen et al. 1966). Size and shape of the components of a spawning substrate can have a profound influence on egg predation (Hacker 1956; Prevost 1956). Deleterious environmental effects, such as excessive wave action and siltation, can be avoided by proper location and construction of reefs (Carline and Brynildson 1977; Newburg 1975).

Gravel or rock spawning shoals may be developed for any species that is selective for spawning substrate. Stone size and reef location, i.e., depth and site, are species specific. The rock shoal or reef has been developed as spawning habitat for walleyes, and its efficacy has been investigated (Johnson 1961; McKnight 1975; Newburg 1975; Sprague 1963; Weber and Imler 1974). Weber and Imler (1974) attributed a 2- to 10-fold increase in young-of-the-year walleyes to the installation of spawning structures; and Johnson (1961) reported a 10-fold increase in walleye egg survival on improved spawning shoals. McKnight (1975) reported that walleye year classes did not develop in 4 years after the installation of spawning shoals and speculated that predation by crayfish, yellow perch, or other fauna, or the lack of a sufficiently large spawning population may have been the cause.

In the construction and placement of walleye spawning shoals, the following factors should be considered (Newburg 1975):

1. There should be demonstrated need for the shoal in the area.

2. Shoals should be placed in an area of previous spawning activity or in the path of a known spawning run.

3. Shoals that are installed should cover 600 acres or more.

4. A walleye spawning population should be present.

5. If periphyton growth is overabundant or wave action is severe, the shoal should be covered by no less than 3 ft of water at lowest spring levels.

6. The shoal should have a gradual slope (no more than 10%).

7. Shoals placed near shore should be extended to the high water mark to stabilize the shoreline and prevent siltation that could result from shoreline erosion.

Experimental results indicate that the following elements are essential to reef construction plans (Newburg 1975):

1. The shoal should be placed on very firm substrate to control sinking. Substrate preparation and stabilization may be done by placing a 4- to 6-in. layer of 0.5- to 2-in. rock screening underneath a covering of the larger "spawning materials." Alternatively, a synthetic filter-cloth stretched on the bottom before freeze-up may produce the same results as the rock screenings. The spawning substrate would be placed on the ice and allowed to drop onto the filter-cloth during spring breakup.

2. Materials should be a mixture of rock sizes as follows:

   a. If needed, a bottom substrate stabilizer, 4 to 6 in. thick, made of 0.5- to 1-in. rock.

   b. A layer of spawing shoal rock, 12 in. deep, should consist of a mixture of rocks of the following diameters: 3 to 5 in., 10%; 5 to 7 in., 50%; and 7 to 9 in., 40%.

3. A reconnaissance of the immediate shoal area should be made to determine if there is sufficient material from the lake bed and erodible shoreline to present a serious siltation and detritus problem, and to determine the predominant direction and extent of shore drift. If there is a potential problem, one of the following solutions should be considered: Relocation of the shoal site, stabilization of the sediment source area, or construction of a jetty on the up-drift side of the shoal. Placing a temporary obstruction perpendicular to shore at the proposed site will cause sediments and detritus to build up on the up-drift side of the obstruction; however, periodic cleaning with stiff brooms and jets of water from a 1.5-in. pump may be needed to remove sediments, detritus, and periphyton from the rocks.

The black basses prefer gravel-rubble substrate (Coble 1975; Mraz et al.

1961; Vogele 1975). Shoal development should be similar in design to that used for walleyes; however, the area of the substrate should be smaller and the site should be sheltered from the wind (Heidinger 1975). In addition, all three black basses prefer to build nests near cover (Hunsacker and Crawford 1964; Coble 1975; Heidinger 1975; Kramer and Smith 1962; Miller and Kramer 1971; Vogele 1975; Vogele and Rainwater 1975); therefore, the reef should have large boulders or small fish attractors (see Chapter 22) incorporated in the design.

Spawning boxes, consisting of shallow wooden frames filled with gravel, have been used for black basses and other centrarchids (Hubbs and Eschmeyer 1938; U.S. Forest Service 1969). The boxes are placed at appropriate sites in small lakes or hatchery ponds.

Spawning platforms were developed to facilitate the spawning of bluntnose and fathead minnows (U.S. Forest Service 1969); however, modifications of the technique may be advantageous for some centrarchids, particularly in steep sided reservoirs that lack sufficient littoral habitat. Reeves et al. (1977) observed a spotted bass using an artificial midwater fish attractor as a spawning platform; and Brouha and von Geldern (1979) reported seeing largemouth bass, bluegills, and green sunfish spawning on a suspended spawning platform. The gravel-covered platforms, 4 X 6 ft, were spaced 5 ft apart, vertically, in three or four layers; they were generally installed adjacent to steep shorelines where water depth exceeded 100 ft and within 30 ft from shore. Platforms located at depths of 5 to 15 ft were used for spawning. The second bed from the top usually received the most use. Brouha and von Geldern (1979) speculated that shading was an important factor and suggested that the platforms be combined with existing floating structures such as fishing piers, breakwaters, floating docks, and buoys.

Catfish spawning success can often be improved by installing spawning cavities constructed of various types of non-metallic pipe, or milk cans, nail kegs, or used-tire fish attractors (Bennett 1970; Prince et al. 1977; U.S. Forest Service 1969; Wilbur 1974). If pipes are used, one end should be plugged with 3 to 4 in. of concrete. All of the materials should be placed almost horizontally in 3 to 5 ft of water, with the open end tilted only slightly upward (U.S. Forest Service 1969).

23.3. IMPACTS ON THE ENVIRONMENT

Few adverse effects are likely to result from spawning reef installations. If reefs are improperly located or constructed from inappropriate materials, they can have a negative effect on fish communities, but usually such planning errors merely render the structure ineffective.

Several problems can develop if a structure is not properly located. The reef may not be used by the desired species, but may instead provide quality habitat for competitive species (Newburg 1975). Moreover, the reef may promote overpopulation by a less desirable species, especially if the population density of the less desirable species is already excessive. If a reef is located at a site where wind and wave action can become severe, the target species may be induced to spawn on the reef, only to have the eggs destroyed by a storm or unusually gusty winds (Miller and Kramer 1971; Newburg 1975).

Reefs constructed from inappropriately sized rocks can have negative effects on established populations. If fish are induced to spawn on a reef, and the particle size incorporated in the reef does not afford eggs adequate protection from predators, the reef may merely develop into a convenient feeding ground for predators (Hacker 1956; Prevost 1956). Furthermore, the reef may not protect eggs from the dislodging effects of wave action and the smothering effects of siltation (Johnson 1961).

Some ancillary benefits may accrue from the installation of spawning reefs. The reefs may promote increased primary production by providing a stable substrate for benthic algal communities and further the production of benthic fish-food organisms.

23.4. COSTS

The construction of a rock spawning reef usually requires a high initial expenditure. The operation generally requires intensive labor and heavy equipment to haul and spread the rock. The rock may be expensive, depending on its availability and its proximity to the construction site.

Several investigators presented analyses for construction of rock spawning reefs. Weber and Imler (1974) installed a 5000-ft^2 rock spawning reef for walleyes that cost $3608 (1971 dollars). Inasmuch as the installation resulted in 2- to 10-fold increases in young-of-the-year walleyes, it was considered very cost-effective. Newburg (1975), who installed a 25,000-ft^2 rock spawning reef for walleyes, estimated the cost of the reef to be $11.10 per cubic yard (1973 dollars) of rock substrate. The reef was not cost-effective because walleye fry production increased by only 10%. He developed an amortization schedule based on costs of equivalent fry stocking (Table 8). McKnight (1975) wrote that it took 18 man-days and the use of heavy equipment to install 53 cubic yards of rock; the approximate cost of the rock was $26 per cubic yard. The project was not cost-effective because a walleye year class did not develop.

Cost estimates for used-tire, clay-pipe, and brush-shelter installations

Table 8. Cost of walleye fry stocking compared with amortized cost of new improved spawning shoal, based on observed production of walleye fry on improved shoal, Lake Osakis, Minnesota (from Newburg 1975).

Item	Cost in 1970	Cost in 1975
Cost of shoal installation	$6400	$11,110
Hatchery production cost for 1 million walleye fry	$600[a]	$750
Maximum walleye fry production, spawning shoal	285,000	285,000
Cost of comparable hatchery production	$171	$213
Average walleye fry production, spawning shoal	165,000	165,000
Cost of comparable hatchery production	$99	$123
Amortization at maximum shoal production	$\frac{\$6400}{\$171 \text{ per year}}$ = 37 years	$\frac{\$11,110}{\$213 \text{ per year}}$ = 52 years
Amortization at average shoal production	$\frac{\$6400}{\$99 \text{ per year}}$ = 65 years	$\frac{\$11,110}{\$123 \text{ per year}}$ = 90 years

[a]Estimated cost of fry production based on 1973 dollars.

are discussed in Chapter 22.

23.5. EVALUATION FOR USE ON UMRS

Spawning structures can be used in almost any body of water capable of sustaining natural fish populations; UMRS is not an exception. Walleyes, black basses, and catfishes are all important sport fishes in UMRS; however, spawning habitat for these species does not appear to be limiting. Nevertheless, such structures may be useful in discrete backwater lakes and sloughs where the effects of deteriorating spawning habitats are known and the benefits of spawning habitat improvement techniques can be quickly realized.

CHAPTER 24. NURSERY PONDS, COVES, AND MARSHES

24.1. SITUATION TO BE MITIGATED OR ENHANCED

Recruitment of young to desirable fish stocks depends on many factors. In addition to suitable spawning habitats, fish require adequate nursery areas. Several factors affect the adequacy of nursery areas, including water level fluctuation, predation, and interspecific competition. Control of these factors as they relate to valued fishes can help to improve recruitment.

Attempts to introduce exotic or non-native fishes into reservoirs have often failed, especially in reservoirs with established native fish populations. In particular, the planting of fry has been unsuccessful because of the lack of nursery areas (Keith 1969). Isolated nursery waters that provide a secure and productive environment for young fish can be used to help ensure better recruitment in fish populations and successful introduction of exotics.

The classification of a nursery water technique depends on the application by the resource manager. If nursery facilities are developed to facilitate the establishment of exotic species, to promote a "put-grow-and-take" fishery, or to stabilize or increase recruitment, the development would be considered as an enhancement technique. If nursery facilities are developed to offset the destruction of pristine spawning marshes or nursery habitat due to construction projects, poor land use practices, or catastrophic climatological or geological events, their development would be classified as a mitigation technique. In all of the applications mentioned, improved recruitment is the objective. This goal is achieved by providing a more secure and productive environment for fish in vulnerable early-life stages.

24.2. DESCRIPTION OF TECHNIQUES

Isolated nursery waters are usually developed adjacent to or within a target system (Nelson et al. 1978). However, outlying ponds that meet certain requirements may also be used.

Nursery ponds, nursery coves, and managed nursery marshes are structural variants that are developed as adaptations to the requirements of target species and to financial and topographic limitations. Because nursery pond construction can be very costly (Keith 1969), the nursery cove technique was developed as a less expensive alternative (Smith 1976). The managed marsh technique was developed to increase and stabilize the recruitment of northern pike, especially where pristine spawning marshes have been damaged or

destroyed (Fago 1977; Kleinert 1970; Williams and Jacob 1971). The manipulation of lakes and ponds as nursery areas for stream basins has been tried in efforts to improve stream fishing (Mathis 1964; Smith and Swingle 1944).

24.2.1. Nursery Ponds

Keith (1969) described the separate-structure nursery pond. It is a strictly controlled, separate pond located adjacent to the receiving reservoir and is connected with the reservoir by a pipe, a manually operated gate system, and a canal. Because runoff is the water source the characteristics of the watershed are critically important, and pond size becomes a function of the drainage area incorporated. The pond must be filled at least once annually, but excessive flushing of nutrients should be avoided. Moreover, if pollution and immigration of unwanted fish are to be prevented, the entire watershed should be under managerial control.

Keith (1969) provided the following guidelines for site selection:

1. The facility should be located where it can be drained directly into the receiving water.
2. The ratio of drainage area to pond surface area ratio should approximate 10:1 (based on hydrological characteristics in Arkansas).
3. The site should not be costly. State and Federal land holdings, which do not require outright purchase, are often desirable locations.
4. Adequate access to the site is necessary.
5. The watershed should not contain private ponds. If it does, complete control over the ponds must be obtained.

Pond design and construction should permit complete draining. Poorly shaped bottoms develop potholes where fish readily become stranded when the pond is emptied.

24.2.2. Nursery Coves

The nursery cove technique was developed to provide a more economical alternative to nursery ponds (Smith 1976). The principal key to success was the development of a barrier net design that would withstand animal depredation and other destructive environmental forces (e.g., wave action).

The barrier net (Fig. 35) is constructed with 1/16-in.-mesh nylon webbing suspended from a 3/16-in. steel cable; the cable is stretched between two vertical I beams posted on opposing shores. Five-gallon Freon containers are welded together in pairs and attached to the cable at 10-ft intervals to provide flotation. Galvanized wire (1/2-in. mesh) is placed on each side of the nylon webbing and secured to the cable with hog rings. The wire mesh extends 3 ft below the surface and the bottom edge of the wire is folded away from the net to prevent snagging. The bottom of the net is formed into a sleeve, and 1/4-in. chain is inserted to fix the barrier to the substrate (Smith 1976).

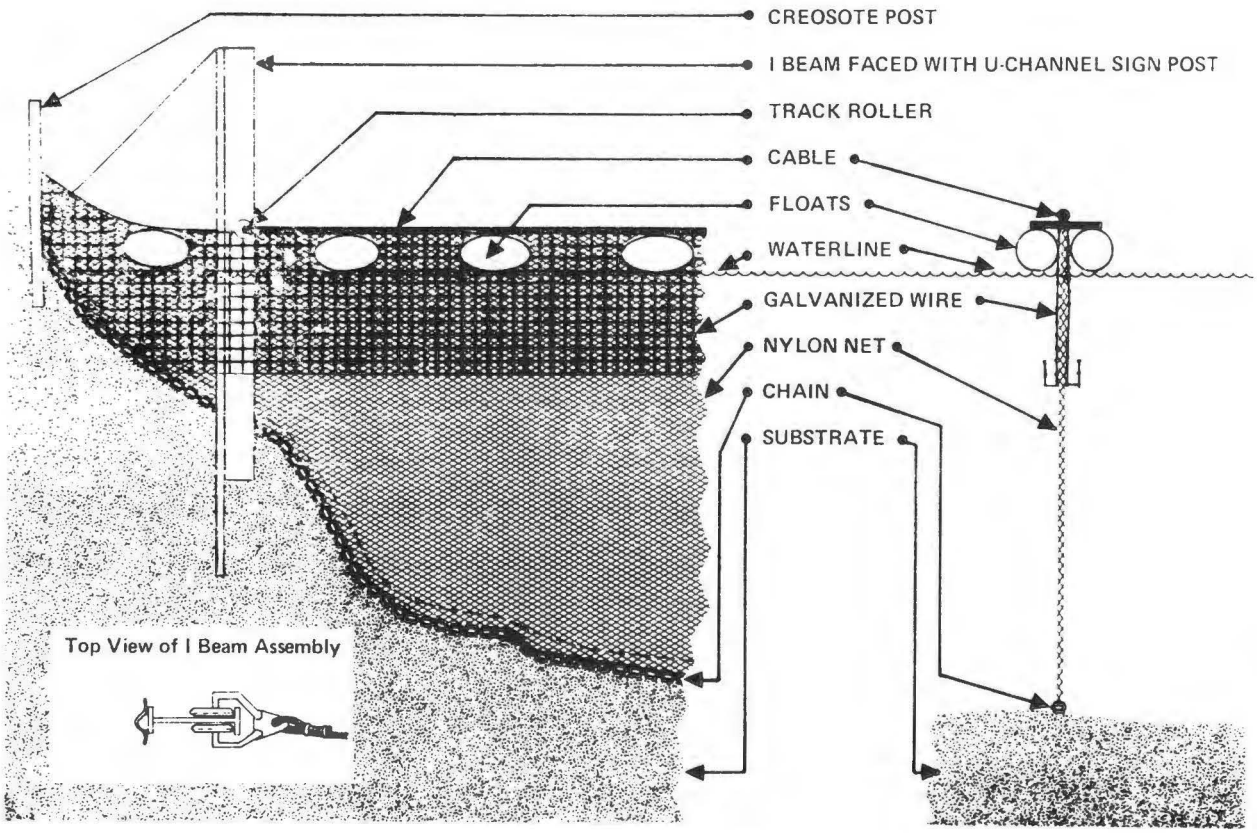


Fig. 35. Temporary nursery cove barrier used on Lake Tyler East and Lake Jacksonville, Texas, 1975 (Smith 1976).

After a suitable cove is isolated and the net is in position, game fish behind the net should be captured, if possible, and relocated. The remaining fish should then be eradicated (e.g., by the application of rotenone) to eliminate competition and predation. The cove is then stocked with fry. When the fish attain desirable size, the net is removed and the fish are allowed to emigrate freely. In some situations, capturing and hauling the fingerlings to

desirable locations may be a more effective dispersal method.

24.2.3. Nursery Marshes

Managed nursery marshes can be developed on upland, marshland, or swampland. The principal structural components are dikes and low-head dams. Spring flooding is facilitated by trapping surface water runoff or by pumping water from a nearby lake or stream (Kleinert 1970).

Fago (1977) identified the three qualities that characterize a marsh that can be properly developed and managed: (1) the marsh structures should facilitate complete drainage; (2) the marsh should be located near adequate water supplies; and (3) a vegetative cover of sedges and grasses should be predominant. The water inlet structures (if any) should be screened to prevent the entry of predators and the outlet structures should allow surface drawdown. Fish-capture facilities may be incorporated into outlet structures as needed.

After the marsh has been filled with water, either of two methods of fish introduction can be used. One is to capture adult spawners from receiving water and transfer them to the marsh at a ratio of three males to one female (Fago 1977). After the fish have spawned, the adults are recaptured and returned to the receiving water. Alternatively, eggs may be stripped from ripe adults and incubated at a hatchery, and the fry stocked in the marshes. This method ensures a much higher hatching rate, and may increase recruitment potential (Williams and Jacob 1971).

Both Mathis (1964) and Smith and Swingle (1944) attempted to improve stream fishing by manipulating the fish populations of ponds in river basins. Mathis (1964) eradicated fish populations in oxbow lakes (dominated by rough fish species). The lakes were then restocked with an overabundance of game species. He believed that the overcrowded conditions would encourage emigration to the river during flood periods; thus, the oxbow lakes would serve as nursery ponds for the river. Smith and Swingle (1944) constructed small ponds adjacent to the receiving stream. The ponds were then stocked with desirable species, on the theory that the ponds would serve as nurseries and would continuously add small fish to the stream through the outlet; large fish would emigrate to the river during floods.

24.3. IMPACTS ON THE ENVIRONMENT

Nursery habitat development techniques are methods of habitat enhancement directed at increasing fish stock recruitment rates and, as a rule, have little potential for negative environmental effects; however, two adverse effects have been reported. Williams and Jacob (1971) reported unaccountable

severe losses of northern pike brood fish in managed spawning marshes. They suggested that stocking fry, instead of allowing brood fish to spawn freely, would not only eliminate the loss of brood fish, but would offer several other advantages: fry densities in the marsh would be controlled, which should result in better growth rates; fingerlings would be of uniform size, which should reduce cannibalism; predation by brood stock would be eliminated; and rearing, handling, stocking, and transportation costs might be reduced.

Keith (1969) reported that when fingerlings were released from separate-structure nursery ponds, immediate losses to predators occurred. Large numbers of fish were evidently attracted to the water draining from the nursery pond. Plankton feeders were the first to appear and were followed by predators. Predators seized the fingerlings as the fish entered the receiving water.

Several ancillary benefits often accrue when nursery waters are developed. Nursery ponds that are constructed adjacent to streams perform as sedimentation basins and can greatly reduce sediment deposition in the receiving stream (Smith and Swingle 1944). By developing managed marshes for northern pike spawning, the resultant increased stock of predatory fish may sometimes help to alleviate stunting in panfish populations (Williams and Jacob 1971). Lastly, fingerlings that are reared in nursery coves and nursery marshes may be more vigorous than fingerlings raised in hatchery rearing ponds because conditions are more demanding during early development of the fish.

24.4. COSTS

Construction costs for separate-structure nursery ponds are high, though they are variable and strongly influenced by the topography of the construction site. The height, length, and strength requirements of the dikes are generally the principal cost determinants (Keith 1969). Smith (1976) reported that the cost of nursery ponds (5 to 40 acres) in Arkansas ranged from $50,000 to $200,000 (1975 dollars).

The nursery cove technique was developed as a less expensive alternative. Smith (1976) reported that the cost of the nylon webbing was $0.29 per square foot (1975 dollars) and that additional expenditures for materials amounted to about $3.00 per linear foot. A list of labor requirements was also provided (Table 9). If fry are stocked, consideration must be given to the hatchery costs involved.

No cost analysis was obtained for the development of managed spawning marshes; however, cost determinants should be similar to those for nursery ponds.

Table 9. Man-days of labor required for building barrier nets at Lake Tyler East and Lake Jacksonville, Texas, 1975 (from Smith 1976).

Activity	Lake Tyler East	Lake Jacksonville
Preparation of site	0	9.5
Preparation of net	5.0	3.5
Installation	8.5	7.0
Observation	15.0	12.5
Maintenance	1.5	1.5
Removal	5.0	4.0
Total	35.0	38.0

24.5. EVALUATION FOR USE ON UMRS

Both managed spawning marshes and nursery coves may be used in UMRS if recruitment problems arise among desirable sport fish populations. If northern pike populations in UMRS are affected, and a decision is made to attempt to augment recruitment, many potential locations for managed marshes should be available for development. The nursery cove technique could be applied to small sloughs that meet appropriate requirements. In the Middle Mississippi River, where more habitat is known to be needed, it could be provided by flooding portions of levee and drainage districts.

It is doubtful that the construction of nursery ponds would ever be warranted on UMRS. The cost alone may be prohibitive. Moreover, the nature of the riparian topography of UMRS may preclude its use.

CHAPTER 25. FISH SCREENS AND BARRIERS

25.1. SITUATION TO BE MITIGATED OR ENHANCED

Industrial, irrigational, hydroelectric, and municipal water diversion projects have the potential to adversely affect sport and commercial fisheries and sensitive ecosystems. The quality and quantity of the plankton, benthos, and nekton can be severely diminished if precautions are not taken in the design and operation of such installations.

Damage to aquatic organisms occurs by either entrapping or impinging larger organisms against the outer parts of the water intake structure or by entraining small organisms in the water as it is pumped through a canal system or inner plant. Impingement of nektonic species can be caused by hydraulic forces in the intake stream before it flows through screens. In general, impingement is lethal to most species, owing to physical injury, starvation, and exhaustion in the screen well; asphyxiation when fish are forced against a screen by velocity forces that prevent proper gill movement; descaling by screen wash sprays; and asphyxiation when water is removed for prolonged periods. Inner-plant or entrainment damage to organisms may result from the passage of relatively small benthic, planktonic, and nektonic forms through the condenser cooling system or turbine. Mortality of these organisms can occur from one or more of the following causes:

1. Physical impact in the turbine.
2. Physical impact in the pump and condenser tubing.
3. Pressure changes caused by diversion of the cooling water into the plant or by the hydraulic effects of the condensers.
4. Thermal shock in the condenser and discharge tunnel.
5. Chemical toxemia induced by antifouling agents such as chlorine.

Fishes entering irrigational diversions are lost from the system. Though they may live for some time in a canal, their loss must be equated with mortality in the stream or lake from which they were lost.

The first steps taken in determining the environmental design of intake structures should be the identification of the critical organisms that require protection. The approach has been outlined by the Atomic Energy Commission (Barnes 1976).

All of the fish screening devices described here either prevent or guide

fish movement and, except for barrier dams and the McClusky Canal screen, are designed to mitigate fish losses incurred by various water-related construction projects. Specifically, the screening devices are designed to prevent entrainment of fish and fish eggs in industrial, irrigational, hydroelectric, and domestic water diversions. A variety of designs have resulted from attempts to improve screening efficiencies and to reduce impingement losses.

Barrier dams direct fish migrating upstream to a fishway or holding pond and prevent the upstream movement of undesirable species. The dams can also be used to prevent emigration of desirable species from an impoundment, restrict the availability of spawning habitat to undesirable species, and prevent the intermingling of fish populations. An absolute barrier to fish may be necessary to prevent potentially damaging species from gaining entry into a drainage system. Screens are designed to prevent downstream movement and barrier dams to restrict upstream movement.

25.2. DESCRIPTION OF TECHNIQUES

The numerous fish screen and barrier designs offer varying degrees of effectiveness and ranges of applicability. The devices can be divided into two categories: those that impose an absolute physical barrier to fish movement and those that take advantage of behavioral characteristics to restrict fish movement. In the category of structures intended to be absolute barriers are the revolving drum screens, perforated plate screen, parallel bar screen, rotating disk screen, link belt screen, horizontal traveling screen, inclined plane screen, passive intake screens, electric fences, high-capacity sand filters, perforated pipe filters, and barrier dams (Barnes 1976; Burns 1966; Clay 1961; Johnson Division UOP, Inc. 1979; Leitritz 1952; Nelson et al. 1978; Sonnichsen et al. 1975; Wales et al. 1950). The louver diverter (Rhone and Bates 1960) and fish excluder (Nelson et al. 1978) are behavioral barriers.

25.2.1. Fish Screens

Several questions must be considered in the design of a fish screen: How wide and deep should the intake conduit be? What mesh and wire size is appropriate? How large should the bypass opening be? and Where should the screen be placed? The answers depend on the swimming ability, physical size, and behavior of the fish (Clay 1961). The maximum allowable approach velocity is limited by the cruising speed of the fishes involved, and the design specifications for the actual screen and bypass are determined by the physical size and behavior of the species. The design criteria for the other devices are unique to each, and the swimming ability, size, and behavior of fish may or may not be important considerations.

The bypass is a structure that allows fish to leave the area of the screen and return to a desirable location away from the diversion. The effectiveness of a bypass depends on its location and flow characteristics of the water--i.e., its velocity and quantity (Clay 1961).

Several general guidelines should be kept in mind when intake structures are designed (Barnes 1976):

1. Systems employing a guidance principle, such as louvers, may have highest guidance efficiency at relatively high approach velocities, generally in the range of 1 to 3 fps.

2. Intakes employing a fish recovery and handling system, such as vertical traveling screens with scoops for lifting fish, may result in the highest survival rate when the approach velocity is relatively high. Fish tend to swim against a low approach velocity until they are fatigued; when they are eventually picked up in the recovery device, they are more susceptible to the stress imposed by handling. At higher velocities, the fish are carried into the recovery system and picked up before they are fatigued.

3. Low approach velocities may be more desirable for intake systems that rely on sustained swimming capability of fish to avoid entrapment.

4. Higher approach velocities may be permitted when an efficient, properly designed, or naturally occurring bypass system moves fish quickly past and out of the influence of the screens.

The horizontal revolving drum screen was first developed by the Oregon Game Commission in 1921 for use in irrigation ditches (Clay 1961). Several design variations that have been developed were discussed by Barnes (1976), Burns (1966), Clay (1961), Leitritz (1952), Mayo (1974), and Nelson et al. (1978). The designs evolved around two operational modes--either a partly or a fully submerged drum. In the design with the partly submerged drum design, the drum is submerged for only two-thirds to three-fourths of its diameter to reduce the incidence of fish being carried over the top of the drum. Debris, however, is carried over the drums and washed off on the downstream side. The totally submerged drum has a collection and bypass channel located on top (Mayo 1974). A trash rack and sand trap, consisting of a depression ahead of the drum, enhance the operational efficiency of a horizontal drum screen.

The important design characteristics for the drum screen are mesh size, drum diameter, drum rotation velocity, and velocity of water through the screen. The operational effectiveness of the horizontal drum screen is also sensitive to water level changes (Barnes 1976).

The horizontal drum screen is popular throughout the Pacific drainage because it is inexpensive and easy to install (Burns 1966; Clay 1961). California has discontinued its use, however, because too many fish escape past the screen and because screen maintenance is a serious problem (Burns 1966).

The vertical axis revolving drum screen was developed primarily for pumped diversions, but it is equally effective for gravity diversions (Burns 1966). The vertical model, unlike the horizontal model, revolves on a vertical axis and is cleaned by internal water jets. It requires about 3 ft^2 of surface area for each cubic foot of flow; hence it is one of the most efficient screen designs in use (Burns 1966).

On irrigation diversions, the drive mechanism is a paddle wheel downstream from the screen. It rotates the drum screen at a much slower rate and in the opposite direction by means of a chain and a system of reduction gears (Clay 1961). Electric drive mechanisms are also used when necessary.

The rotating disk screen consists of a screen-covered disk set at right angles to the intake flow. The disk rotates around a horizontal axis. As the screen face leaves the water, spray nozzles wash debris and fish into a collection trough (Barnes 1976).

The rotating disk screen has no general advantages over other common screens. It does have most of the drawbacks. The provision of sufficient protection for aquatic life requires that a very large screen be installed; thus the utility of the design is reduced (Barnes 1976).

The perforated plate screen consists of a metal plate set at a 30° angle to the flow. The plate, 50% of the surface of which is perforated, is cleaned by a bar that travels along the face of the plate.

Different drive mechanisms may be used to operate the wiping arm: a "direct drive" system without gears, a system that employs a reducing gear to increase power and dependability in slow flow conditions, or a hydraulic drive system that may be required when large volumes of water are being screened. Power may be supplied by either a paddle wheel or an electric motor in the first two drive systems; an electric motor is required to power the hydraulic system (Wales et al. 1950).

Special attention must be given to construction of the bypass and regulation of approach velocities. Because dead water space is created at the nonperforated base of the plate, the bypass must be incorporated with great care (Clay 1961). Furthermore, excessive numbers of chinook and coho salmon

fry were impinged on the plate and destroyed by the cleaning bar at approach velocities exceeding 0.4 fps. The device should therefore be operated at slower approach velocities when fry are present (Clay 1961).

The parallel bar screen has several design deficiencies that preclude its effective operation: the flexible bottom seal allows fish passage; the lower shaft and gear arrangement is completely submerged, and therefore wears excessively; and the wiper bars do not exert sufficient pressure to effectively remove accumulated debris (Leitritz 1952). Because these deficiencies appear to be inherent in the design, the parallel bar screen does not warrant further consideration.

The link belt screen or vertical traveling screen is used primarily for industrial intakes (Clay 1961; Nelson et al. 1978). The device incorporates screened frames linked together in a continuous belt that travels vertically or on an inclined plane. Water jets wash debris and fish into a collection flume located at the top, and automated controls, which monitor head differential, allow the screen to move intermittently as dictated by trash accumulation (Clay 1961; Nelson et al. 1978). The need for a bypass may be avoided by locating the screen at the entrance to the intake, but approach velocities should not exceed 0.4 fps when fry are present (Clay 1961).

The horizontal traveling screen, which is a modification of the link belt screen, was first designed and operated by the U.S. Bureau of Commercial Fisheries between 1965 and 1969 (Fig. 36). The structure consists of a vertically hung, endless belt of wire-cloth screen panels that is flush with the face of the water intake structure or set at an angle to the direction of flow (Bates 1970).

The screen travels on rails at a speed near the velocity of flow, which minimizes head loss (Bates 1970; Burns 1966). As the belt reaches the downstream axis, the screen is cleaned by water jets and swung out parallel to the current. The screen then is turned and carried to the upstream axis, where it is again swung into position to face the current.

As a fish protection device, this screen has several advantages over other screen designs. Since the travel speed can be matched to flow velocities, impingment of fish and fish eggs is gentle and far less damaging. Moreover, the horizontal travel mode keeps fish in the water, preventing potentially damaging exposure to air.

The velocity-matching screen also offers several operational advantages over vertical traveling screens. All major operating parts are out of water, reducing corrosion and wear; and screens are easily removed and returned when inspection, repair, or replacement is necessary. In addition, because

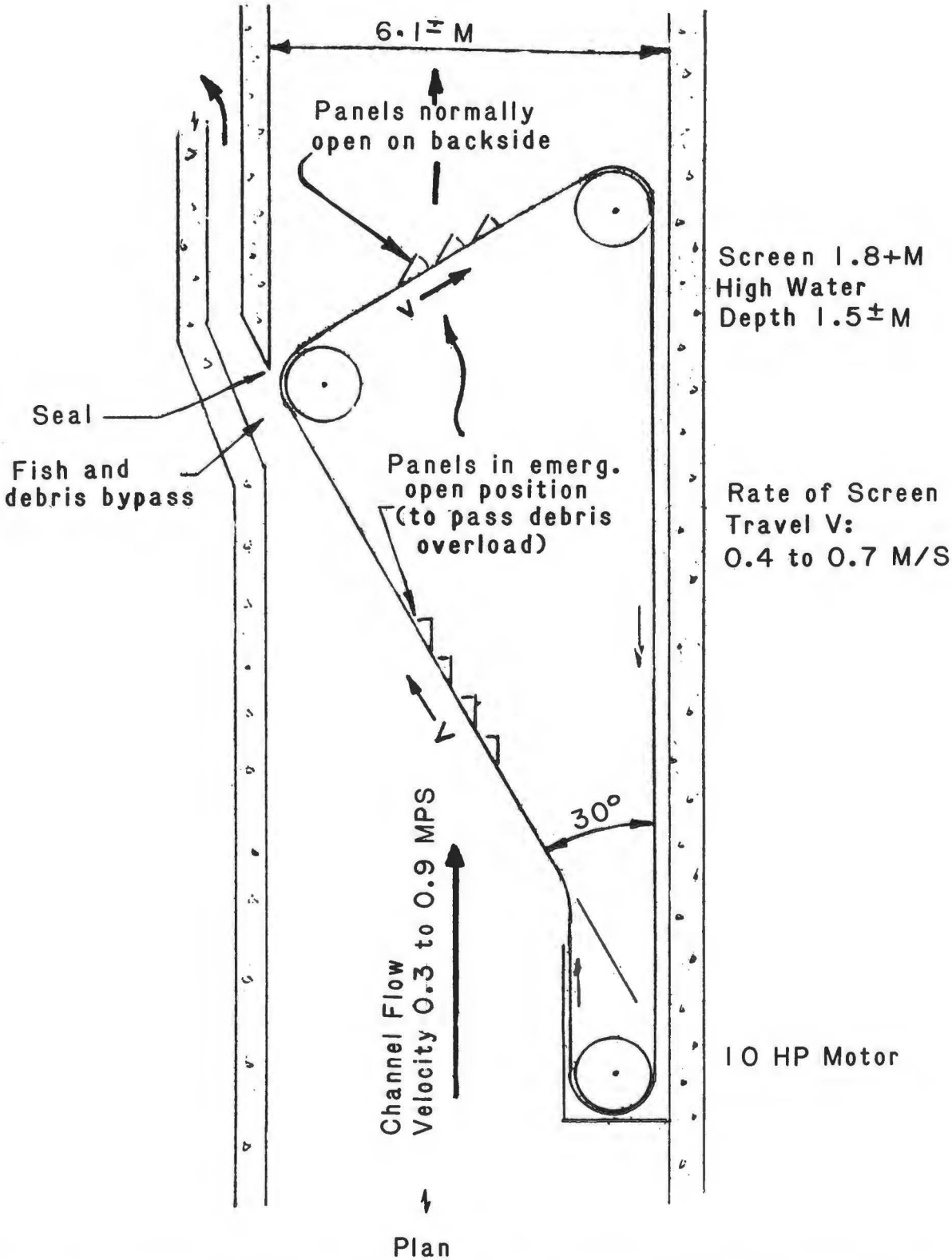


Fig. 36. Schematic of a Mark VII horizontal traveling screen (Barnes 1976).

fewer bypass entryways are necessary, little water is lost to the bypass facility (Bates 1970).

Inclined plane screens are designed to facilitate fish passage at hydroelectric installations. The devices collect downstream migrants at dams by chuting water onto a perforated plate or screen. The water falls through the screen into a sump, and fish and debris slide into a collection trough (Burns 1966; Clay 1961). The flow through the screen is controlled by the slope of the screen or a solid plate under the screen, and the collecting trough conveys the fish to a fishway where they can continue their downstream migration.

Skimmers and gulpers are modifications of the inclined plane. Skimmers are passive collectors that function on a flow of 200 cfs and divert fish as previously described. A gulper is an active collector; a pump that generates 50 cfs creates flow conditions that attract and direct fish over the screen and into a live-box, in which the fish are transported downstream (Clay 1961).

The simple inclined plane screen may be used in any diversion where incoming water depth can be held constant. Skimmers and gulpers are adaptations of the inclined plane screen that facilitate downstream passage of fish at large impoundments. The gulper, which floats, is designed to eliminate the problems resulting from extensive water level fluctuations (Clay 1961).

The passive intake screen, as defined by Fritz (1980), is any device that "screens-out debris and biota with little or no mechanical activity required." However, the present discussion is confined to screens similar to the designs developed and manufactured by the Johnson Division UOP, Inc. The technology of passive screens is based on the principle of controlling the approach velocity field at the screen face to minimize impingement and entrainment of motile and non-motile aquatic life (Johnson Division UOP, Inc. 1979).

Passive intake screen systems have some general, common characteristics. The screens are self-supporting. They can consist of cylindrical, drum-shaped, or flat panels, and the screen material incorporated is usually wedge wire. Further, the systems may be self-cleaning when located in flowing water; however, stand-by backflushing systems should be incorporated (Fritz 1980).

Biofouling can be a chronic problem affecting passive screens constructed of stainless steel; however, biofouling seems to be significantly reduced if the screens are constructed of certain copper alloys (Thiele 1979; Wiersema

et al. 1979). The effective life of screens made of copper alloys is about 30 years (Thiele 1979). The material thus has merit from an engineering and an economic perspective.

The design of passive screening systems is still in the developmental stages; nevertheless, a passive intake screening system was considered to be the best technology available for St. Johns River generating station of the Seminole Electric Cooperative (Lifton 1979).

The McClusky canal screen, a modification of the inclined plane screen concept, is designed to filter out all material larger than .04 in. in a flow of 1950 cfs (Nelson et al. 1978). The structure, constructed of 40-mesh brass screen, is mounted on a 5° downward slope over which the flow passes. The waste and debris are gradually pushed into a collection channel and routed to a holding pond (U.S. Bureau of Reclamation 1974).

Electric fences have been used primarily to guide upstream movement of migrating salmon (Burns 1966). The fences usually incorporate a double row of hanging electrodes, but a single row of electrodes is often used in conjunction with a ground line flush to the bottom of the stream. Alternating and direct currents have been used, but pulsating direct current has been most successful.

Design criteria vary with the unique demands of each installation. The following characteristics must be considered: the spacing of the electrodes, the separation between rows of electrodes, the voltage applied to the system, the pulse frequency, the pulse duration, and the specific conductance of the water (Barnes 1976).

Several drawbacks limit the use of electric fences. Fish generally avoid electric fields; however they often become disoriented, dart into the field, and are injured by overexposure (Bell 1973). Similarly, electric fences are not effective barriers to downstream movement, especially in fast current, because fish are often merely stunned and swept downstream through the electrodes. Electric fences should not be installed where bottom contours are irregular because under such conditions the continuity of the electric field is difficult to maintain. Lastly, appropriate power sources are often unavailable (Clay 1961).

High-capacity sand filters have been used extensively for municipal water supplies, but only recently have attempts been made to adapt the concept to power plant and canal water intakes (Nelson et al. 1978). The experimental design developed for the proposed Marias-Milk Canal, Montana, has a surface area of 30,000 ft^2. It was designed to be 5 ft deep with layers ranging from coarse sand to 3- to 6-in. rounded cobble (Nelson et al. 1978;

Stober et al. 1974). Some preliminary designs have been developed to serve a major power plant facility. It is constructed of precast filter modules that can be isolated for maintenance (Barnes 1976).

Barnes (1976) also discussed a "leaky dam" design, which consists of a stone and rock embankment surrounding the pump structure. Since the water flows through the "dam," the dam acts as a screen. A facility of this type has been operated since 1972, and is reported to be 70 to 75% effective in screening out fish.

The high-capacity sand filter has several attractive features. It is capable of screening large quantities of water at low approach velocities, thus reducing impingement of fish, invertebrates, and debris. It also requires little space and maintenance. The only apparent problem appears to be clogging by microflora and microfauna (Strandberg 1974).

A perforated pipe filter fish screen developed by McSwain and Schmidt (1976), is composed of perforated pipe, a metal slide gate, concrete head wall, an emergency weir box, and endemic stream gravel and cobble. The device is particularly suited for sceening diversions to irrigation canals. It performs by allowing water to seep through gravel into a perforated pipe that in turn channels the flow into the diversion canal.

The device is constructed as follows. A gabion dam is constructed as near the canal head as practical, and a weir box fitted with flash boards is incorporated in the dam for emergency water supply. Then, a 36-in. diameter perforated pipe ($^3/_{16}$-in. holes account for 33% of the surface area) is encased in a layer of gravel and extended upstream 7 in. below the surface of the riverbed. Lastly, a concrete headwall and metal slide gate are installed downstream for positive flow regulation.

Water supply is regulated by the number and length of the pipes installed. The optimum pipe length is 32 ft; at greater lengths, friction-induced water loss offsets increased seepage. The structure requires little maintenance and protects fish in much the same way as high-capacity sand filters; a very low approach velocity eliminates the impingement of fishes.

Another perforated pipe screen was discussed by Barnes (1976). The device, placed above the stream bottom, relies on passing current to sweep debris and fish away from the intake. Although the device was developed without consideration for fish protection, it appears to be effective in reducing fish mortality.

The radial well is another form of the perforated pipe intake. The collectors are located in highly permeable alluvial aquifers where the water table is high and in direct contact with a surface stream or lake (Fritz 1980). Fritz (1980) listed three fundamental characteristics of the radial well intake:

1. A submerged concrete caisson is sunk into the base of an aquifer adjacent to a recharge source.

2. A number of perforated pipes radiate from the base of the caisson into the aquifer.

3. A pump moves water from the well to the plant.

25.2.2. *Fish Barriers*

Barrier dams prevent fish passage, as a result of either having an elevated spillway or having an apron that produces shallow, fast, turbulent flow. Minimum head differentials range from 10 ft for chinook salmon to 3 ft for common carp and other rough fish (Clay 1961).

Barrier dam construction design and techniques are function- and site-specific. Designs range in complexity from concrete buttresses with elaborate aprons to timber cribs and earthen dams fitted with weirs.

The louver diverter (Fig. 37) is a behavioral barrier that takes advantage of the avoidance response of drifting fish to obstructions. The device guides downstream migrant fish to a bypass system in high-flow diversions where installation of conventional screening would be a problem.

Schuler (1974) reported the following results after extensive testing of louver diverters:

1. The louver efficiency increased with flow up to 2 fps, which was considered optimum.

2. The bypass design is important; the optimum bypass velocity was 3.5 fps.

3. A 1-in. louver spacing gave good results. Increasing the louver spacing to $^{3}/_{4}$ in. reduced efficiency significantly.

4. Louvers should be at an angle of 20° or less to flow direction. Increasing this angle markedly reduced louver efficiency.

5. The louver system worked as well at night as during the day.

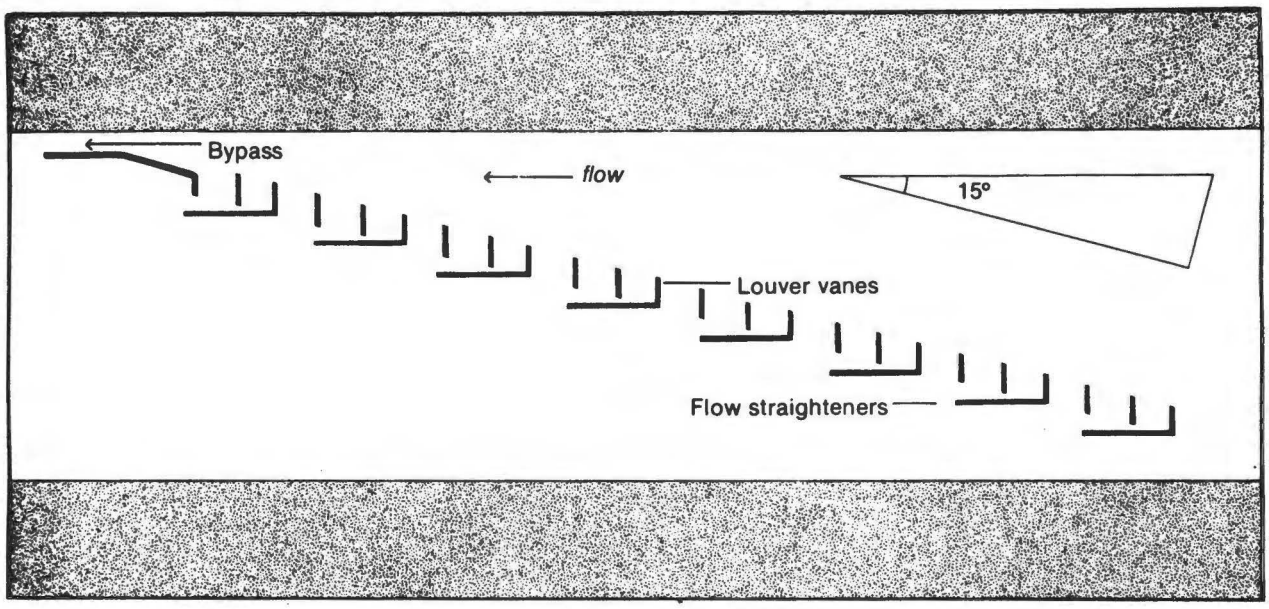


Fig. 37. Functional components of the louver diverter, which is designed to guide fish to a bypass system (Nelson et al. 1978).

Barnes (1976) listed the following major disadvantages of the louver diverter system:

1. The shallow angle of louvers with respect to the channel flow requires a rather long line of louvers, which increases the cost of the intake.

2. The louver system may not effect satisfactory removal of trash. A conventional trash rack may be required upstream, and for more complete trash removal, a set of conventional screens is required downstream from the louvers. The performance of the louver may be adversely affected in streams with a heavy trash load, thus possibly necessitating the use of conventional coarse trash racks upstream to remove heavy debris.

3. A rather complex fish handling system may be required to safely return fish to the water source.

4. Water level changes and flow variations must be kept small to permit maintenance of the required flow velocity.

Efficiency of a louver diverter at Tracy, California, ranged from 80 to 90% for young striped bass and salmon (Clay 1961). Rhone and Bates (1960)

stated that diversion efficiencies dropped to about 74% for catfish less than 1 in. long.

The fish excluder, another behavioral barrier, consists of a concrete and gravel sill that surrounds a canal intake (Nelson et al. 1978). The structure is positioned with a slight upward slope toward the headworks. It functions by taking advantage of the reluctance of fish to expose themselves in very shallow water. A fish approaching the headworks senses that it is moving into shallower water and turns away.

The only representative of this design, which was discussed by Nelson et al. (1978), is located at the East Bend Unit of the Beaverhead River, Montana. Design and efficiency statistics were not reviewed.

25.3. IMPACTS ON THE ENVIRONMENT

Few adverse impacts result from the installation of fish screening devices. From a biological perspective, fish losses incurred because of a screening device would have occurred whether or not the device was present. Losses can be reduced only by incorporating the best technology available. Dorn and Johnson (1981) presented state-of-the-art intake systems, including physical and behaviorial barriers and collection and guidance return systems. From an engineering perspective, fish screens cause a loss of hydraulic head; appropriate design (i.e., size of intake and type of device) can control this loss. In addition, fish bypasses may result in a loss of available water, an important consideration in irrigation diversions (Clay 1961).

Adverse impacts of some barrier devices have been identified. Electric fences pose a potential hazard to humans and animals, particularly in areas of high visitor use (Clay 1961). When barrier dams are used to block upstream passage of fish, a small impoundment is formed that may cause loss of habitat due to reduced flow and increased siltation; unfavorably high water temperatures may result when barrier dams are installed on small coldwater streams.

25.4. COSTS

Cost estimates were not obtained for every device. Barnes (1976), however, presented an extensive cost analysis for screens and intake structures. Plant size and approach velocity directly affect screen cost. The range of prices (1971 dollars), based on flow, was from $57 to $10,700 per cubic feet per second.

Clay (1961) presented costs for louver diverters. The Tracy unit cost $394 per cubic feet per second the Puntledge River project cost projection was $300 per cubic feet per second.

Strandberg (1974) estimated the cost of construction (at 1972 prices) of his conceptual design of a high-capacity sand filter. The estimated cost for the filter and control unit, which included a sump for the main circulating pump and auxiliary fish screens, was about $8.6 million. Operation and maintenance expenditures were estimated to be 0.12 mill per kilowatt-hour over a 30-year life when the filter served a 1100-megawatt nuclear plant with a 30-year average capacity factor of 0.70.

25.5. EVALUATION FOR USE ON UMRS

Applicability of fish screens on UMRS is limited to mitigating the entrainment of fish at municipal, industrial, and cooling water intakes. If hydroelectric facilities that have been proposed were developed, fish would need to be protected at the turbine penstocks.

The applicability of fish barriers is also limited. If a problem involving fish barriers exists on UMRS, it relates to facilitating rather than restricting fish movement. One potential application of barriers might be to direct fish to fishways, if such structures were to be constructed. Neither the need, nor the lack of need, for fishways has been documented on UMRS.

CHAPTER 26. FISH PASSAGE

26.1. SITUATION TO BE MITIGATED OR ENHANCED

Periods of migration are often critical in the life histories of stream fishes. Anadromous fish must move into rivers and often travel hundreds of miles to headwater streams to spawn. Spawning migrations of resident populations often proceed from river pools or lakes into faster flowing reaches or more stable headwater brooks. If migratory movements are impeded or blocked, fish populations may be severely diminished or lost entirely.

Dams have been constructed to harness the energy of rivers and to improve the navigability of rivers. They have also been built to collect and store water for irrigation, domestic, and industrial purposes, and to protect against destructive floods. Dams can impede or obstruct fish migration, and their construction has resulted in decimation and loss of valuable fishery resources. Principal examples include the salmonids of the Columbia River (Schwiebert 1977), various species in UMR (Carlander 1954), and Atlantic salmon and American shad in some rivers of the eastern seaboard (Day 1963; White and Pennino 1980).

Improper installation of highway culverts also obstructs fish passage (Dane 1978; Dryden and Stein 1975; Engel 1974; Evans and Johnston 1974; Metsker 1970). The cumulative effects of several poorly installed culverts within a stream drainage can be substantial.

Dane (1978) defined obstructions as (1) total (impassable to all fish all of the time), (2) partial (impassable to some fish all of the time), and (3) temporary (impassable to all fish some of the time).

Obstructions in the first category limit occupancy of the upstream reaches to the species that can complete their entire life history above that location; those in the second serve as a selective barrier and determine the distribution of fish (i.e., size and species) in the stream; and those in the third are responsive to external influences, such as stream discharge and debris accumulation, and become a detriment to fish populations only when periods of migration and blockage coincide.

The problem of moving fish past obstructions has long been recognized (Day 1963); however, mitigation efforts have often not been started until after the endemic fishery was lost--e.g., that for Atlantic salmon in the Penobscot and Connecticut rivers. Since the problem was first recognized there, several functional fishways, fish locks and lifts, and modified and

improved culverts have been designed.

There is only one reason for installing a fish passage facility: to provide fish with a means of negotiating barriers in streams that interfere with or prevent movement or migration essential to completion of the life history of a fish. Barriers result from the construction of dams and highway crossings, from rock slides, and from the effects of seismic events. When such barriers develop, fish populations may be severely diminished or eliminated.

Fish passage facilities are used primarily to mitigate the negative impact of structural barriers placed in streams where the movement of fish was previously unimpeded; they also have potential as fishery enhancement measures. Specifically, new sections of a stream drainage, previously unavailable to fish populations due to geomorphic obstructions such as waterfalls, may be made available for spawning.

26.2. DESCRIPTION OF TECHNIQUES

26.2.1. Fishways

A fishway is a "water passage around or through an obstruction, so designed as to dissipate the energy in the water in such a manner as to enable fish to ascend without undue stress" (Clay 1961). Fishways, in contrast to fish lock and lifts, enable fish to swim past obstructions by their own effort.

Fishways have been in use for at least 300 years (Clay 1961), but the workable designs were developed in the present century. Four basic designs are widely accepted: (1) the weir fishway; (2) the orifice fishway; (3) the Denil fishway; and (4) the vertical-slot or Hell's gate fishway. Each has unique qualities and limitations.

Fishways have four principal components, each of which must be properly designed for each installation: the entrance approach, the entrance, the fishway proper, and the exit into the upstream water (Mahmood 1973).

The approach to the fishway entrance is critical. Obviously, the fish must first be able to find the entrance. It should be located in the path of migrating fish, if that path is well defined. The entrance should not be blocked by sediment deposits or islands, and it should be free of slack water, reverse currents, and excessive velocity. Moreover, the attractive flow coming from the fishway should be somehow distinct from any other portions of the river flow. Care should also be taken to keep the attraction flow free of

odors that might fish repel--e.g., salmon are distracted by human odors (Mahmood 1973).

Once a fish is attracted to the entrance, it must be able to negotiate it (Mahmood 1973). Orifice entrances are more efficient than weir entrances under similar flow conditions. An entrance set 2 to 8 ft below the tailwater level is most attractive. Slot entrances may be the preferred design when widely varying discharges are encountered (Mahmood 1973). Mahmood (1973) and Clay (1961) provided a detailed discussion of fishway entrance locations.

The fishway exit, the upstream section where the fish leave the fishway, has three functions (Mahmood 1973): (1) to deliver the fish to an appropriate location in the upstream water; (2) to admit correct discharge into the fishway and to allow for upstream water level fluctuations; and (3) to prevent trash from entering and clogging the fishway.

The exit must be located outside the zone of influence of dam spillways and other areas of quickening current. If pool levels fluctuate, gates that adjust automatically should be installed. Moreover, a supplemental flow may be required; trash racks should also be provided. More detailed discussions of fishway exits were provided by Mahmood (1973) and Clay (1961).

The fishway itself--the portion between the entrance and the exit--should be designed to provide a flow that will not overtax a fish's energy reserve, and provide a passage free of risk of injury.

The weir and orifice fishways are similar in some respects. Both are constructed as a series of steplike pools, and both are designed to be used at dams where the water level can be controlled. The weir-type fishway allows water to flow over crosswalls, called baffles, that act as weirs. Fish proceed from "step to step" by swimming over the baffle. In most modern installations of the weir fishway, orifices are installed in the baffle walls and fish may proceed from step to step either over the baffle or through the orifice (Clay 1961). The distinguishing feature of the orifice fishway is that fish pass from step to step through the orifice only, because water is not allowed to spill over the baffles, as it does in the weir fishway.

The vertical-slot or Hell's gate fishway, which repeats a constant flow pattern at all operational depths, is best adapted to conditions where pool regulation is not possible (Bell 1973). Clay (1961) described the vertical slot fishway (Fig. 38) as follows:

"This fishway is constructed by installing a series of baffles at regular intervals between the walls of a flume. The baffles are so

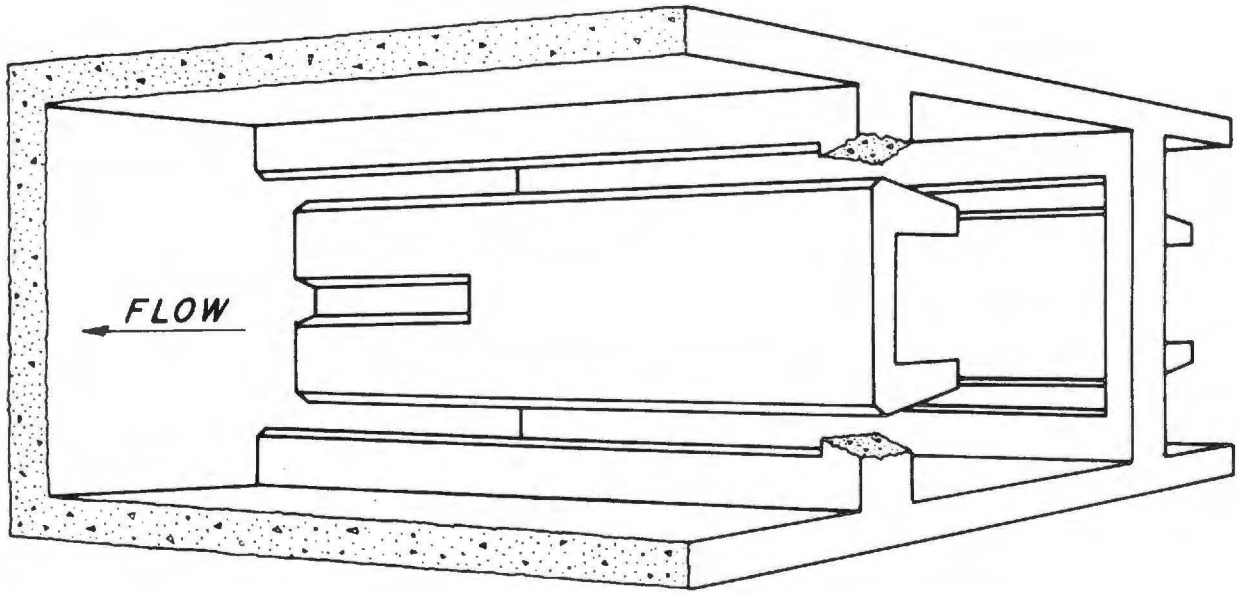


Fig. 38. The Hell's Gate paired vertical slot fish baffle (Clay 1961).

shaped as to partially turn flow from the slots back upstream, with the result that if the slots are properly shaped and dimensioned, energy dissipation is excellent over a wide range of levels and discharges. It has the added advantages of permitting the fish to swim through the slots from one pool to the next at any desired depth, since the slot extends from top to bottom of the flume."

The vertical slot design has several advantages in relation to behavior of adult salmon:

1. Ascent of the fishway is possible at any depth the fish chooses. There can be considerable variation in depth selection by the fish according to the time of day, light conditions in the fishway, turbidity of water, and other factors.

2. The path of a fish ascending the fishway is not tortuous. Many fishway designers in recent years have expressed the view that fishways with staggered orifices or slots in the weirs or

baffles are not entirely satisfactory. Apparently this view has resulted from observations of fish that have shown difficulty or distress in passing through or over a series of such baffles. The reason may be that the fish orient themselves to a certain extent in relation to their distance from the fishway walls. The fact that passage through the slots of the vertical slot fishway is near the walls, in addition to the symmetry of the baffles, may have some bearing on their success.

3. Conditions for resting in the pools are satisfactory, if required. The physiological requirements in this respect are not clearly understood, but recent tests have indicated that fish tend to accumulate in long fishways, so that it is still generally believed that areas in which fish can maintain position without undue stress (if this can be described as resting) are a necessary requirement.

The Denil fishway is named for a French fishery scientist who, in the early 1900's, conceived the idea that the energy of water flowing down a trough may be dissipated by installing vanes on the sides and bottom of the flume (Clay 1961). The vanes turn the water back on itself, which in turn reduces the flow velocity against which the fish must swim. Because the design does not provide a resting area, Denil fishways are usually composed of short stretches of flume connected by resting pools.

The Denil fishway has many of the advantages of the vertical slot fishway. It operates well where water levels vary, and it allows fish to swim at various depths.

Although fishway design is, to a large degree, site specific, certain general design criteria must be met. These were listed by Bell (1973).

26.2.2. Fish Locks and Lifts

The application of fish locks and lifts began on a practical scale in the mid-1920's, at first because of the expense of building fishways for dams over 50 ft high, and then because of the fear that fish were physically incapable of ascending fishways over high dams (Clay 1961). Clay (1961) defined a fish lock as "a device to raise fish over dams by filling with water a chamber which the fish have entered at tailwater level or from a short fishway, until the water surface in it reaches or comes sufficiently close to forebay level to permit the fish to swim into the forebay or reservoir above the dam. It is similar to a navigation lock." He defined fish lifts or elevators as "any mechanical means of transporting fish upstream over a dam, such as tanks on rails, tank trucks, buckets hung on a cable, etc., and include the means of collecting and loading the fish into the conveyance."

Fish locks, used throughout Europe, have not been favored in the United States. In 1961 the only known installations in the United States were at Bonneville, McNary, and Dalles dams on the Columbia River and at Holyoke Dam on the Connecticut River (Clay 1961). The fish locks on the Columbia River were developed as auxiliary, experimental fish passage facilities. The fish lock at Holyoke has since been abandoned in favor of elevator facilities. Most fish locks are of the Borland design (Fig. 39). A typical operational

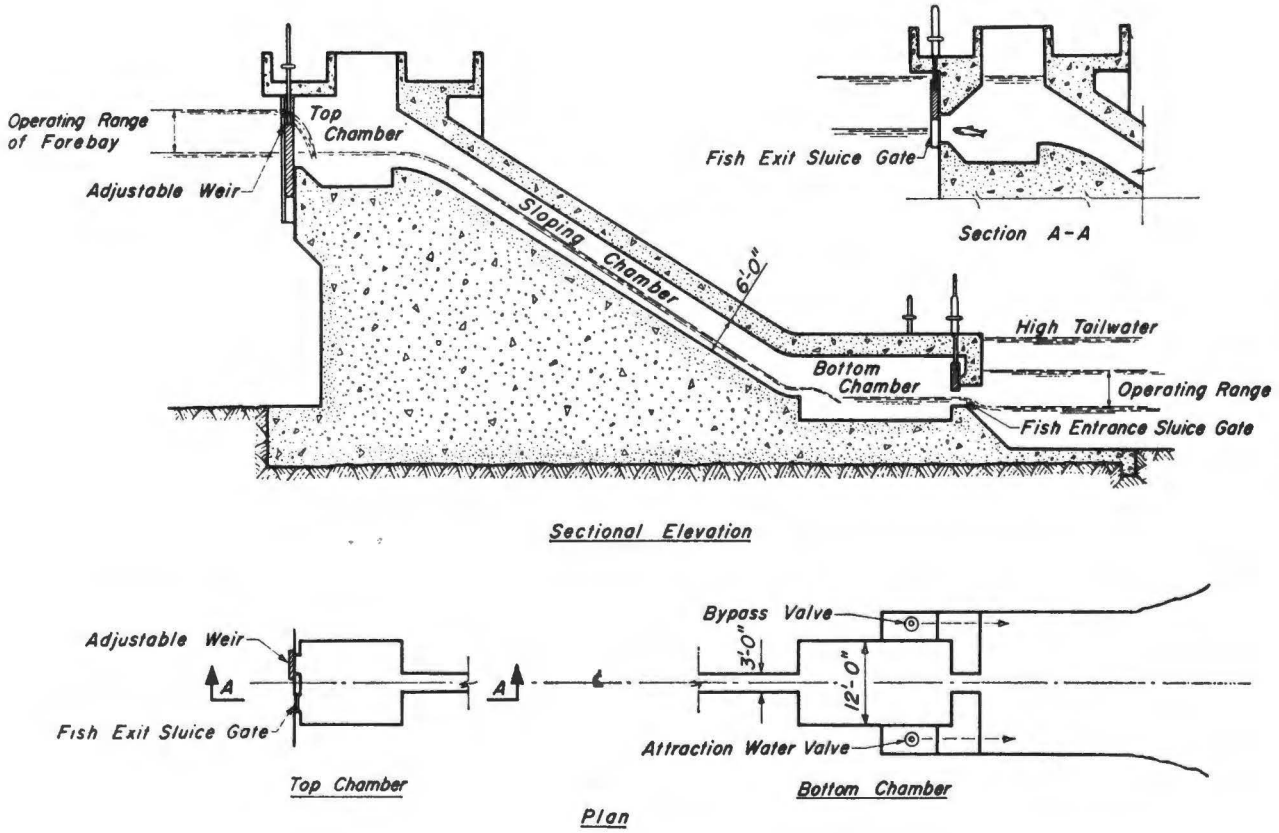


Fig. 39. Schematic plan of a typical Borland fish lock (Clay 1961).

mode was described by Clay (1961) as follows:

> "With the lock controls adjusted to operate on a one-hour cycle, starting with the fish entrance sluice-gate open, the adjustable weir in the top chamber is set to permit about 10 cfs to flow in and down the sloping chamber. This flows out the fish entrance sluice-gate and attracts the fish into the bottom chamber. At the end of 25 minutes the fish entrance sluice-gate closes, and the flow of 10 cfs now is collected in the bottom chamber for five minutes. At this time the fish exit sluice-gate opens, increasing the rate of flow and causing the bottom chamber, the sloping chamber and top chamber to fill in about five minutes. The fish rise to the top

chamber as the water level rises, and are free to enter the reservoir for 25 minutes after the top chamber is filled. They are encouraged to leave by the flow inwards through the exit gate induced by opening the bypass valve beside the bottom chamber. At the end of 25 minutes the fish exit sluice closes, and five minutes later the fish entrance sluice in the chamber opens and the cycle is repeated."

Water economy is considered by some resource managers as the principal advantage to fish locks; but Clay (1961) disputed that rationale. An alternative to fish locks is the fish lift or elevator. In general, a mechanical lifting facility "consists of a barrier dam to halt upstream migrants, a fish entrance and trapping facility, and the collecting and lifting arrangement" (Mahmood 1973).

A typical fish lift is located at the Lower Baker Dam on the Baker River Project, Washington. The barrier dam maintains a minimum head differential of 8 ft. Two 75-ft radial gates were installed on the dam to maintain the differential during peak discharges. The fishtrap, located along the river bank, consists of an entrance, two holding ponds, a brail pond, and hopper pond. The attraction flow is 80 cfs and is fed through a diffuser. Mahmood (1973) provided further information on the fish lift:

"The weir gates in the trap are automatically controlled with the fluctuations in the tail water. A head of 10 ft is maintained on each weir. 'Crowders' (grating) are used to clear the fish from the holding ponds. The brail is similar to those described for fishlocks and is used to transfer the fish to hoppers. The hoppers are 1000 gallon steel tanks. After about 100 adult salmon have been collected in the hopper, the entrance to the hopper is closed and it is lifted by an overhead travelling crane. The fish are then transferred to steel tanks mounted on trucks. These trucks are provided with ice chambers to control the temperature, recirculating pumps and air injectors. The trucks travel about 14 miles to dump the fish upstream of the Upper Baker Dam."

This system has handled as many as 10,000 fish in a month and 3000 in a day (Mahmood 1973). More detailed discussions of fish locks and fish lifts were given by Bell (1973), Clay (1961), and Mahmood (1973).

26.2.3. Modified or Improved Culverts

Improperly installed culverts can obstruct passage by fish. In addition to proper placement in the streambed, structural modifications of culverts may be necessary if fish passage problems are to be avoided.

Dane (1978) stated that excessive water velocity, insufficient water depth, elevated outlets, and debris accumulation are causes of obstruction at culvert sites. Excessive water velocity can develop because a culvert tends to decrease cross-sectional area and channel roughness of the stream channel it replaces. Moreover, the gradient is often increased by straightening, which subsequently reduces the length of the flow channel. Culverts can reduce water depth below that needed by fish because they are generally designed for maximum discharges. Flow depth can also be reduced as a result of the cross-sectional shape of the structure, i.e., the wide, flat bottom. Elevated outlets usually result when culverts are installed without due consideration for the stability of the channel downstream. Degradation of the streambed to a level below the downstream invert resulted in an elevated outlet with a non-negotiable head differential. Though normally designed to be self-cleaning, culverts can become jammed by debris and ice because they usually cause a restriction of the normal flood channel.

The two most important considerations for culvert installation are maximum acceptable water velocity and minimum acceptable water depth (Evans and Johnston 1974). The criteria for both of these conditions depend on the species. For a culvert of moderate length, the mean velocity of the flow should not exceed the fish's sustained swimming speed (the speed a fish can maintain for a period of several minutes, ranging from 4 to 7 body lengths per second). For culverts longer than 150 ft, the mean flow velocity should not exceed a fish's cruising speed (the speed at which a fish can swim for an extended period of time [an hour or longer], ranging from 2 to 4 body lengths per second).

Baffled culverts are necessary if mean flow velocity is in the lower range of the fish's burst swimming speed (the speed at which a fish can swim for a few seconds, ranging from 8 to 12 body lengths per second). Water depth of the culverts should always be great enough to submerge the largest fish that may use the culvert (Dane 1978). Bell (1973) and Haley (1966) listed the swimming speeds of various species of fish.

Although baffles may greatly facilitate fish passage through a culvert, Evans and Johnston (1974) recommended avoiding their use because of increased maintenance requirements. Should baffling be necessary, offset baffles, vertical slot designs, and spoilers can be used (Dane 1978; Engel 1974; Evans and Johnston 1974; Watts 1974).

Detailed descriptions of culvert design and installation considerations were given by Dane (1978), Engel (1974), Evans and Johnston (1974), Katopodis et al. (1978), McClellan (1970), and Watts (1974).

26.3. IMPACTS ON THE ENVIRONMENT

Fish passage facilities have only one beneficial effect--that of allowing fish to negotiate total or partial barriers to their movement; there are no ancillary beneficial effects.

A few adverse effects, however, may develop. Depending on the size of the structure, fishways may require a substantial volume of water to function effectively. If the fishway is installed at a hydroelectric or irrigation storage facility, the water lost to the fishway is lost to the principal operations of the facility concerned.

Fishways may also allow undesirable fish species to pass into a watershed where they did not previously live. Furthermore, fishways may provide access to quality spawning and nursery habitat that would permit a fish species to proliferate beyond previous population levels.

When culverts are baffled to promote fish passage, the structures must be made larger to permit the same discharge; costs increase accordingly. Moreover, culverts with baffles tend to accumulate debris and require extra maintenance.

26.4. COSTS

The cost of fishways depends on the specifications of individual installations, but Clay (1961) provided some insight into the costs in the following summary of fishway cost criteria:

1. Fishways at natural obstructions. Cost is based on a number of vertical slot fishways averaging about 8 ft wide and 10 ft deep (from floor to top of walls) with baffles at 10-ft intervals and surmounting obstructions up to 35 ft high. Cost per cubic foot of volume encompassed by fishway's structure, $3.60 to $7.00.

2. Basic fishway structures at dams on large rivers. Cost is based on a number of structures averaging about 30 ft wide by 10 ft deep (from floor to top of walls) with baffles at 16-ft intervals and surmounting dams up to 100 ft high--cost per cubic foot of volume encompassed by fishway structure, $6.50 (1956 dollars)

3. Miscellaneous items appurtenant to the fishway include control weirs at its upstream end and at the fish entrance. Cost is based on fully automatic operation (described in Clay's text). Add 29% to the cost of the basic fishway structure (item 2, above).

4. Auxiliary water supply for fishways adjacent to spillways (spillway fishways). Cost is based on velocity criteria described in Clay's text; it can vary between 30% and 75% of the cost of the basic structure (item 2), because it depends on the quantity of auxiliary water needed to meet the criteria; an average of 50% is recommended for preliminary calculations. Add 50% to item 2.

5. Auxiliary water supply for fishways at powerhouses with offshore entrance adjacent to spillway. Cost is based on velocity criteria described in Clay's text; this cost also depends on the quantity of auxiliary water needed, which is larger than that for the spillway because of the multiple entrances to the collection gallery. This cost can vary between 50% and 80% of item (2); an average of 80% is recommended for preliminary calculations. Add 80% to item 2.

6. Powerhouse collection system. Cost varies almost directly with the length of the powerhouse; for a dam on a large river having large runs of fish, the cost per lineal foot of length of powerhouse will be about $2200.

7. Offshore entrance to powerhouse fishway. Cost varies from 6% to 10% of item 2; add 8% to item 2.

Clay (1961) also provided several examples of cost analyses.

Clay (1961) stated that, excluding the cost of the barrier dams, the cost of fish locks and fish elevators should be similar. He cited the cost of two facilities constructed in the early 1950's, which was about $200,000 each.

Cost analyses for modified culverts were not obtained.

26.5. EVALUATION FOR USE ON UMRS

It is likely that the installation of fishways at the dams on UMRS would facilitate fish passage beyond its present level. Populations of skipjack herring would probably gain immediate benefits from the installation of fishways at the Keokuk Dam. How other fish populations would respond is not certain.

Carlander (1954) stated that Keokuk Dam is an effective barrier to the upstream migration of paddlefish, American eel, skipjack herring, Alabama shad, buffalo, shortnose gar, freshwater drum, common carp, shovelnose sturgeon, and three species of catfish. However, the ultimate effect of this interference could not be established due to rapidly changing environmental

conditions. Dane (1978) asserted that partial and temporary migratory obstructions can have significant negative effects on fish populations. Eddy and Underhill (1974) also discussed the influence of navigation dams (as partial and temporary migratory obstructions) on the UMRS fishery and concluded that such structures significantly obstruct the movements of fish.

The UMRS fishery is far more complex than those in the rivers of the Pacific seaboard, and the complexity may make the design of adequate fishways more difficult. Variability in swimming ability and time of use of the species present would probably be two of the most important considerations.

Culvert fishways may be useful, but problem culverts need to be identified. We found no references to fish passage problems at culverts in UMRS.

CHAPTER 27. WATER CONTROL STRUCTURES

27.1. SITUATION TO BE MITIGATED OR ENHANCED

Dams have varied and numerous effects on rivers. Dam operation influences water levels, flows, fish passage, and several constituents of water quality. Changes can be either beneficial or detrimental to endemic fish populations (Blahm et al. 1976; Krenkel et al. 1979).

The impoundment of water always alters the heat budget of a stream (Hutchinson 1975). The presence of shallow, nonstratified impoundments generally results in warming of the water in the impounded reach and in the tailwaters. Deep, density-stratified impoundments store cold water in the hypolimnion and, depending on the location of the outlet, may greatly reduce temperatures in the tailwater (Baxter and Glaude 1980). A stream that previously maintained a coldwater fishery may, because of an impoundment, support only warmwater species. Conversely, former warmwater streams may support only coldwater species in the tailwater zones (Baxter and Glaude 1980). Some tailwaters become so cold that almost no fish can endure--e.g., the Flaming Gorge tailwater on the Green River, Utah, circa 1965.

The chemistry of water may change significantly after the water enters a reservoir, and the change may, in turn, result in serious environmental consequences downstream. Hannan (1979) summarized the principal factors influencing chemical conditions of reservoir discharge as listed by four authors: (1) Love (1961)--density flow; reduction in velocity of inflow; evaporation; wind movements; dissolution or precipitation of mineral species; and biological activity. (2) Neel (1963)--age of impoundment; extent and duration of thermal stratification; frequency of density currents; depth of water release through or over dams; operational objectives; extent of drawdown and refill; and a types of release structure. (3) Sylvester (1968)--water depth; extent of shallows; storage volume in relation to quantity of inflow; length to width ratio; depth of water withdrawal; orientation of axis with the prevailing wind direction; characteristics of the soils in the reservoir flow area; quality of incoming water; climate conditions of rainfall and temperature; depth of reservoir drawdown; and presence or absence of stratification. (4) Wunderlich and Elder (1973)--geometry and size of reservoir; storage management of the yearly cycle; geometry and location of the outlet; amount, distribution, and quality of the inflow; internal mixing processes; optical properties of the water; climate of the environment; heat and mass transfer process across the water surface and the ground; and biological and chemical processes in the water.

Hannan (1979) also stated that biological activities may have a greater effect on the chemical changes that take place in an impoundment than previously thought.

Changes in dissolved gas concentrations, a consequence of river impoundment, are almost always detrimental to fish. Hypolimnetic oxygen deficits often occur in deep, density-stratified impoundments. Such deficits restrict the availability of fish habitat in the reservoirs, promote the dissolution of chemical constituents from the sediments, and may cause oxygen deficits in the tailwater if the dam is designed with a deep-water release. The tailwaters of high dams may also experience nitrogen supersaturation. The condition occurs when released water plunges deeply into a stilling basin, and the pressures force nitrogen in the water into supersaturation (Hannan 1979).

High-energy discharges from reservoirs constitute a special problem to fishery managers and hydraulics engineers. If the energy of the release water is not dissipated, it will threaten the structural integrity of the dam and the morphology of the tailwater channel, as well as preclude the survival of most aquatic life in the zone under its influence.

Dams, especially those constructed on floodplain rivers, alter the hydrology and sedimentology of the river. Backwaters and side channels can be profoundly affected; some become filled with sediment and others become stagnant sloughs cut off from fresh water supplies.

The structures described in this chapter can be used to mitigate the various adverse impacts of dam construction and operation on riverine habitat and fisheries. They are designed to help control water quality within the impoundment and the tailwaters, dissipate the destructive force of high-energy releases, stabilize extreme variability of release flows, and maintain the quality of backwaters and side channels.

Skimming weirs, multi-level penstocks, and deep-water withdrawal can be helpful in maintaining desirable water quality in both reservoirs and tailwaters by controlling reservoir mixing and water exchange. Flip buckets, stilling basins, and baffle-type energy dissipators control the destructive forces of high-energy reservoir discharges. Flip buckets and high-turbulence stilling basins can also reduce nitrogen supersaturation problems. Reregulation dams relieve the environmental flux caused by hydroelectric generating facilities. These dams are especially valuable when they can be used to stabilize the combined flows of several offstream hydroelectric facilities. Complete and partial closing dams, gated culverts, and vortex tube sand traps mitigate the effects of altered river hydraulics on backwaters and side channels. The structures can be used to facilitate flows of fresh water and reduce harmful influx of sediments.

27.2. DESCRIPTION OF TECHNIQUES

27.2.1. Skimming Weirs and Penstocks

Skimming weirs, low-level penstocks, and multi-level penstocks, when incorporated into the construction and operation of dams, facilitate the withdrawal of water strata or mixtures of water strata that have desirable water quality characteristics.

Skimming weirs or walls are submerged damlike structures built upstream from the dam proper (Bohan 1970b). Depending on the depth of the layer of water lying over the weir crest proper, either the uppermost surface layer or a somewhat lower subsurface layer is withdrawn.

Low-level penstock releases can promote several desirable water quality conditions in reservoirs. Hypolimnial releases can reduce the severity of stratification, increase overall reservoir water temperatures (at depths greater than 10 ft), and promote substantially higher dissolved oxygen concentrations throughout the deeper reservoir strata (Martin and Stroud 1973). Hypolimnial release can also be used to sustain a coldwater fishery in the tailwater zone (Wirth et al. 1970).

Multi-level penstock intakes are elaborate mechanisms that permit selection of discharge water from various reservoir strata. Their primary purpose is to control tailwater temperatures for the benefit of fish. Secondarily, the device can be used to aid in the control of dissolved gases and solids in turbine releases (Nelson et al. 1978). The design and hydraulic characteristics have been investigated in detail (Bohan and Gloriod 1972; Bohan and Grace 1973; Gloriod and Bohan 1973).

A more detailed explanation of the influence of discharge location on water quality, biology, and sport fisheries of reservoirs and tailwaters was given by Martin and Stroud (1973) and Monkmeyer et al. (1977).

27.2.2. Energy Dissipators

A spillway deflector, often called a "flip bucket" or a "flip lip," is an energy dissipator that can be built onto a spillway to prevent the formation of nitrogen supersaturated water (Fig. 40). It does so by redirecting the flow horizontally along the surface of the water (Nelson et al. 1978). These devices can be retrofitted to existing dams, but cost less if they are included in the original design. A more detailed examination of spillway deflector designs was presented by Basco (1969), Bastian (1971), and U.S. Army Engineer Waterways Experiment Station (1959).

Stilling basins and baffle-type energy dissipators are usually incorporated into dams to dissipate the energy in high-energy dam releases. If properly designed, they prevent downstream erosion and scour and protect the tailrace fishery from destructive flow velocities. Examples of such devices were discussed by Grace and Pickering (1971), Melsheimer and Murphy (1967), and Oswalt and Pickering (1974).

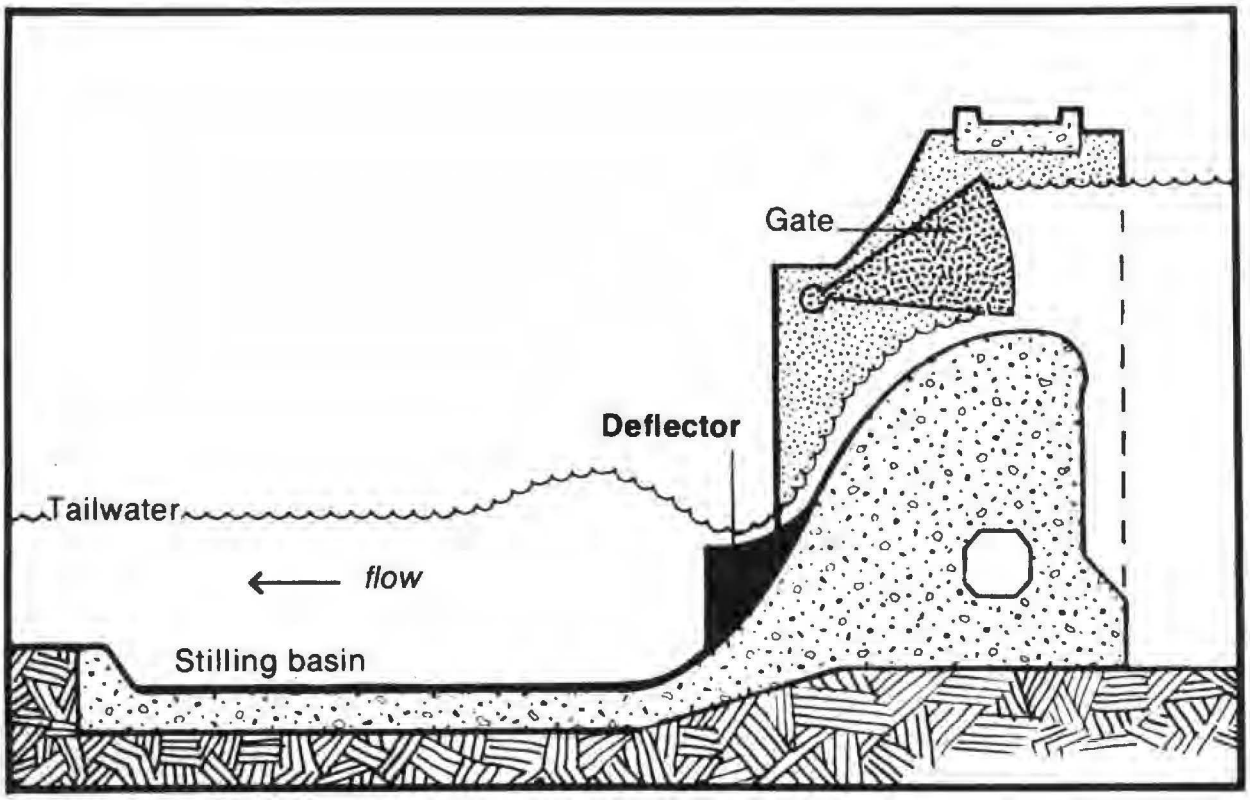


Fig. 40. Cross section of spillway with deflector or flip-lip (Nelson et al. 1978).

27.2.3. Reregulating Dams

Reregulating dams are primarily constructed below hydroelectric generating facilities. The dams are designed to even out the highly variable pulse flows associated with power production, and thereby protect fish from being stranded by rapidly receding water levels. The dams help ensure minimum flows for fish, wildlife, and recreational needs (Nelson et al. 1978).

27.2.4. Side Channel Modification Structures

Gated culverts, complete and partial closing dams, and vortex sand traps may be useful in altering the hydraulics in backwaters and side channels, and thus reduce erosion and the damaging effect of sediments. (The use of gated culverts is cited in Chapter 30 and their construction and installation specifications are given in Chapter 39). Whole or partial closing dams are incorporated in side channel modification plans to block or partly occlude highly erosive or sediment carrying cuts. The structures can be constructed of dredged material armored by riprap (Great I 1980e).

Vortex tube sand traps (Fig. 41) may be useful on UMRS, but none have so far been incorporated into existing modification structures in side channels. The vortex tube sand trap is usually used to prevent sediment from entering canals. The device is an open tube lying across the canal (or modified cut), with the bottom either normal to the flow or at 30° to 45° angles to the flow. The vortex tubes are usually tapered, e.g., from 60 in. at the upstream end to 80 in. at the downstream end. The rate of outflow at the downstream end is controlled by a valve. As the water flows over the tube, vortex flow with a speed of rotation of the order of 200 to 500 revolutions per minute is set up, which is sufficient to eject coarse gravel, cobbles, and other materials up to 6 in. in size. Efficiency is usually highest when both lips of the tube are at the same level.

Tests also revealed that if the concentration of incoming sediment increases beyond a certain limit, for given flow conditions, the efficiency falls due to plugging of the tube (Garde and Ranga Raju 1977). Hayward and Sutherland (1974) provided additional information on vortex tube sand traps.

The vortex tube sand trap may be useful when it is installed at cuts with desirable flow characteristics but undesirable sediment loads. Vital water exchange then continues but undesirable sediment transport is reduced.

Erickson and Camougis (1980) discussed several devices used to control sedimentation into wetlands as a result of highway construction. These structures--inlet sediment traps, earthen dikes with filter dams, check dams,

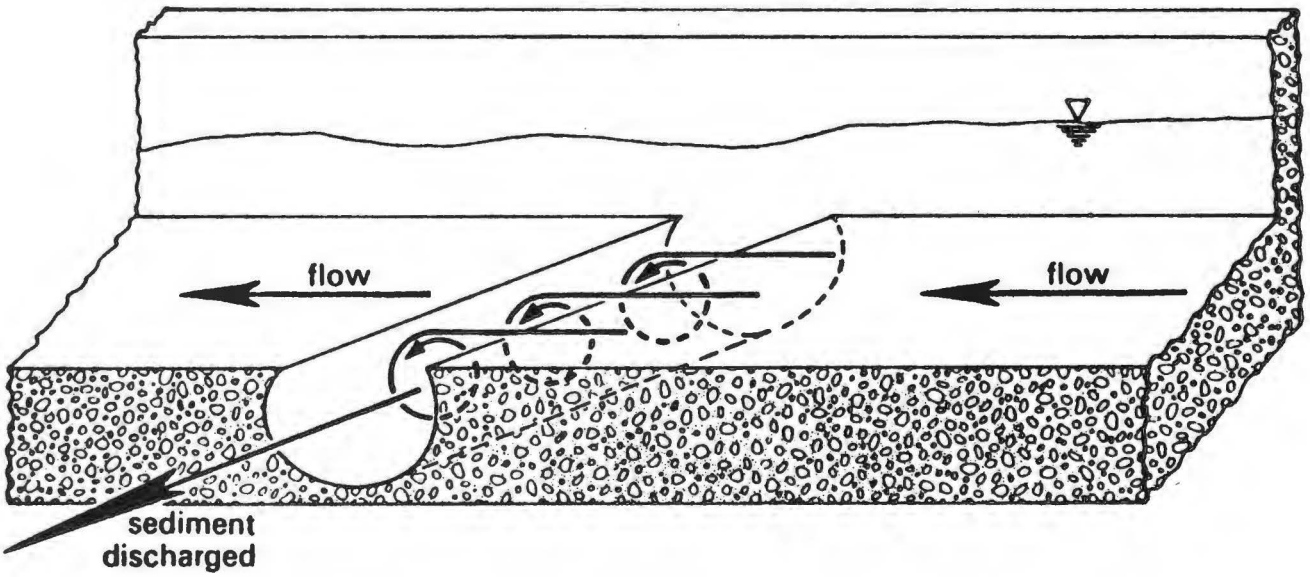


Fig. 41. A vortex tube sediment trap illustrating the ejection of sediment through the flow in the tube (Hayward and Sutherland 1974).

and silt fences--may have some merit in controlling sedimentation into wetlands from other sources. Except for earthen dikes, the construction and maintenance costs are low.

27.3. IMPACTS ON THE ENVIRONMENT

The water control structures described in this chapter impart few adverse effects. The structures generally benefit aquatic environments; they are sometimes a part of normal construction and water management plans. Some of the structures, particularly multi-level penstocks and reregulation dams, are very costly.

Multi-level penstocks are far more versatile than skimming weirs and deep-water intakes. The structures are adaptable to changes in reservoir hydrology and stratification patterns. Deep-water intakes sometimes benefit a

reservoir by flushing silt; however, the release of silt may destroy downstream spawning habitat and harm fish populations by increasing stream turbidity (Nelson et al. 1978).

Stilling basins can provide ancillary benefits to tailwater fisheries. In arid regions, where large offstream water diversions are often allocated, stilling basins may provide a survival pool for fish. They are particularly important when maintenance flow provisions are not incorporated into water management plans.

When culverts are installed to supply side channels with fresh water, impoundment storage capacity is lost. The culverts, however, are usually installed in closing dams on floodplain river navigation projects; such water losses have almost no effect in these situations. Improperly placed closing dams can have an adverse effect on water quality in backwaters and side channels (Lubinski et al. 1981).

Vortex tube sand traps may require substantial maintenance. Moreover, the devices are largely untested, except on strictly controlled canals. The vortex tube sand trap is useful for bed load investigations (Hayward and Sutherland 1974).

27.4. COSTS

The only cost analyses found for the structures described here were presented by Nelson et al. (1978). Capital costs (in 1977 dollars) for the low-level intakes at Navajo Dam, New Mexico, and Beaver Creek, Montana, were $1,704,000 and $275,000 respectively; and annual operation and maintenance costs were $6,000 and $14,000, respectively. Capital costs for multi-level intakes at Oroville Dam and New Bullards Bar Dam, California, were $16.4 and $1.4 million (1977 dollars), respectively. No operation and maintenance costs were provided.

Flip buckets and stilling basins are incorporated into normal dam design and should not be considered an additional cost.

The costs of side channel modification structures vary. Culvert costs are discussed in Chapter 39. Closing dam costs can be reduced by using dredged materials derived from navigation channel maintenance. We found no cost analyses for vortex tube sand traps.

27.5. EVALUATION FOR USE ON UMRS

Among the water control structures discussed here only complete and partial dams, gated culverts, and vortex tube sand traps have applicability on UMRS. The dams on UMRS are not of the type that would make other mitigative devices useful. Closing dams, gated culverts, and vortex tube sand traps can all be used as side channel modification measures (see Chapter 30).

CHAPTER 28. MANAGEMENT OF WATER LEVELS AND FLOWS

28.1. SITUATION TO BE MITIGATED OR ENHANCED

The consequences of river and stream impoundment are always severe. Changes occur in the chemical and physical characteristics of the river, and changes in resident biotic communities reflect the change in environment. A full understanding of the environmental requirements of the resultant communities and the types of changes brought about by impoundment is necessary if the newly "tamed" river is to be managed (as well as it can be) to the advantage of the biota. An attempt to develop such an understanding was made in a comprehensive review by Ward amd Stanford (1979).

Central to the consequences that result from impoundment is the change in the flow regime of the river. Organisms inhabiting lotic environments are rigidly adapted to unidirectional flow, relatively unstable substrates, linear morphology, and relatively shallow water (Fraser 1975). When the system changes, a more nearly lentic assemblage develops in the impounded reach; the biotic communities below the dams also change, depending on how the flow regime is altered.

Two ecological concepts are particularly important when one is considering the consequences of impoundment on fluvial ecosystems. The first is the concept of ecotone or the border zone between two habitats. Ecotones are areas of abundant and diversified life that are very sensitive to any manipulation of the lakes or streams associated with them (Baxter and Glaude 1980). The second important concept is that of pulse stabilization--the maintenance of long-term ecological stability by periodic perturbations (Baxter and Glaude 1980). The maintenance of prairie habitat by periodic fire, or for that matter, the maintenance of a grassy lawn by periodic mowing, are familiar examples of pulse stabilization. Fluvial ecosystems are largely maintained in their normal state by periodic flooding. Fluvial biotic communities are altered by changing the flood regime of a stream; if a stream is impounded, the biota of the entire area will be altered as well (Baxter and Glaude 1980).

River system water management plans must consider the complementarity of environmental effects in the river reaches above and below a dam. Baxter and Glaude (1980) gave some examples of complementary effects: sedimentation above a dam leads to erosion below it; retention of heat in the impoundment causes cooling of the water downstream; and (most important, with respect to the management of water levels and flows) a decreased annual variation in water level below a dam is associated with an increased annual fluctuation above it, and vice versa.

This complementarity of water level and flow fluctuations above and below dams makes it difficult to manage both the impoundments and the tailwaters for the maximum benefit of the fisheries of each area. Management of water levels and flows for the benefit of the fishery requires that the management of the fishery be considered a legitimate function of the waterway and water must be allocated for such management. But that allocation has not always been forthcoming. Competitive, and usually primary, uses of impounded water are hydroelectric generation, irrigation, domestic and industrial water supply, navigation, water quality management, and flood control. Those uses have had primacy in the past, often to the detriment or elimination of endemic fish populations (Orsborn and Allman 1976).

Generally, a great deal of energy has been expended in the development of management techniques for impoundment fisheries (Fraser 1975). Until recently, far less attention has been given to the instream flow needs below dams and diversions. In 1968 the First National Water Quality Assessment stressed a need for an analysis of adequacy of flow for instream uses (Bayha 1978). Since then, a growing concern for instream flow needs has developed, and assessment and allocation techniques and strategies have been sought and developed (Orsborn and Allman 1976; Bayha 1978; Dewsnup et al. 1977; Garling 1976; Lamb 1977; Orsborn et al. 1973; Stalnaker and Arnette 1976).

White (1976) stated that attempts to meet an accelerating demand for water has resulted in large-river waters being overallocated at a rapid rate. This overallocation of available water, especially for offstream uses, has often resulted in a general decline in the fisheries of rivers and reservoirs.

Instream flow requirements for fish, wildlife, recreation, and other uses are now recognized in many places as legitimate uses under water law (Lamb 1977). Objective, scientific methodologies for determining instream flow requirements for fish are being or have been developed so that appropriate allocations can be made for the management of reservoir level and river flow.

Flow and water level management strategies are aimed at optimizing the quality of fish habitat in impoundments and regulated streams. Specifically, the strategies seek to ameliorate the effects of water level fluctuations and reduced stream discharges resulting from offstream diversions and impoundment operations.

Reservoir water level manipulation strategies are implemented for several reasons. They improve fish production by creating quality environmental conditions for primary and secondary producers (i.e., fish food) and improve spawning and rearing success by promoting stable spawning substrate, stable water levels during spawning, and quality rearing cover for young fish. Minimum pool allowances protect the carryover capacity of the system.

Instream flow strategies are implemented to maintain flow requirements for fish passage, spawning, incubation, and rearing. Such strategies also help to protect water quality, promote benthic invertebrate production, and maintain escape cover.

28.2. DESCRIPTION OF TECHNIQUES

Water retention time and the drawdown zone are the principal factors to consider when one is managing reservoir water levels and flows. The length of the retention time affects the fish populations indirectly by influencing the sedimentation rate of incoming suspended material, and plankton development (Benson 1968; Baxter and Glaude 1980). Longer retention times promote higher sedimentation rates that, in turn, result in greater water clarity. Water clarity further facilitates primary production and the feeding efficiency of sight-feeding fish. Plankton production is also facilitated by a reduced current velocity (Berner 1951; Rheinhard 1931; Taylor 1971). The increased plankton production in turn provides a larger food base for fish. Retention time can affect fish populations directly. When it is too short, water velocities in the reservoir may be swift enough to carry fish through the outlet and out of the system (Paragamian 1977; Walburg 1976). The drawdown zone often approximates the productive littoral zone of a lake and is the location of most fish spawning activity. If fluctuations within this zone are not properly regulated, benthic invertebrate populations can be greatly reduced (Baxter and Glaude 1980; Benson 1968; Kaster 1976; Kaster and Jacobi 1978) and spawning of some species of fish can be hampered or prevented (Fourt 1978; Groen and Schroder 1978; Paragamian 1977; Walburg 1976).

The extent to which species of riverine fish are affected by water level fluctuations depends upon their use of shoreline zones for spawning and rearing young. Juvenile fish, in particular, are very susceptible to entrapment and stranding (Becker et al. 1981).

Ploskey (1982) prepared an annotated bibliography concerning the effects of fluctuating water levels on physical and chemical characteristics, algae, aquatic invertebrates, fish, and fishing. The information was applied basically to reservoirs, but results on natural lakes, ponds, marshes, and floodplains were included when insight was given on how changing water levels affected aquatic ecosystems.

28.2.1. Management of Water Levels

Water level drawdowns have been used as a fishery management tool for some time (Shields 1957) and continue to be used to facilitate certain responses in reservoir biotic communities (Beard 1971b; Beard and Snow 1970; Heman et al. 1969; Jester 1971; Lantz et al. 1964; Pierce et al. 1963; Wegener

et al. 1974; Wegener and Williams 1974; Wilson 1959); however, comprehensive reservoir water level management plans for the benefit of a fishery are only now coming into widespread use (Fourt 1978; Groen and Schroeder 1978; Nelson et al. 1978).

"Stage filling," fluctuation control, minimum pools, and seasonal manipulation have been identified as discrete reservoir water level management measures (Nelson et al. 1978). Stage filling refers to partial filling of a reservoir to meet only immediate storage requirements. Filling increments are based on projections of 5-year water demands. Obviously, stage filling is limited to new reservoirs in which the immediate water need is much less than the available storage capacity.

If rapid and severe fluctuations of reservoir pools can be prevented, potential damage to the fishery and reservoir habitat can be avoided. Rapid decreases in water levels, such as those experienced in hydroelectric storage facilities, can adversely affect benthic fauna, fish spawning success, and riparian vegetation. Excessive bank sloughing may also ensue.

Minimum pools are generally of a size considered essential to the survival of fish populations. In general, the holdover capacity of a reservoir is positively correlated with the size of the minimum pool. Moreover, longer water retention times result in increased plankton production, and thus increase the carrying capacity for fish.

Comprehensive seasonal water level manipulation can improve spawning and rearing habitat for fish, as well as overall water quality conditions. Seasonal manipulation is a methodology for use with warmwater and coolwater fishes that are dependent on littoral (drawdown zone) habitat during particular phases of their life histories (i.e., spawning and rearing).

Comprehensive seasonal water level manipulation of reservoirs was reported by both Groen and Schroeder (1978) and Fourt (1978). Both plans were successful; however, the plan reported by Fourt was much less elaborate than that reported by Groen and Schroeder.

The plan used by Fourt (1978) for Beaver Reservoir, Arkansas, focused primarily on the improvement of spawning and rearing habitat. The management regime resulted in record densities of young-of-the-year black bass. The reservoir was drawn down for the entire growing season, which allowed dense stands of vegetation to develop in the drawdown zone. During the following spring, the reservoir was filled to a high level, and about 21 vertical feet of vegetative growth was inundated. After about 6 weeks, the water was allowed to recede at the rate of 0.5 ft per week. The plan called for vegetation to remain inundated as long as possible. Continuation plans called for drawdown and flooding of the vegetative zone in alternate years.

The more comprehensive water level management plan begun by Groen and Schroeder (1978) on Council Grove Reservoir, Kansas, incorporated tight controls over water level fluctuations. The authors presented the following five-point rationale:

1. Gradually rising water level in the spring inundates terrestial vegetation and rocky areas; this inundation enhances spawning and nursery habitat. Increased area and volume encourage increased production of forage fishes. Any sudden drawdown should be avoided to prevent interruption of spawning activity or stranding and desiccation of eggs and fry.

2. A relatively stable or slightly rising water level through late spring and early summer provides additional favorable spawning and nursery conditions. Flooded terrestrial vegetation provides additional protective cover for certain species. Decomposing vegetation adds nutrients to the lake and reduces colloidal clay turbidity.

3. Near mid-summer, a steady drawdown is begun to expose previously inundated areas for revegetation, to make forage fish more available to predator fish, and to control rough fish.

4. In fall, inflows are retained in the reservoir to inundate the lower band of terrestrial vegetation. This partial inundation enhances waterfowl habitat.

5. Drawdown in the winter sets the stage for favorable fish spawning conditions the next spring. This drawdown reduces ice and wave damage to existing shoreline vegetation, and provides additional water storage capacity to serve as a buffer against large inflows, thereby reducing chances for untimely spring drawdowns.

The management plan (Fig. 42) resulted in an improved forage base, increased growth, recruitment, and harvest of walleyes; increased survival of stocked walleye fry and northern pike fingerlings; and improved fish population structure and water quality.

28.2.2. Management of Water Flows

Stream flow management methodologies for fishery resources address two negative impacts of various watershed development projects: severe, repetitive, flow fluctuations and excessive stream dewatering. Severe water level fluctuations below hydroelectric facilities constitute a hazard to endemic aquatic fauna and to the quality of riparian ecotone habitat. If the

Calendar Period	Level Manipulation	Habitat and Population Improvement Purposes
Jan 1 – Feb 28	Hold low	Provide spring runoff and flood capacity; allow weather to clean rocky shorelines of algae, silt.
Mar 1 – May 15	Increase gradually	Inundate vegetation and rocks for improved spawning; reduce walleye losses through dam outlets.
May 16 – Jun 30	Hold high	Maintain fish nursery habitat; decompose vegetation for nutrients and turbidity control.
Jul 1 – Jul 15	Decrease abruptly	Expose shorelines for revegetation; dessicate rough fish spawn.
Jul 16 – Sep 30	Hold low	Expose forage fish to predation; allow vegetation to mature.
Oct 1 – Nov 15	Increase gradually	Partially inundate vegetation for increased waterfowl food and cover.
Nov 16 – Dec 15	Hold intermediate	Maintain for maximum waterfowl use.
Dec 16 – Dec 31	Decrease gradually	Reduce ice and wave damage to vegetation; prepare for next season.

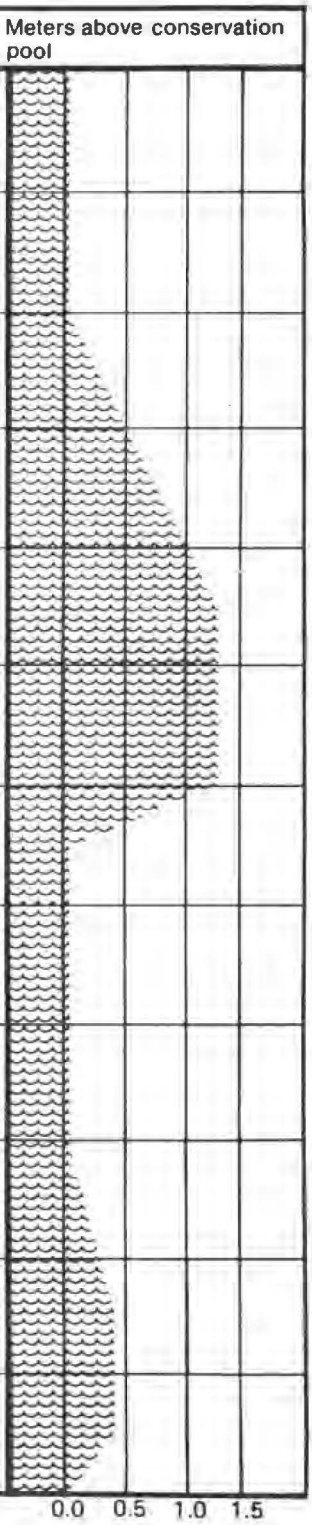


Fig. 42. Graph and synopsis of a typical water level manipulation plan for a warmwater reservoir (Nelson et al. 1978).

water level below a dam drops more than 6 in. in 6 hours, significant degradation of aquatic resources may occur (Kraft and Mundahl 1980; Kroger 1973; Tennant 1976). Slumping stream banks and stranded fish are common consequences of such a rapid reduction of water level.

Excessive stream dewatering affects most aspects of riparian ecology (Fraser 1975). Therefore, developing minimum or maintenance streamflow recommendations is a difficult, multifarious process. As a result, a number of methods for determining the instream flow needs of fishes have been developed. Certain criteria related to the ecology and life histories of instream flow requirements include water quality (i.e., dissolved oxygen and temperature), food production, escape cover, fish passage, spawning flows, egg incubation, and rearing (Fraser 1975). A summary of methods and methodologies for assessment of fishery and stream habitat flow requirements was presented by Stalnaker and Arnette (1976).

The state-of-the-art method for determining available fish habitat when flows vary is a computer simulation model called the Physical Habitat Simulation System or PHABSIM (Milhous and Grenney 1980). The simulation system is a major step toward standardization of the methodology for the assessment of maintenance flow. An earlier version of the model, known as the "increment method" was discussed by Bovel and Milhous (1978) and Stalnaker (1978). Stalnaker (1978) stated that the method "allows the quantification of the amount of potential physical habitat available for fish species and life history phases in a given reach of stream at different stream-flow regimes with different channel configurations and slopes."

The PHABSIM method is composed of four components: (1) simulation of the stream; (2) determination of the distribution of combinations of depths, velocities, substrates, and cover objects by area; (3) determination of a composite probability of use for each combination of depth, velocity, substrate, and cover (where applicable) found within the stream reach, for each species and life history phase under investigation; and (4) the calculation of a weighted usable area (roughly, a habitat's carrying capacity based on physical conditions alone) for each discharge, species, and life history phase under investigation. The primary products of the PHABSIM system are the variation of physical habitat as a function of flow and the variation of physical habitat over time (Milhous and Grenney 1980).

The PHABSIM system can be combined with water quality and temperature information for a total habitat analysis (Fig. 43). Further efforts must be generated toward improving PHABSIM, increasing the knowledge of the relation between physical habitat and the standing crop of fish, and establishing the use of PHABSIM-generated information in fishery and water management.

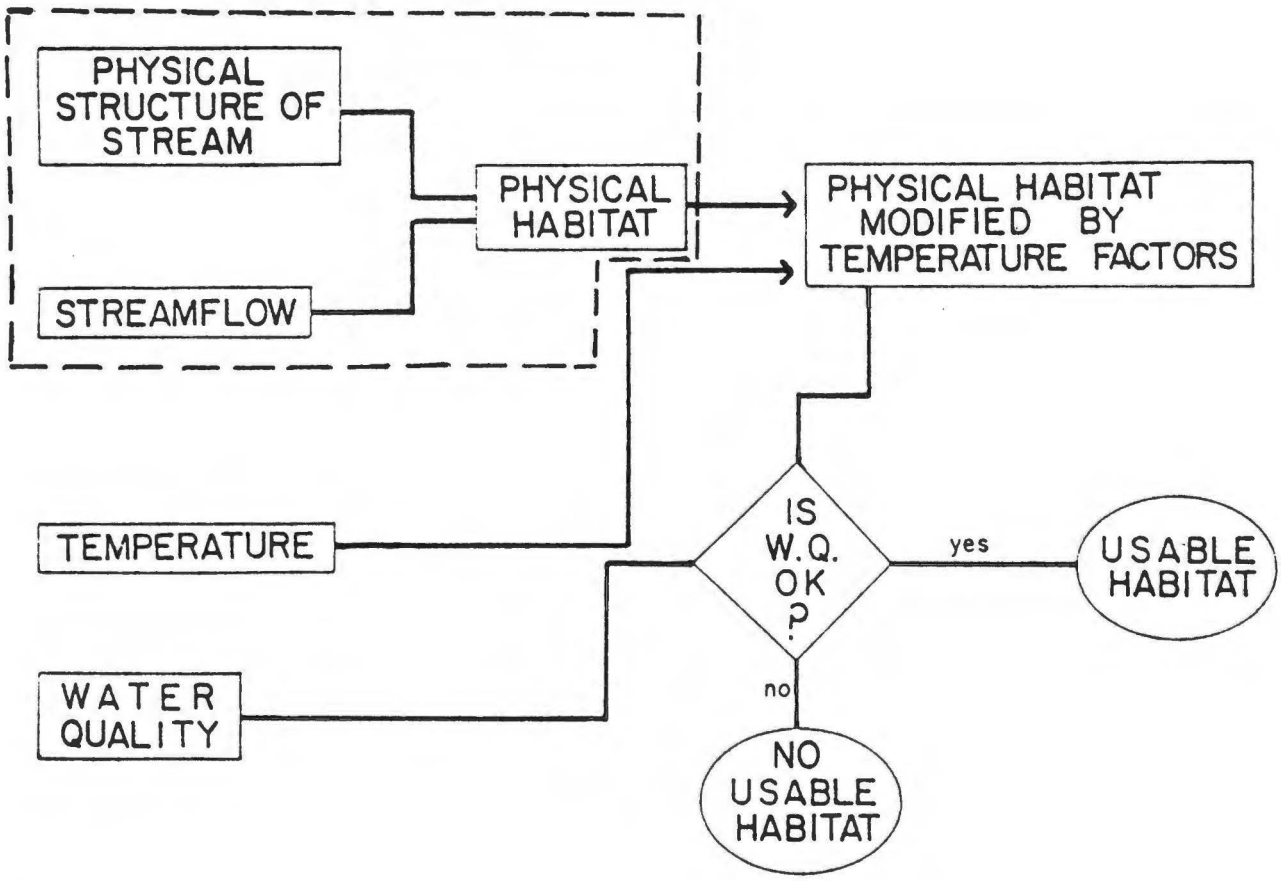


Fig. 43. Information flow for the habitat analysis approach in which the Physical Habitat Simulation System (PHABSIM) is used (Milhous and Grenney 1980).

28.3. IMPACTS ON THE ENVIRONMENT

The management of reservoir and stream water levels and flows for fisheries often conflicts with water management strategies for many of the primary functions of a reservoir. Establishment of minimum instream flows in streams in arid areas, for example, would create conflict in almost all instances (Anderson 1982). The effectiveness and efficiency of hydroelectric projects, navigational impoundments, and irrigational storage and diversion projects would be impaired by maximum management of fish production.

If long-term stabilization of streamflows for the benefit of fisheries is achieved, deleterious changes may develop in the streambed of the river, as well as in the streambeds of the tributaries. Baxter and Glaude (1980) stated that if high flows are abolished in the main stream when the tributaries are in spate, flows will increase in the tributaries near their mouths, and degradation of their channels will occur. Meanwhile, since the materials

deposited in the main stream can no longer be swept away, aggradation will occur, and bars and deltas will be formed. They also maintained that the abolishment of flood flows can have serious deleterious impacts if a river flows through a marsh or estuary (e.g., Peace-Athabasca Delta, Canada). The water necessary to maintain marsh vegetation will not be replenished.

Comprehensive water level and flow management plans should benefit fish throughout their life histories. The same management plans can also benefit wildlife, recreation, and aesthetics (Kadlec 1976; Masteller et al. 1976). The management strategies should also help protect against bank erosion and the resultant loss of what is often highly valued land.

28.4. COSTS

The only cost analyses of water level and flow management strategies in the literature we reviewed was presented by Nelson et al. (1978). Their analyses should be adequate for determining the cost of every component measure of a comprehensive water level and flow management plan. The following information was liberally abstracted from their text.

The cost for controlling reservoir pool fluctuation is equivalent to the quantity of water use foregone, multiplied by the unit price of the water. (No actual costs were calculated.) The cost for controlling flow fluctuation below hydroelectric facilities is considered equivalent to the amount of peak power production foregone, multiplied by the difference between the price of peak-period power and the price of off-peak power. The calculated cost for flow fluctuation control at the Palisades Dam, Idaho, was about $11,500 (1977 dollars).

To derive an equivalent cost of reservoir storage capacity reserved as a minimum pool, Nelson and his colleagues made the following assumptions:

1. The specific minimum pool, exclusive of dead storage in the reservoir, represents the actual storage reserved for conservation.

2. Total live capacity (total capacity minus dead storage) represents the storage repayment potential.

3. Potential repayment by irrigators, power producers, and municipal and industrial users is a surrogate for a cost of live storage forfeited to maintain a minimum pool.

Therefore, for each reservoir a dollar value per acre-foot of capacity was derived by dividing expected repayment over the project life by the

remainder of the amount of live storage minus the amount of the conservation pool. This figure was then multiplied by acre-feet of conservation storage exclusive of dead storage. For the seven applications lending to this analysis, costs ranged from $30,000 to $7.9 million and averaged $1.8 million.

Costs for meeting minimum instream flow requirements are difficult to isolate because the specified flow quantities may partly or wholly meet other downstream project needs. The costs should be equal to the market value of the water forfeited solely to ensure adequate instream flows for fish and wildlife.

In some states, it is permissible to make direct purchases of appropriated water rights for fish and wildlife purposes. For example, a 1-cfs water right was purchased along Boulder Creek, Colorado, for $18,000 (1977 dollars). The cost of water rights ranges widely, depending on factors such as the location, previous use, and seniority of the right.

28.5. EVALUATION FOR USE ON UMRS

The management of water levels and flows may have considerable applicability on the navigational pools of UMRS, particularly in the management of pool water levels for fisheries. If the fluctuations of water levels during spawning periods of pikes and sunfishes can be reduced, spawning success by fish of these populations should be increased.

Water level management would be most applicable on pools with the greatest storage capacity, i.e., in vertical distance above the 9-ft channel maintenance elevation. Alternating water level control from year to year and from pool to pool may optimize the effectiveness of the technique.

This management technique can be one of the most important mitigation techniques available on the pooled portion of UMR; large-scale benefits can result to both fish and wildlife. Adverse impacts of the navigation system can be mitigated and resources enhanced by a fine-tuning of current U.S. Army Corps of Engineers practices at certain times and for specific reasons (e.g., spawning, migrations, establishment of vegetation). In addition, more communication is needed between districts. It is highly recommended that river biologists and U.S. Army Corps of Engineer personnel jointly prepare a plan or set guidelines for managing water levels to benefit both navigation and fish and wildlife.

Minimum instream flows and minimum conservation pools are not an issue on UMRS because navigational water requirements have primacy. These requirements

are such that a 9-ft navigational channel will be maintained, which in turn will provide adequate water for fishery needs. However, if severe drought should occur, contingency plans for such an event should include provisions for the maintenance of minimum instream flow requirements of fish and wildlife.

CHAPTER 29. WING DAM MODIFICATION

29.1. SITUATION TO BE MITIGATED OR ENHANCED

Wing dams made of stone and stone-filled timber pile in the main channel border of UMR provide an important source of fish cover and substrate for periphyton. Biologists and fishermen on the river generally acknowledge that main channel wing dams offer some of the highest densities and best catches of fish (see Chapter 6). The wing dams compensate somewhat for the negative impacts of snag and log removal (Hickman 1975; Marzolf 1978) from the UMR main channel begun more than 160 years ago by the U.S. Army Corps of Engineers. Construction of emergent dike fields in the lower stretches of UMR, however, has led to the loss of substantial aquatic habitat as a result of sedimentation caused by the dikes.

A slack water area is initially formed behind a wing dam. Garde and Ranga Raju (1977) noted that a standing eddy behind a short dike is generally on the order of 4 to 5 times the length of the dike. In a dike field, this region of reduced water velocity (Fig. 44) often fills with sediment (Simons et al. 1975). Boland (1980) reported that 32.6% of the wing and closing dams on the Iowa border of UMR have been covered with sediment. If the structures are not covered with sediment, they form a stable substrate that provides important interstitial space, serves as a catchment for detritus, and provides a high surface to volume ratio for aufwuchs colonization (Lubinski et al. 1980). Sedimentation also reduces the area and depth of water areas created by wing dams.

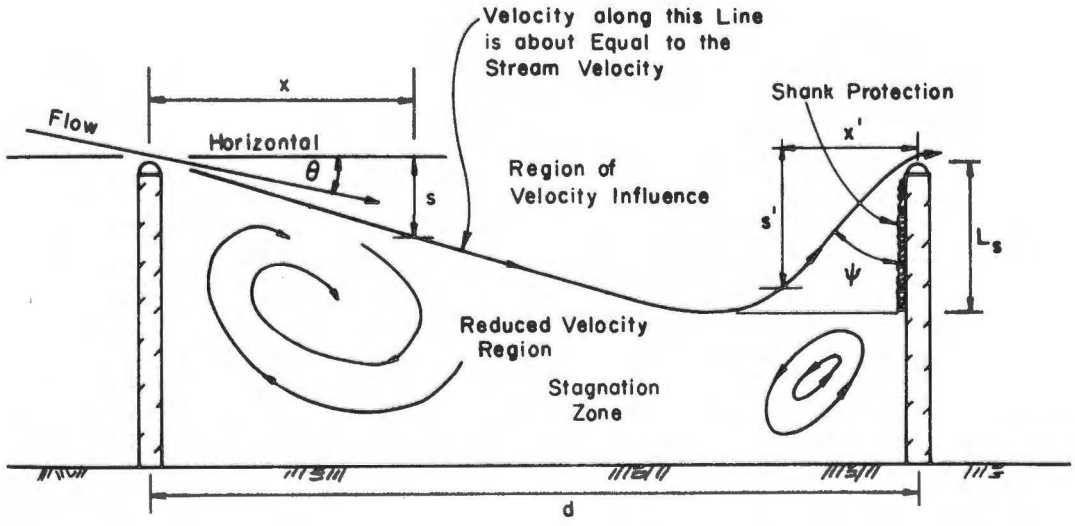


Fig. 44. Regions of reduced flow velocity between stone dikes (Simons et al. 1979).

Sedimentation behind impermeable wing dams may be inhibited by modifying the structure to create high velocity flows over and around the structure, and thereby scouring out deposited sediments and discouraging the deposition of new sediments.

The enhancement potential of wing dam modifications to fish and wildlife resources are discussed in this chapter. Some of the limitations of wing dam modifications are also described.

29.2. DESCRIPTION OF TECHNIQUES

Descriptions of modifications of wing dams in the Missouri and Mississippi rivers are presented for both pooled and open reaches. J. R. Niemi (personal communication) noted that "Great care must be taken when interpolating Missouri River data to the Upper Mississippi River since there are many hydrologic differences. The Missouri River is open and swift and can be partially regulated by upstream reservoirs. Structure modifications may not give the same results on both rivers; each site in the same river must be evaluated individually."

Since 1974, the U.S. Army Corps of Engineers has been engaged in an ongoing program to modify stone dikes in the Missouri River; about 1500 wing and closure dikes have been altered (U.S. Army Corps of Engineers, Missouri River Division 1980). These modifications include notching, eliminating the root, and lowering the height of the structure (Burke and Robinson 1979). Where notches or gaps are created, the accretion process is reduced and about a half-acre of slack water is typically formed downstream from the structure (U.S. Army Corps of Engineers, Missouri River Division 1980).

Notches are gaps or openings created in the crest of a dike. These openings (one or more) allow water to flow through the structure to reduce sediment accretion and reduce the subsequent loss of slack water areas created by dike fields.

In general, the notches created as part of the Missouri River program have ranged from 20 to 100 ft wide and 3 to 12 ft lower than the crest (Burke and Robinson 1979). Burke (1976) reported that these notches can be created by excavating a gap in an existing stone dike, by building new dikes with a notch, or by creating a notch when existing structures are raised or repaired.

The notches in the dikes of the upper reaches of the river have generally been narrower and deeper than those in dikes farther downstream. The dikes in the lower reach are excavated to a depth that allows flow through the notch

95% of the time; river flow through the notch is continuous, except during the period of low water discharge in winter (Burke 1976). Notches created as part of new wing dike construction have been 50 or 100 ft wide. Like excavated notches, these gaps have been constructed at an elevation that permits water flow 95% of the time. On the other hand, notches formed by leaving an area intact when the rest of an existing structure is raised or repaired have been 20 or 50 ft wide, and of variable depths. Burke (1976) noted that no attempt is made to regulate the depth of the notch and that this depth may vary from 3 ft above normal water level to 4 ft below it.

The Omaha and Kansas City Districts of the U.S. Army Corps of Engineers have entered into a contract with the National Stream Alteration Team of the U.S. Fish and Wildlife Service to evaluate the merits of the dike notching program on the Missouri River. Preliminary results indicate that fish spawning, nursery, and feeding areas are being restored (U.S. Army Corps of Engineers, Missouri River Division 1980, 1981). An additional 2000 notches are planned, subject to the results of the study (U.S. Army Corps of Engineers, Missouri River Division 1981).

To date, dike modification by the U.S. Army Corps of Engineers on the UMR has been generally limited to the installation of culverts or creation of notches in the closing dams and spillways that flank the locks and dams (GREAT I 1980e; Green 1960). However, the St. Louis District of the U.S. Army Corps of Engineers modified more than 60 emerged structures between St. Louis and Cairo in 1972-82. The notches ranged from 90 to 400 ft long and from 4 to 15 ft deep. The notches were either V shaped or trapezoidal (C. N. Strauser, personal communication). In a study being conducted for GREAT III, the effects of the notching of dikes in the Middle Mississippi River is being checked (J. R. Niemi; C. Strauser; W. Bertrand, personal communication).

Thackston and Sneed (1982) reported that the notching programs differed between the Missouri and Mississippi rivers because much greater stage fluctuations occur on the Mississippi River. As a result the notches created on the Missouri River dikes are smaller and deeper. The higher and wider notches on the Mississippi River allow more flow but on a less frequent basis.

The Wisconsin Cooperative Fishery Research Unit, Stevens Point, is also currently evaluating the effects of notching on aquatic invertebrate and fish populations (Pierce 1980; Hall 1980; Corley and Coble 1982). As part of the post-notching study on UMR conducted by the Unit, notches were made in three submerged wing dams in Pool 13 (Pierce 1980). These notches were 150 to 300 ft wide, 5 ft below the crest, and centered 200 to 325 ft from the bank. Corley and Coble (1982) evaluated the effects of these modifications on water quality and aquatic organisms and found that several changes occurred; namely, increases in current velocity, proportion of sand in the substrate of the side channel, benthos in the main channel border, gravel content in the substrate,

and benthic invertebrate densities below a notch. Benthos did not increase significantly in the side channel after notching and fish populations were not appreciably affected by the notching.

Rootless dikes are a modification of the notched structure. They are dikes constructed perpendicular to the flow and are not tied into the bank. The distance between the dike and bank may vary from 50 to 250 ft (Burke and Robinson 1979). Because flow is allowed to pass around the landward end of the dike, a potential erosion problem exists along the adjacent shoreline. Typically this area is protected with riprap. Robinson (1980) investigated a rootless dike on the Missouri River that was connected to the bank by an old timber pile dike. Although bank erosion was evident below the dike, Robinson noted that the pilings offered submerged permanent cover for fish at all river stages, a feature that no other dike had.

A variation of the rootless dike is the vane dike, which is essentially a rootless dike with its alignment oriented 15 to 30° downstream, rather than normal to the flow (Burke and Robinson 1979). The construction of vane dikes has been given low priority in the Missouri River notched dike program because of the lower cost of the rootless dikes and the excellent results achieved (Burke and Robinson 1979). In the lower 500 miles of the Missouri River, 130 vane dikes have been constructed (Thackston and Sneed 1982). A type of vane dike ("King's vanes") has been used for many years in India to control sediment entry into diversion canals (Garde and Ranga Raju 1977). King's vanes are a series of submerged curved vanes that are parallel to each other. Two possible configurations of King's vanes that are designed to divert the sediment bed load away from the canal entry but permit water flow are shown in Fig. 45. The King's vane is suggested as a possible device to control the flow of sediment-laden water into backwater channels and sloughs. Its use would certainly be restricted to areas of the channel other than the main navigation thalweg because the heights of King's vanes are typically one-third to one-fourth of the depth of water flow at the point of diversion; this height would obviously interfere with commercial barge traffic.

Another dike modification used in the Missouri River notched dike program has been that of lowering the height of the structure to an elevation that is below the water surface 95% of the time. The low elevations have reduced sediment accretion and have been effective in developing more diverse water depths. A deep hole usually develops immediately downstream from the structure, and a submerged bar 2 to 5 ft below the water surface develops farther downstream (Burke and Robinson 1979).

The dike modifications described thus far (notching, lowering the elevation, and eliminating the root) are essentially designed to promote scouring behind the dike. The scour hole is caused by increased flow velocities as water moves around or over the dike (Simons et al. 1975). Lund (1976) suggested using random rock clusters near the end of wing deflectors to

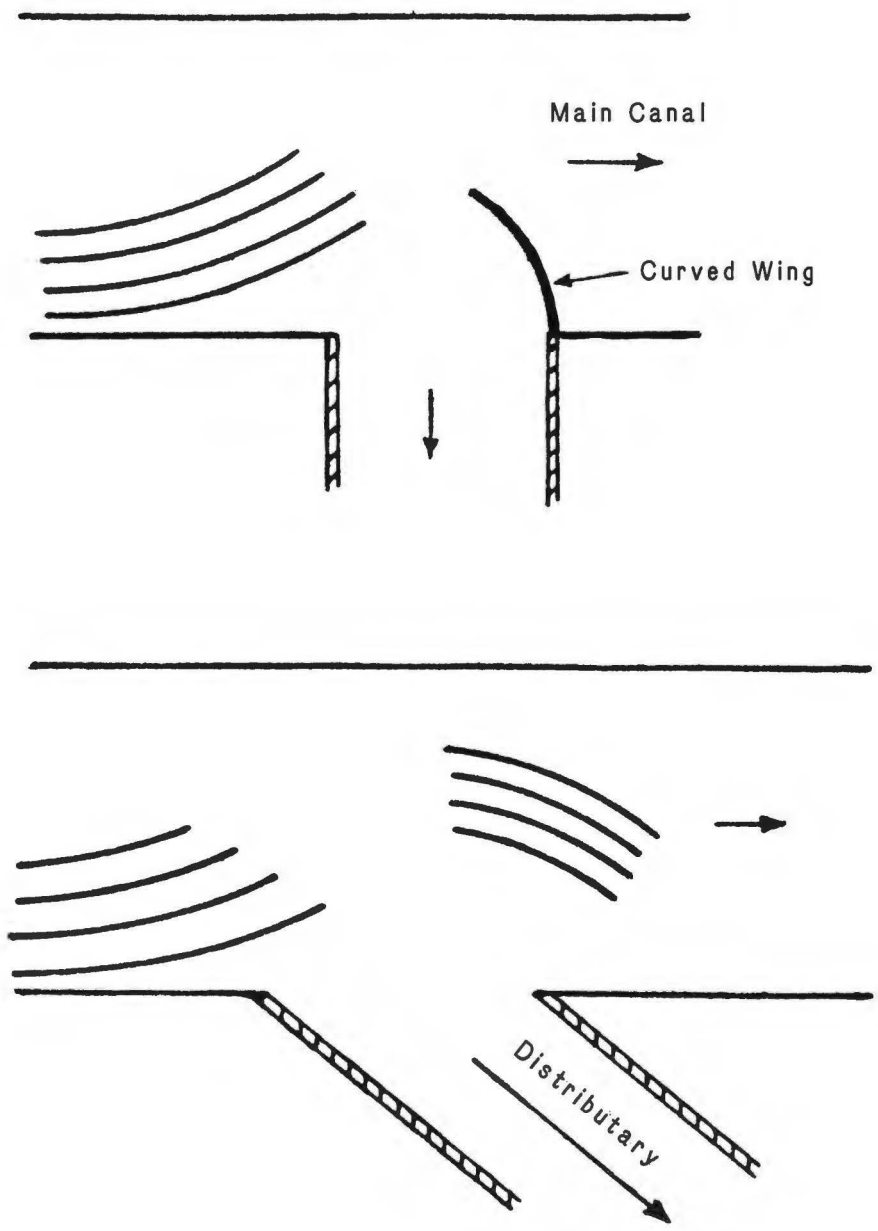


Fig. 45. King's vanes with curved wing (upper panel) and reverse wing (lower panel) (Garde and Ranga Raju 1977).

increase this scouring action. The clusters would create larger mid-channel pools and provide instream cover for fish.

Other possible enhancement measures take advantage of the scoured area and the reduced accretion that results. As part of the mitigation efforts being carried out on the Missouri River, FWS (1980a) suggested placing gravel or boulders below some of the notched structures to create spawning habitat. Brush piles, pilings, and other suitable structures could also be placed in

this zone of turbulence to provide cover. Robinson (1972) also recommended that if, trees must be removed when dikes are repaired, constructed, or notched, the dropped trees should be cabled together and placed downstream from the dike to create fish habitat and shelter.

29.3 IMPACTS ON THE ENVIRONMENT

The modification of wing dikes is intended primarily to be an immediate and inexpensive means of partly restoring main channel habitat for fish and aufwuchs by retarding or eliminating sediment accretion. The modification also functions as a method of reducing the development of land downstream from a wing dam such as has occurred on the Missouri River. The effect of wing dike modifications on habitat quality and fish populations were investigated on the Missouri River by Robinson (1980) and Jennings (1979).

Robinson (1980) studied eight modified (i.e., notched, rootless, low elevation) stone dikes to determine their effects on the diversity of fish habitat and the habitat preferences and use of modified dikes by fish. No significant differences were found in the abundance or composition of the fish population at any of the dikes studied, but the highest catch rate was below a dike where there was semi-permanent slack water. This observation suggests that slack water may be preferred by some species of fish over areas where current is faster. Robinson concluded that when dike levels are low enough or when river stages are high enough for extended periods of time, deposited material can be moved (with properly placed notches) to benefit fish and wildlife.

After FWS (1981c) completed the evaluation of the value of notched dikes to fish habitat in the lower Missouri River, the following conclusions and recommendations were offered:

1. Deeply notched dams speed the removal of accumulated sediments behind structures during high river levels. Obviously, scouring is most effective when the sediment load of the inflowing water is least--in winter, and when the flow is mainly from reservoir releases rather than from direct runoff.

2. Once an open-water area exists, a heavy flow of water through the notch is detrimental. The area needs instead to be buffered from river currents. Further, muddy inflow through the deep notches speeds silting of the backwater.

3. In maintaining the open water behind a structure, the following considerations are important:

    a) Shallow notches are ideal in buffering backwaters from the river, because they operate only at high river stages,

flushing out accumulated sediments. An optimal level for the bottom of the notch may be within 0.0 to +0.3 m of the Construction Reference Plane (CRP), an arbitrary elevation established by the U.S. Army Corps of Engineers that relates elevations near sea level to known river stages.

b) Dams should not be so low that they frequently overflow. The optimal height probably is at least +1.0 m CRP. Coupled with shallow notches at the head of the structure, dams of that height should allow periodic scouring of the structures.

c) Open-ended dams need to be partly closed by wing dams to reduce siltation caused by eddying of river water around the end of the main dam. The wing dams should have a deep notch to promote scouring and to allow access of fish and fishermen; the wing dams should be low along their full length, also to promote scouring.

d) Pairs or series of dams need to be considered together in designing modifications. This configuration is likely to be the only way to overcome silt deposition when the current slackens, while maintaining notches for scouring the structures. Some design features for strings of L-head dams appeared promising in trials at the U.S. Army Corps of Engineers experimental stream at Omaha: deep notches at the head of a string, combined with notches in the wing dams of the lower units. The uppermost units served as sediment basins but those farther downstream remained open and calm.

e) Creek mouths should be protected by notched L-head dams to prevent their silting in. At these points, dams without notches have especially detrimental effects, causing sediment deposits that block discharge from the small stream and filling its lower backwater area. Notches should alleviate this problem and enhance the habitat by affording semi-protected pools where the small stream joins the river.

f) Optimum notch width could not be evaluated, but it appeared that the wider notches were less likely to be blocked by debris.

g) Plans for structure modification should be applied to long reaches of the river channel. Because habitat conditions within each structure change with changes in river stage, it is important that notched dams along the river be of varied designs. In that respect, the extensive notching of numerous dams along most of the river's length, before the evaluative study, had some advantages. The diversity of structures and effects at different river levels aided in

perpetuating habitats, although the locations of the habitats shifted frequently.

4. Many characteristics of catches during the 2 years of study indicated that the fauna is, by necessity, extremely mobile. Probably few fishes hatch, mature, and die near the same structure, as the structures now operate. All fish probably move or are transported by high flows from one area to another. Movement is not necessarily bad, so long as suitable habitat is available for the fish when the river recedes. (Similar shifts may occur during low flows.) The "natural" river had many of the same characteristics in its original condition; the native fauna is adapted to this problem. Minor shifts in position (location) of specific habitats are acceptable if the habitats remain available throughout the river's course. Therefore, extensive structure modification, as opposed to intensive concentration on a few dams only, should have cumulative benefits to fish habitat in the lower Missouri River.

Peterson and Segelquest ([ca. 1981]) reported on the potential impact that the Missouri River notching program may have had on wildlife. The major changes in wildlife habitat have been accretion of sandbars in open waters behind structures, the maintenance of chutes between newly formed bars and the river bank, and the maintenance of deeper lakelike pools behind certain structures. The authors offered three principal conclusions:

1. Chutes may provide habitat for aquatic furbearers, wading birds, and shorebirds, but their main value is in maintaining islands and preventing the usual agricultural encroachment that follows the filling of abandoned chutes. Pools provide sources of aquatic organisms for food and resting places for waterfowl.

2. Newly accreted sandbars provide additional loafing and resting habitat for waterfowl, but they may not compensate for the loss of slack water habitat that they replace. Furthermore, they become wooded islands that have little value to waterfowl as succession proceeds and that are too small to significantly influence woodland species.

3. Shallow-water areas created by the notching program will not replace the wildlife habitats lost by channelization and stabilization of the river. However, the program may serve to maintain existing diversity of aquatic and terrestrial types and associated wildlife populations by preventing the complete elimination of islands, chutes, pools, and sandbar habitats along the river.

Jennings (1979) investigated eight notched dikes on the Missouri River, of which two were enclosed pools, two were notched wing dikes associated with

chutes, and four were L-head dikes in the main channel (Fig. 46-48). The enclosed pools provided substantially better aquatic habitat for fish than any of the L-head dikes studied, in terms of catch per unit of effort, species diversity, and the length-frequency distribution of the fishes caught. These enclosed pools provided nursery and rearing grounds for several fish species, and the greater occurrence of centrarchids in the enclosed pools indicated potential for sport fishing.

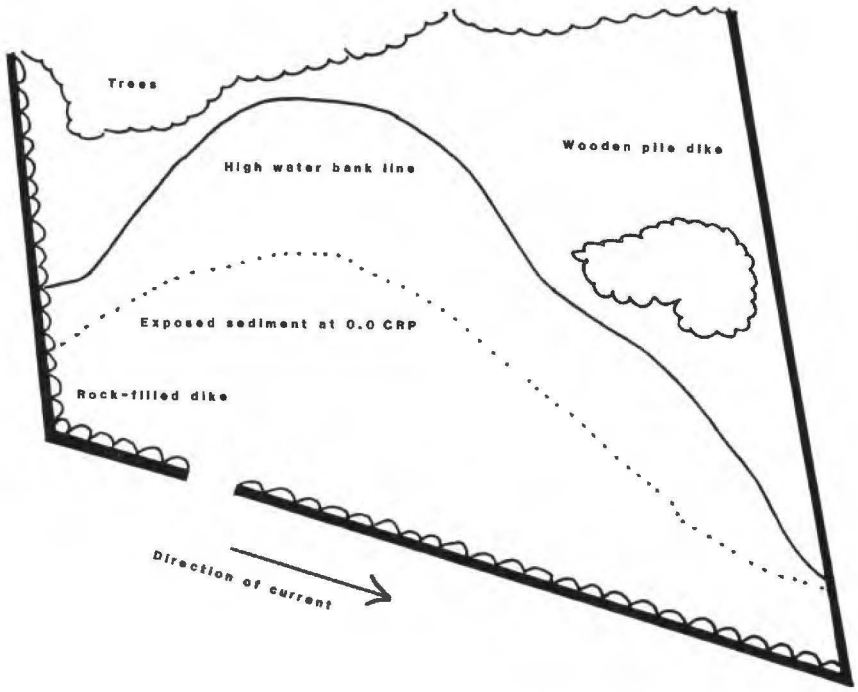


Fig. 46. Enclosed pool dike, a modification of a wing dam on the Missouri River (Jennings 1979).

The chute habitat produced greater numbers and weights of benthic organisms per sample than did most of the other modified dike habitats. The presence of many channel catfish and freshwater drum was believed to be related to the high densities of benthic organisms in the chutes. These areas were also considered to be important nursery and rearing areas for some fishes (Jennings 1979).

The L-head dikes that were studied appeared to offer only marginal fish habitat. Fish food organisms were not as abundant as in the enclosed pools (i.e., zooplankton) or in the chutes (i.e., benthos). Although the habitats created by this type of notched dike offer little potential as fish nursery areas, Jennings (1979) noted that L-head dikes were used by some fishes and that they offered more suitable habitat than the border of the main channel.

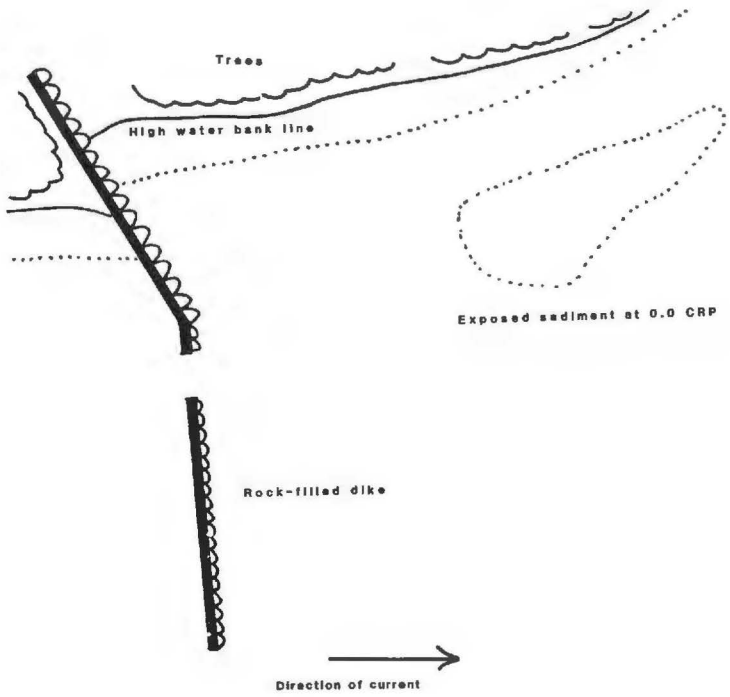


Fig. 47. Chute dike, a modification of a wing dam on the Missouri River (Jennings 1979).

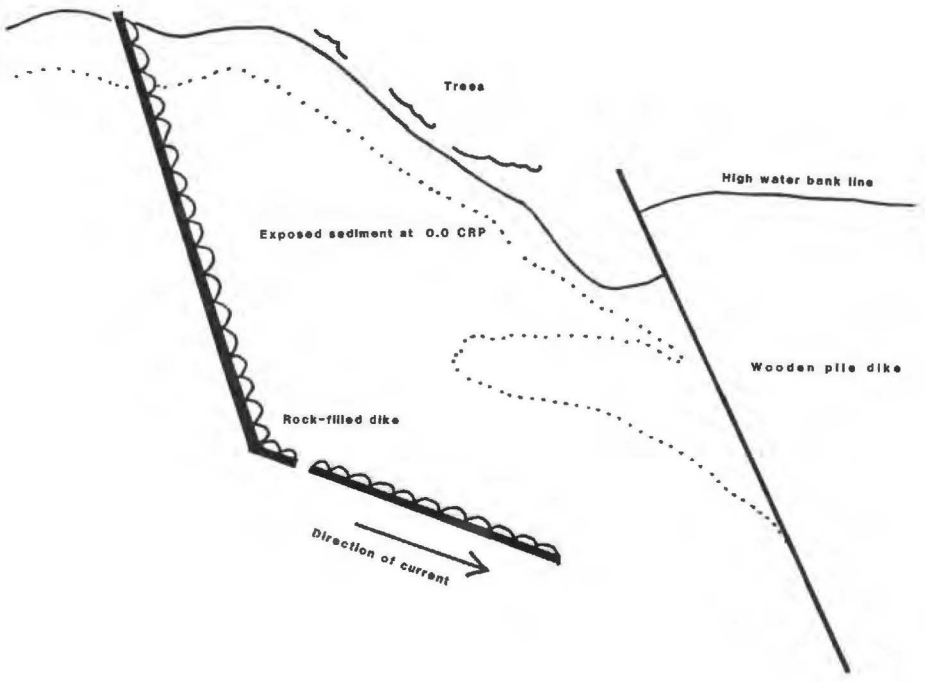


Fig. 48. L-head dike, a modification of a wing dam on the Missouri River (Jennings 1979).

The prenotching study on UMR completed by the Wisconsin Cooperative Fishery Research Unit provided evidence of the benefits that might be expected from other wing dike modifications, such as placing gravel or instream cover in the scoured area below notches. Hall (1980) found that the highest benthic invertebrate density, biomass, and number of taxa occurred in the gravel (as compared with silt and sand substrate) around submerged wing dams. Pierce (1980) found that species diversity was greatest and catch rates of fish highest in two of the six wing dams studied in Pool 13 that had the most riprap, stumps, and logs along the channel border.

The adverse impacts of wing dike modification are generally associated with improperly placed notches, which cause increased rather than decreased sedimentation. Bank erosion below notched and rootless dikes has also been cited as an adverse impact associated with wing dike modification (Robinson 1980).

Many of these adverse situations can be eliminated through good engineering and more study. The creation of notches, elimination of the root, and the lowering of the crest elevation cannot be an arbitrary decision. Jennings (1979) reported that the effectiveness of a notch depends on its position in the dike, the dike's position relative to the main channel flow, the height of the structure, and river stage. The fact that notch design is very site-specific prompted Simons et al. (1975) to conclude that, in general, the proper location of a notched dike depends on local circumstances. Robinson (1980) further emphasized this dilemma by stating that "cooperation between the engineer and biologist is essential, so that dike modifications and locations can be selected to improve habitat conditions for fish and wildlife without increasing land accretion, permanent water loss, or affecting navigation."

The primary purpose for constructing wing dikes is contraction of the river flow (Degenhardt 1973). Wing dams make large alluvial rivers more efficient and "self-cleaning" for navigation (Robinson 1972). The creation of gaps in these structures essentially reduces the overall efficiency of the river. Franco (1967), for example, found that the height of the dike is inversely related to a dredging index: the lower the dike, the greater the need for main channel dredging because of reduced flow velocities. This relation implies that overindulgence in wing dam modification may require increased dredging, with its many associated negative impacts (e.g., increased temporary turbidity, destruction of benthos).

Pierce (1980) suggested that the removal of 150 to 300 ft of wing dams that previously provided both shelter from currents and substrate for aquatic macroinvertebrates is another potentially detrimental impact of notching a dike (and presumably, eliminating the root or lowering the elevation). Furthermore, moderate to high river stages are needed to make notched high wing dikes in open reaches work effectively (Jennings 1979); the most critical

period for aquatic organisms is at low river stage. Coble (1980) speculated that increased velocity could adversely affect the fish wintering areas downstream from the notch in UMR. In light of these observations and the difficulties associated with properly placing a notch, wing dam modification is suggested only where accretion behind wing dams has been demonstrated to be a problem.

29.4. COSTS

Burke (1976) reviewed the costs of wing dam notching on the Missouri River. In general, costs vary because notch placement is site specific and because notches may be created by different means: excavation, new dikes built with a notch, and notch creation when existing structures are raised or repaired.

The cost for excavating a notch in an existing stone dike ranges from $500 to $2000, depending on the amount of stone to be removed and the difficulty of removing it. The creation of a notch when a new dike is built or an existing dike is repaired entails no additional cost; the structure actually requires less stone. Any saving, however, is offset by the extra cost of surveying and placement of the stone.

Cost estimates of other wing dam modifications (i.e., eliminating the root, lowering the elevation) have apparently not been published. It is reasonable to assume that any cost savings that occur as a result of re-using stones that are removed from a dike will be offset by the additional costs of engineering and providing protection for the bank adjacent to the notch.

29.5. EVALUATION FOR USE ON UMRS

Various modifications of wing dikes have been described as a means of improving habitat in the main channel border of UMR. Reservations about the overuse of this enhancement measure were stated earlier. Wing dam modifications for fishery mitigation depend on site-specific characteristics. The depth, width, and placement of notches on submerged wing dams in the pooled reaches of UMR, for example, will differ considerably from notches on the emergent wing dams of the Middle Mississippi River. Nevertheless, J. W. Robinson (personal communication) believed that engineers can design and place notches that will enhance aquatic habitat. If properly used, wing dike modification should prove to be an effective, inexpensive, and immediate means of mitigating aquatic habitat loss in UMR.

Robinson (1980) concluded that no single type of dike or dike modification was significantly better than another for fish, but he did

suggest that rootless dikes may have the best potential for developing the needed diversity of habitat in the Missouri River. The two rootless dikes that were studied developed low sand islands below them and channels on either side of the island. Properly designed rootless high dikes, placed in the right location, could be used to create high islands with flowing side channels that would be an asset to fish and wildlife (Robinson 1980). Erosion of the adjacent bankline could be inhibited with riprap or vegetation, or by connecting the shore and dike with timber pilings. As previously mentioned, Robinson (1980) found that the pilings offered submerged permanent cover for fish at all river stages, an advantage offered by no other dike that was studied.

In future investigations of the environmental impact of wing dams or of wing dam modifications, the Construction Reference Plane (CRP) should be used to describe elevation. (As previously mentioned, CRP is an arbitrary elevation established by the U.S. Army Corps of Engineers that relates mean sea level elevations to known river stages.) The CRP values simplify comparison of wing dike heights or notch elevations because the heights of the structures are related to river discharge. This system enables the U.S. Army Corps of Engineers to build structures at particular heights, knowing that at certain river stages the dike will be overtopped or that water will be flowing through the notch (Jennings 1979).

CHAPTER 30. SIDE CHANNEL MODIFICATION

30.1. SITUATION TO BE MITIGATED OR ENHANCED

Side channels and backwaters are important habitats of a river ecosystem. Backwaters often provide quality habitat for the plankton, aquatic vascular plants, and the invertebrates associated with them; provide fish with spawning, nursery, and feeding areas and refuge during high water flows in the the river; and provide waterfowl, shorebirds, and furbearers with nesting, feeding, and resting habitat (GREAT II 1980j; Kennedy 1979). The importance of wetlands (i.e., backwaters), in the UMR floodplain was characterized in GREAT I (1980e). Millions of waterfowl rest, feed, and breed in wetlands. This habitat is also an important spawning, nursery, and feeding area for sport, commercial, and ecologically important fishes. The wetlands support beavers, muskrats, turtles, herons, egrets, and many other wildlife species. Indeed, the value of backwaters to hunters, fishermen, and other recreationists is prodigious.

But backwaters and side channels in many of the national waterways are deteriorating or are being lost at an alarming rate (Bellrose et al. 1977; Funk and Robinson 1974; GREAT I 1980e; GREAT II 1980j; Mills et al. 1968; Robinson 1972; Saiki et al. 1976). In the development of rivers for navigation, man has created stagnant unproductive sloughs from what were once fresh, productive side channels; and turbid, wind swept, less productive riverine lakes out of what were once productive river-bottom marshes. Such conditions are a consequence of the construction of closing dikes, dams, and levees; the disposal of dredged material; and the alteration of flow and sedimentation regimes due to channelization (Bellrose et al. 1977; Claflin et al. 1981; Fremling et al. 1979; GREAT I 1980e; Nielsen et al. 1978). Sediment aggradation is often the principal cause (Fremling et al. 1979). Nielsen et al. (1978), however, identified certain additional elements that influenced the decline of the Weaver Bottoms near Winona, Minnesota: "increased water depth following lock and dam construction, sediment scour associated with increased current velocities caused by flow from the main channel through numerous side channels created by the placement of dredge spoil on the natural levee separating the Weaver Bottoms from the main channel, and high turbidity produced by wave stirring of bottom sediment."

When side channels and backwaters deteriorate, valuable fish and wildlife habitat is lost. Stagnation may benefit rough fish populations for a time, but in extreme cases the entire fishery can be eliminated. Accelerated siltation destroys submergent and emergent vegetation and thereby reduces the suitability of the habitat for fish and wildlife.

A management method that has been developed to alleviate conditions that cause a deterioration of side channels and backwaters entails the opening or

closing of water entryways to backwaters, as described in the following section.

30.2. DESCRIPTION OF TECHNIQUES

Side channel modification or backwater rehabilitation, as practiced on UMR (Fremling et al. 1979; GREAT I 1980e) and the Lower Colorado River (Kennedy 1979; Saiki 1976), is conducted to alter flows through backwater habitats. These alterations in flow can be accomplished by the installation of gated culverts and spillways and by dredging openings. In addition, undesirable openings can be blocked with dredged materials or partly occluded with closing dams. Installation of wave barriers (Nielsen et al. 1978b) and dredging to increase water depth (Kennedy 1979) have also been suggested at locations where appropriate.

Techniques used in side channel modification are by no means fully established. Each management initiative will encounter a site-specific set of circumstances that must be fully investigated before action is taken. After a complete ecological survey, a list of potential modifications can be developed, followed by an engineering assessment of hydraulic effects. The plan can then be completed. A flow diagram (Fig. 49) outlining the decision-making process of the Side Channel Work Group (GREAT I) was presented by GREAT I (1980e).

Modifications made to the Fountain City Bay backwater and proposed modifications to the Weaver Bottoms backwater, located on UMR, serve as examples of how side channel modifications can be approached (Fremling et al. 1979). On Fountain City Bay, a combination of a partial closing structure at Devil's Cut, three gated aeration culverts, and a trash rack over a previously existing culvert were used to decrease head differential between the bay and the main channel, to increase supplies of fresh water to the backwater, and to reduce influx of sediments (Fremling et al. 1979). Nielson et al. (1978) suggested several actions that they believed would increase water clarity and reduce water and sediment inflow in the Weaver Bottoms: (1) partly occluding Murphy's Cut with a notched closing dam to reduce excessive water and sediment influx, (2) stabilizing Botsford's Cut, the cut immediately downstream from Botford's Cut, and the Old Mouth of the Zumbro Cut, with riprap, (3) filling the rest of the Weaverside channels with dredged sand, and (4) constructing a wave barrier projecting into the lower end of the Weaver Bottoms.

Several other side channel modification projects were initiated on UMR by GREAT I that help to illustrate the management method. Some were created for habitat improvement and others for recreational access. An opening was cut at Mule Bend on Island 42, Pool 5, by the Derrickbarge Hauser. The cut was created to restore freshwater flow into the interior of the slough. Maintenance dredging in the opening will be required, because secondary

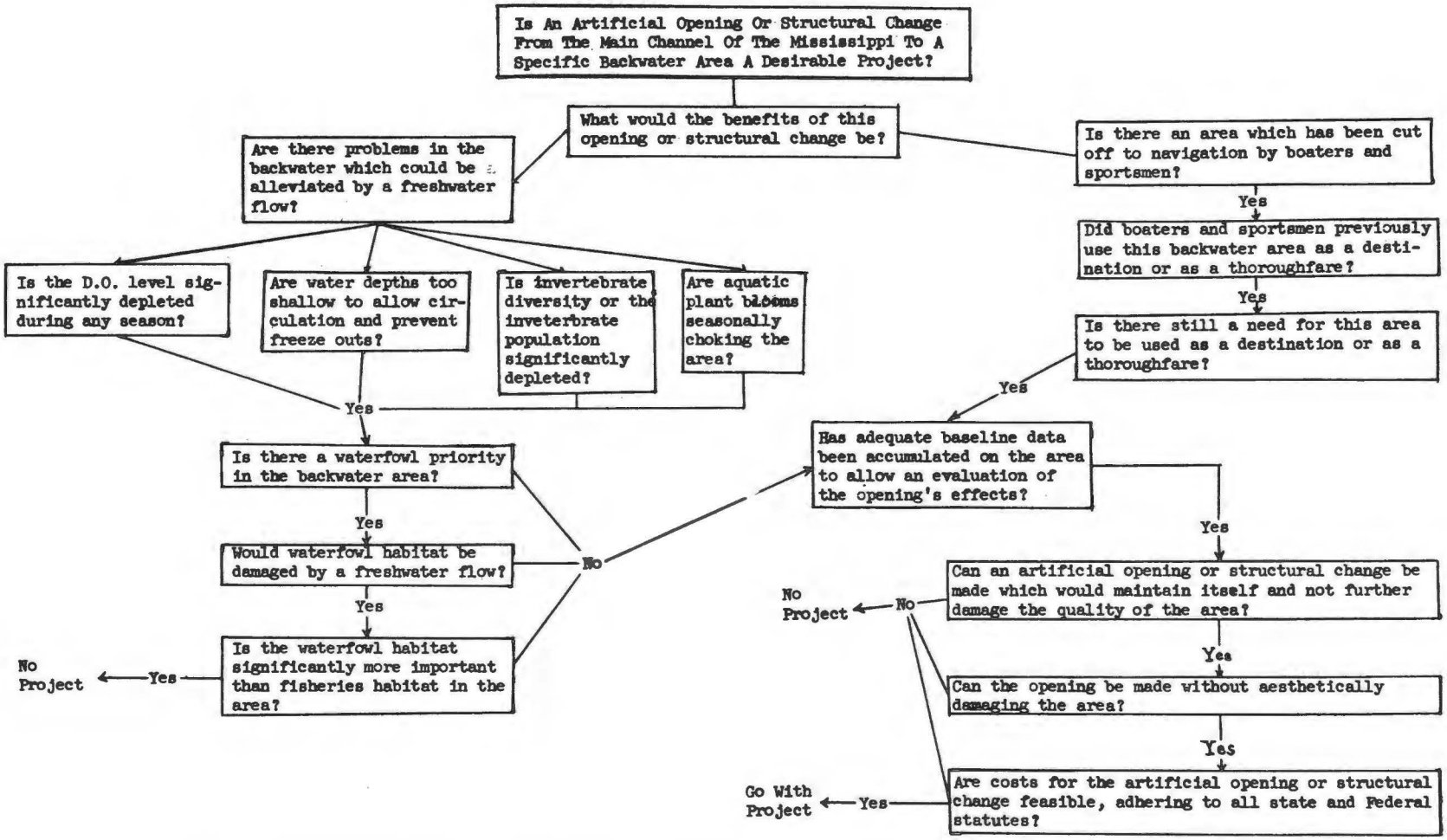


Fig. 49. Decision-making process and criteria designed by the Side Channel Work Group to facilitate recommendations for opening side channels (GREAT I 1980e).

movement of upstream spoil threatens to close the chute (GREAT I 1980e).

An opening into Belvidere Slough for recreational access was cut by a small hydraulic dredge called a "Mudcat" (obtained from National Car Rentals). Monitoring has shown that the cut is slowly narrowing and that maintenance dredging will probably be required. Another similar cut was opened at Fort Snelling State Park, Pool 2 of the Minnesota River. Results were similar and the need for maintenance dredging is anticipated.

Five side channel openings were recommened by the GREAT II Side Channel Work Group (GREAT II 1980j). Three were completed to improve recreational access. Two of these are slowly filling with sediments, but the other is relatively sediment-free. Another site was opened twice but filled with sediment each time and is considered a failure. The fifth opening was made to improve backwater flow and is still being evaluated.

30.3. IMPACTS ON THE ENVIRONMENT

Because the hydraulic characteristics of side channels and backwaters are generally complex and not easily identified, predictions of the effects of side channel modifications may be less than accurate. If the hydraulic characteristics are not properly identified, side channel modifications can promote sediment influx or excessive scouring, necessitating further modifications (Fremling et al. 1979; GREAT II 1980j).

Some ancillary benefits, in addition to improved fish and wildlife habitat, may accrue from side channel modifications. Increased accessibility to backwaters for recreationists (GREAT I 1980e) and a reduction in maintenance dredging (Fremling et al. 1979) are two such benefits.

30.4. COSTS

Only general cost estimates are available. Each modification scheme carried out will have a unique set of cost factors; construction of culverts, weirs, and closing dams, together with dredging operations, will probably constitute the principal expenditures. In some schemes, the structural modifications may be few and simple; pre-modification environmental investigations may constitute a large share of the total cost.

Expenditures for projects sponsored by GREAT I were listed by GREAT I (1980e). These examples illustrate the potential investment required for side channel modifications and appropriate environmental investigations:

1. A field model for the rehabilitation of backwater areas of UMR by modification of standard channel maintenance practices: Weaver Bottoms.

   Project begun: June 1975
   Contract cost: $50,000 GREAT I Funds

2. Phase I study of the Weaver-Belvidere Area, UMR.

   Project begun: July 1977
   Contract cost: $61,206 GREAT I Funds

3. The feasibility and environmental effects of opening side channels in five areas of UMR (West Newton Chute, Fountain City Bay, Sam Gordy's Slough, Kruger Slough, and Island 42).

   Project begun: June 1975
   Contract revised: November 1977
   Operations and maintenance: Original - $159,000, FWS Funds
   Revision - $36,960, GREAT I Funds

4. Side channel opening project at Mule Bend on Island 42 (Pool 5, UMR).

   Project begun: July 1974
   Operations and maintenance: $27,000

5. Side channel opening pilot project at Buffalo City, Wisconsin, in Belvidere Slough.

   Project begun: Spring 1975
   Operations and maintenance: $30,000 GREAT I Funds

6. Side channel opening pilot project at Fort Snelling State Park (Pool 2, Minnesota River).

   Project begun: Summer 1976
   Operations and maintenance: $15,934 GREAT I Funds

Costs for two side channel modification projects reported by GREAT II (1980j) provide further insight into potential costs for side channel modification:

1. Orton-Fabius side channel opening and study.

Action	Completion Date	Cost
Notch wing dike	November 1976	No cost to GREAT II
Opening side channel:		
blasting	April 1977	Missouri Department
dredging	November 1977	of Natural Resources $15,000.00
Post opening studies	May 1977-October 1978	$32,000.00
Report	November 1979	

2. Burnt Pocket backwater.

Pre-opening study	September 1978	$15,866
Fish sampling	September 1980	2,000
Zooplankton sampling	September 1980	3,000
Final Report	March 1981	---
Opening and riprap	October 1979	80,500
Post-opening study	June 1980	18,970
Total		

30.5. EVALUATION FOR USE ON UMRS

Side channel modification methods are widely applicable on UMRS. Deterioration of backwaters due to sediment aggradation is a major problem; side channel modification shows promise as a quality restorative technique. Indeed, a number of modifications that have been developed were listed in GREAT I (1980e) and GREAT II (1980j). However, this technique should not be considered a panacea for all problems of backwaters and side channels.

CHAPTER 31. AERATION TECHNIQUES

31.1. SITUATION TO BE MITIGATED OR ENHANCED

Oxygen is involved in the regulation of metabolic processes of most aquatic communities and organisms, and therefore is one of the most significant chemical substances in water (Reid 1961). The concentration of dissolved oxygen is perhaps the most important chemical quality which affects the distribution of fishes. It affects survival, growth, swimming performance, and larval development, as well as migration among anadromous species.

Oxygen depletion reduces the quantity and quality of habitat for fish and fish food organisms. It causes physiological stress in fish and often leads to the development of imbalanced fish communities dominated by relatively undesirable species such as common carp and bullheads. Anoxic conditions cause taste and odor problems in domestic water supplies, and may cause the chemical reduction of iron, manganese, and sulfides. In addition, anoxic conditions can intensify eutrophication rates by promoting the dissolution of phosphorus across the sediment water interface (Mortimer 1941, 1942).

Oxygen depletions are caused by a variety of factors. The principal causative agents are excessive loads of biodegradable organic wastes (direct) and excessive plant biomasses (indirect). In addition, the disruption of freshwater supplies, particularly in sloughs and backwaters of large river systems, can cause stagnation and oxygen depletions.

Organic pollutants originate from sources such as sewage treatment plant effluents, septic system leachates, sanitary landfill drainages, and concentrated domestic animal wastes. Organic wastes impose a direct oxygen demand when they are oxidized by microbial organisms.

In addition to the sources mentioned above, nutrient inputs (pollutants), may also enter aquatic environments from such sources as crop fertilizers and erosion. Excessive nutrient loading imposes an indirect oxygen demand when it promotes excessive aquatic plant growth, which results in unfavorable P:R ratios (rate of gross primary productivity to rate of respiration) or organic overloading.

Artifical aeration and oxygenation techniques have been developed to help alleviate dissolved oxygen depletions in lakes and streams. Such techniques can be used in a variety of situations to improve conditions in aquatic habitats.

Aeration treats only the symptom (depleted dissolved oxygen) and not the causes (inadequate waste treatment, poor land use practices, altered river hydraulics,...).

31.2. DESCRIPTION OF TECHNIQUES

Aeration techniques can be divided into three major categories: destratification (whole-lake aeration), aeration of the anoxic lower stratum (hypolimnetic aeration), and supplemental stream aeration. Aeration techniques are used to alleviate fishery problems associated with anoxic or near anoxic conditions in bottom waters or under the ice. Aeration affects the biological, chemical, and physical characteristics of a lake or stream and thus has many management implications. Aeration can improve the potability of domestic water supplies by reducing taste and odor problems; by removing hydrogen sulfide, manganese, and iron concentrations; and by satisfying chlorine demand (Barnett 1971; Brezonik et al. 1969; Clair and Beck 1969; Lorenzen and Fast 1977; Toetz et al. 1972). Aeration can also be used to offset the effects of eutrophication in lake restoration projects (Smith et al. 1975; Wirth et al. 1970). In fishery management, aeration techniques can be used to restore trout and salmon fisheries by increasing oxygen levels (Fast 1973; Smith et al. 1975), and to prevent winterkills (Halsey and Galbraith 1971; Smith et al. 1975; Wirth 1970). Aeration can also be used to treat rivers in which biochemical oxygen demand is excessive (Bouthillier 1974; Hunter and Whipple 1970; Whipple et al. 1970), and to supply oxygen to anoxic discharges from high dams (Dortch and Wilhelms 1978).

31.2.1. Destratification

Destratification can be achieved through air-lift circulation (Fast 1968; Torrest and Wen 1976; Wirth et al. 1970) or pumping (Dortch 1979; Garton et al. 1979; Toetz 1977). This technique is used in fishery management as a method for restoring habitat losses caused by anoxic conditions in the hypolimnion of eutrophic, stratified lakes and reservoirs and to prevent winterkills.

Irwin et al. (1966) concluded that the rate at which a water body should be mixed is directly proportional to the rate of oxygen demand. To satisfy mixing requirements, the mixing system must be based on a mechanical performance that may be calculated as the "destratification efficiency" (DE) of the device. The DE is based on stability changes. Stability is defined as the work that must be done to the water (the energy involved) to lift the entire weight of a body of water the vertical distance between the center of gravity when a body of water is in a given state of stratification and the center of gravity when the water mass is isothermal. Stability may also be regarded as the minimum energy required to completely mix a stratified body of water (Symons and Robeck 1969).

It follows that less energy will be required if pumping or circulation begins before the onset of stratification.

The "destratification efficiency" of a system is defined as

$$DE = \frac{\left|\overline{\text{net change in stability from } t_2 \text{ to } t_2}\right|}{\left|\underline{\text{total mechanical energy input from } t_1 \text{ to } t_2}\right|} \times 100$$

where t_1 and t_2 are the times of starting and stopping of mixing, respectively (Symons and Robeck 1969).

A lake or reservoir can be completely mixed if the device used meets destratification efficiency requirements and is located over the deepest site in the lake. Lorenzen and Fast (1977) reported that if there are no unusual oxygen demands within a lake, sufficient mixing will have been imparted (to maintain aerobic conditions) if the temperature difference from top to bottom is no greater than 35.6°F.

Mechanical mixing has not been used as extensively as diffused air mixing. Cooley and Harris (1954) described the use of water jets to destratify pumped storage reservoirs of the Metropolitan Water Board of London. A 500-acre reservoir 70 ft deep, was circulated by six 36-in. diameter jets (flow, 10 fps) set at various angles (horizontal and at 22.5° and 45° from horizontal).

Irwin et al. (1966) used a 12-in. axial flow pump (Fig. 50) to destratify four small impoundments in eastern Ohio. Cold hypolimnetic water was pumped to the surface to mix with the epilimnion (Table 10).

A significantly different pumping device was used by Garton et al. (1977) on Ham's Lake, Oklahoma. Although an axial flow pump design was used, water was pumped from the surface down, instead of the reverse. The destratifier consisted of an electric motor, a right-angle gear reducer, a floating platform, a propeller, and an orifice shroud.

To destratify Lake Arbuckle, Oklahoma, Garton et al. (1979) used a cluster of 16 axial pumps, each 6 ft in diameter, arranged in an open-centered square. The total cluster had an estimated pumping capacity of 416,000 gallons per minute with an energy input of 9.5 kilowatts (12.8 horsepower). Like the device used in Ham's Lake, Oklahoma, the cluster of pumps forced water from the surface downward.

Diffused-air mixing is the most popular method used to disrupt destratification. Ease of installation and simplicity of operation are the

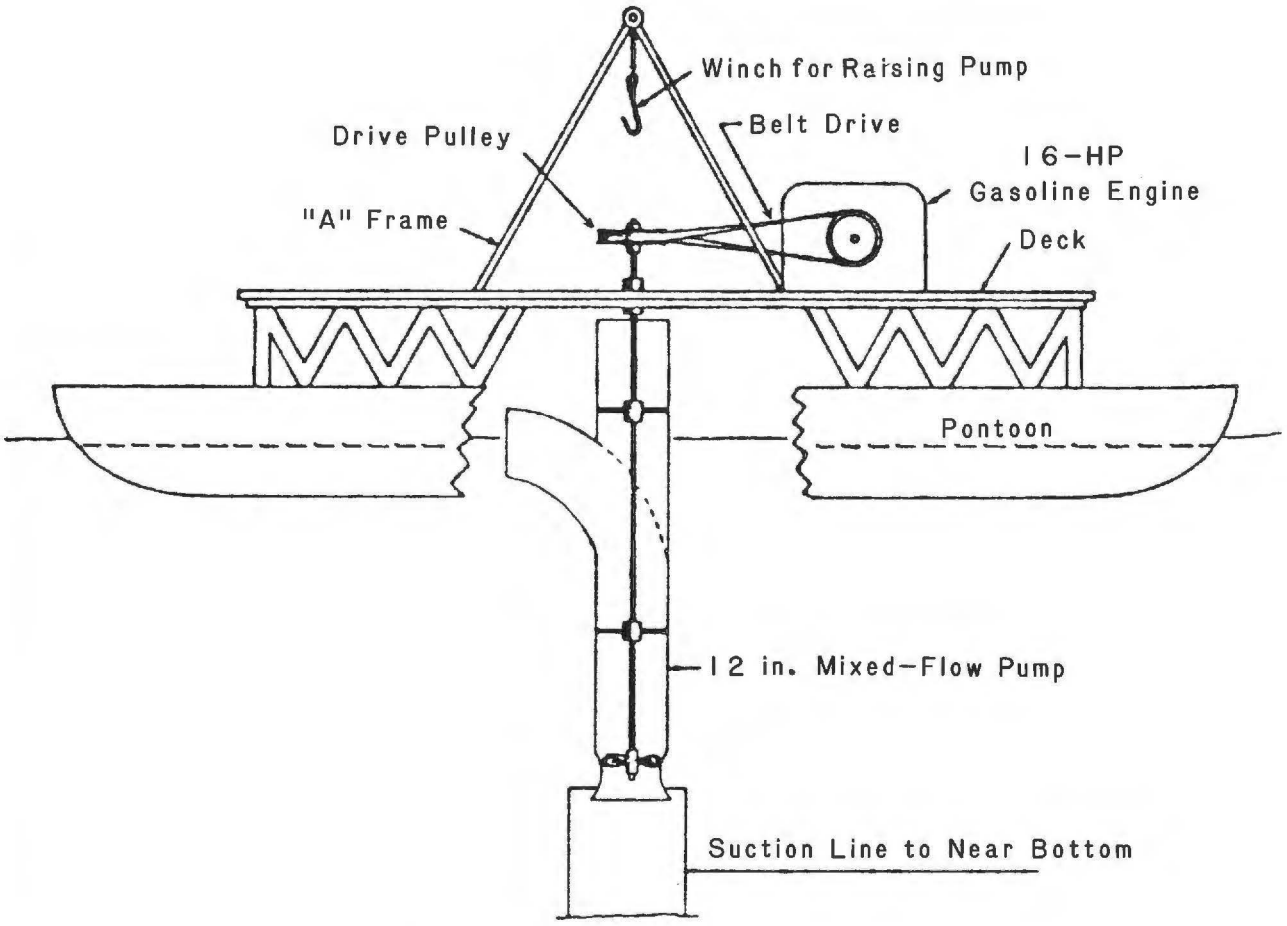


Fig. 50. Design of pump, pontoon, and motor used for destratification of four small lakes in eastern Ohio (Irwin et al. 1966).

principal advantages over mechanical mixing (Lorenzen and Fast 1977). Aeration of the water column (in addition to turbulence-induced aeration at the air-water interface) is a further beneficial feature of this technique. Fast (1968) concluded that diffused-air injection is the most efficient system for destratifying large lakes and reservoirs.

A number of designs for diffused-air mixers have been developed. The systems pipe compressed air to a release apparatus located near the lake bottom in the area of greatest depth. Some of the release apparatus designs used are perforated pipes (Fast 1968; Halsey and Galbraith 1971), diffuser stones (Van Ray 1969), air-cannons or the "Aero-hydraulics gun" (Fast 1968), and helical tubes or the "Helixor" (Wirth et al. 1970). The diffuser stone used by Van Ray (1969) was inadequate for the lake in which it was used. The Aero-hydraulics gun is useful only in small bodies of water (Fast 1968). The perforated pipe design described by Fast (1968) successfully destratified and aerated El Capitan Reservoir, a large impoundment in California. The successful application of a Helixor in Cox Hollow Lake, Wisconsin, promoted

Table 10. Summary of lake volumes and pumping data[a] for destratification of four eastern Ohio lakes (modified from Irwin et al. 1966).

Lake	Area (acres)	Estimated average depth, (feet)	Volume (acre-feet)	Volume cold pumped (acre-feet)	Hours pumped (no.)	Cold line water pumped[b] (%)	Energy impact, horsepower per hour: Total	Per acre-foot cold water pumped	Per acre-foot of lake volume[c]
Stewart Hollow[d]	8	15	120	20.25	37.5	22.5	450	22.2	3.75
Caldwell	10	10	100	4.32	8	5.7	96	22.2	0.94
Pine[e]	14	7	98	8.9	35	25.5	420	39.3	4.2
Vesuvius	105	12	1260	112.3	208	11.2	2496	22.2	1.97

[a]Pump capacity, 13 acre-feet per day; power input, 12 horsepower.
[b]Based on original temperature profile.
[c]This value depends on efficiency of mechanical equipment and percentage of water actually pumped in a given impoundment.
[d]Lake pumped twice.
[e]Lake overpumped (pipe broken).

its widespread use in that state (Smith et al. 1975; Wirth 1970; Wirth et al. 1970). Henderson-Sellers (1981), who experimented with a variety of diffusers, bubble guns, and jets, found that Helixors destratified and reaerated reservoirs more efficiently because they prevent stratification rather than destroy it.

A typical perforated-pipe, diffused-air mixing system (Fig. 51) was described by Fast (1968) and Lorenzen and Fast (1977). The system was designed for use with an on-shore air compressor that delivered 215 ft^3 per minute and was driven by a 50-horsepower electric motor. The design was described as follows:

> "A $1^1/2$ inch nominal size galvanized steel pipe transports air from the compressor to the reservoir. From this point, a 300 foot length of $1-^1/2$ inch PVC plastic pipe extends along the bottom. The plastic pipe is weighted by 15 concrete block anchors. The last 100 feet of the plastic pipe are suspended almost horizontally above the bottom by 13 styrofoam floats and lengths of polyethylene anchor rope. Thirteen sets of floats with anchors are evenly spaced along the 100 feet of plastic pipe. This section is perforated by 90 holes, $^1/8$ inch in diameter, and sealed at its distal end. Clusters of three holes, spaced 120 degrees apart around the circumference of the pipe, are located on this section of pipe. The clusters are unevenly spaced. Beginning 100 feet from the end of the pipe, the

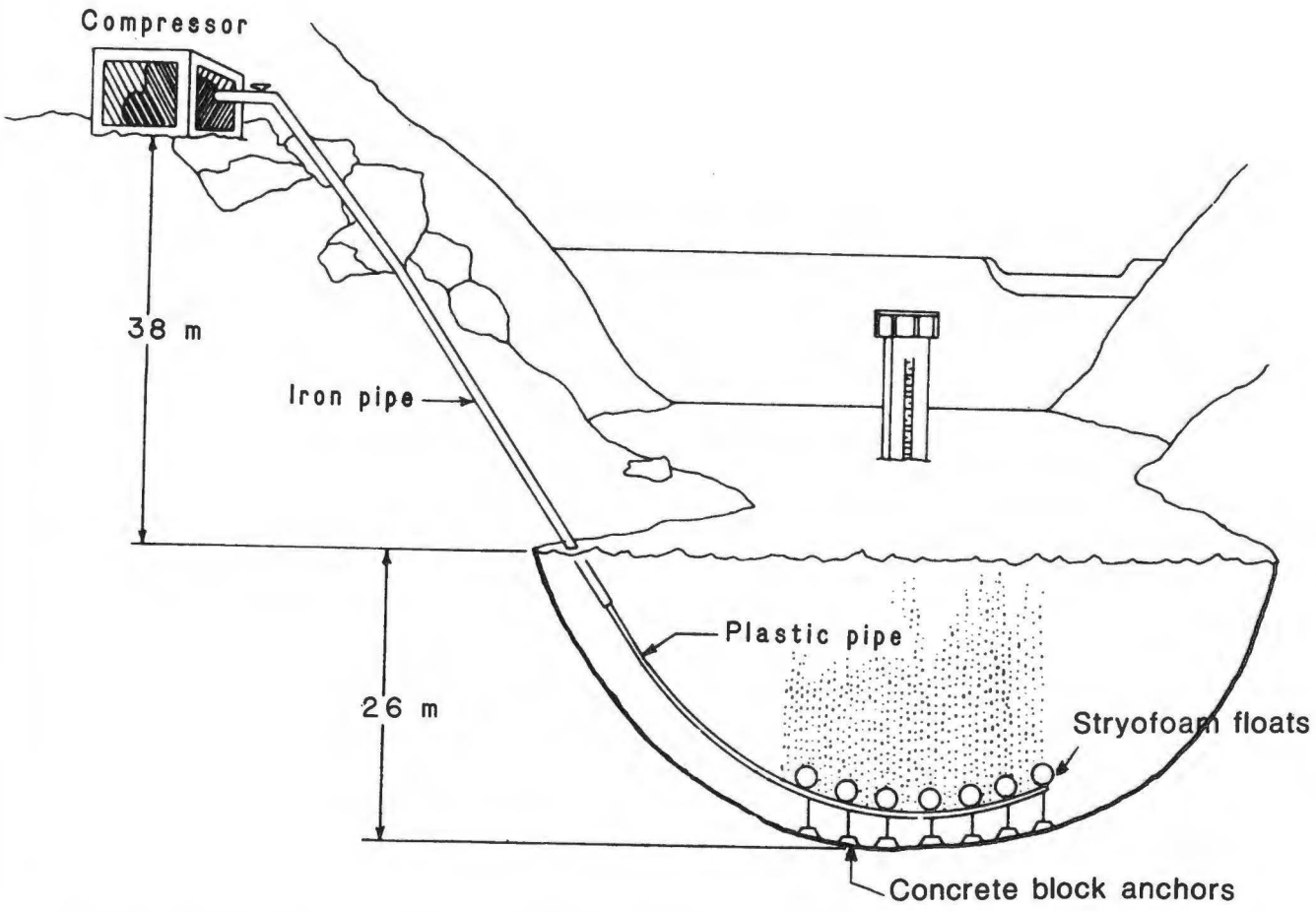


Fig. 51. Destratification system installed at El Capitan Reservoir, California (Lorenzen and Fast 1977).

spacing between the first six clusters is 5 feet, clusters six through 12 are 4 feet apart, clusters 12 through 21 are 3 feet apart and clusters 21 through 30 are 2 feet apart. This non-linear arrangement of air holes was intended to produce a uniform air release over the length of the pipe" (Lorenzen and Fast 1977).

A "Helixor" aeration system used by Wirth et al. (1970) was described as follows:

"The "Helixor" consisted of a vertical plastic tube, five feet in length and 18 inches in diameter, which was divided internally by a longitudinal plastic plate formed to the shape of a helix. The unit was anchored to the bottom and had an air distributor containing several 1/8 inch parts placed so that a mixture of small air bubbles and water moved up each side of the helix."

The aeration mechanics were also described. "After the stream of water left the gun or tube, it acted as a free turbulent jet which entrained additional quantities of water in its upward movement towards the surface. Oxygenation of water took place as the bubbles rose in the tube during entrainment, at the turbulent surface boil above the gun, and in the surrounding boil as the water spread rapidly away from the upwelling region."

31.2.2. Hypolimnetic Aeration and Oxygenation

Hypolimnetic aeration and oxygenation is a method of adding dissolved air and oxygen to the hypolimnion of a lake without disturbing the thermal stratification (Fast and Lorenzen 1976; Fast et al. 1976). The process differs substantially from aeration by destratification and is used when maintenance of cold oxygenated hypolimnetic water is desired (e.g. for a salmonid fishery and for drinking water).

Fast and Lorenzen (1976) stated that at least 21 hypolimnetic aeration and oxygenation designs have been proposed, of which 12 have undergone full-scale testing. Mechanical agitation, air injection, and the injection of pure oxygen are operational modes that have been used.

Fast and Lorenzen (1976) wrote that the first use of hypolimnetic aeration was in Lake Bret, Switzerland, and involved mechanical agitation. Water was withdrawn from the hypolimnion, aerated in a splash basin at the surface, and returned to the hypolimnion through a pipe, by gravity flow.

Hess (1977) modified an air-lift design by incorporating a surface agitator to draw water up through an upwelling tube, aerate it at the surface, and return it through a pipe, by gravity flow. The mechanical agitation increased aeration efficiency, and this design is probably the most efficient for use in shallow lakes, because shallow water does not provide a sufficient vertical column for gas dissolution (Fast and Lorenzen 1976).

Air injection systems can be categorized as full air-lift or partial air-lift designs. In full air-lift systems, air is injected near the bottom of the aerator. As the air rises to the surface, it lifts water with it. The air and water then separate and the water returns to the hypolimnion. Partial air-lift designs operate similarly, except that the air and water are allowed to separate below the surface of the lake. Water is allowed to return to the hypolimnion and air is released through a vent pipe. A full air-lift design was used successfully to aerate the hypolimnion of two Michigan lakes (Fast et al. 1970):

"The aerator floated freely in the center of the lake. Styrofoam

and steel barrel floats suspended it 3 m above the lakes's bottom, while air was delivered through a plastic pipe from an air compressor. The diesel powered compressor had three set levels of air output: 4.2 m^3/min., 3.5 m^3/min., and 2.8 m^3/min., all rated at 7.1 kg/cm^2.

"The aerator consisted of two corrugated, 14 gauge, galvanized iron pipes. One 1.8 m diameter pipe extended 3 m above the surface to 9.2 m below the surface. A 1.4 m diameter pipe extended partly inside and was attached to the larger diameter pipe, and reached from near the surface to 15.5 m depth. A 6.3 m diameter current deflector was attached to the small pipe by clamps and was located 1 m below the bottom of the large diameter pipe. The deflector directed the water flow horizontally and prevented a "short-circuit" flow. It was constructed of nylon parachute material stretched over a steel mesh frame. Air was released from an air diffuser located inside the small pipe 1 m from its bottom."

Smith et al. (1975) successfully used a hypolimnetic aerator on Larson and Mirror Lakes, Wisconsin (Fig. 52). The authors described the construction and installation of the Mirror Lake facility. The device incorporated a Helixor, which was described in the preceding subsection.

"The major component of the aerator consisted of a 40 ft long, 18-in diameter 'Helixor', an extruded polyethylene tube with an internal longitudinal plate dividing the tube in half and twisted to form a helix. Air was supplied to the base of the 'Helixor' via 250 ft of 1.5 in, ID-weighted polyethylene tubing, and two 0.4 in holes in the end of the capped tube released air into each half of the 'Helixor'. Water and air lifted up [through] the 'Helixor' entered a 4 ft by 4 ft by 8 ft styrofoam-covered plywood separation box at the surface of the lake, where the bubbles were vented to the atmosphere. The water returned to the hypolimnion through two 50-ft long, 18-in diameter, neoprene-impregnated flexible nylon tubes."

The "Limno" is a commercially available, partial air-lift hypolimnetic aerator that has often been used and described (Anonymous 1973; Anonymous 1974; Fast et al. 1975; Fast and Lorenzen 1976).

Fast and Lorenzen (1976) concluded that partial air-lift designs are less efficient than full air-lift designs. Although partial air-lift designs develop greater effluent oxygen concentrations than do full air-lift designs, the total volume of oxygen the devices incorporate is actually less because the water volume aerated is less.

A downflow air injection system proposed by Speece (1971) was a

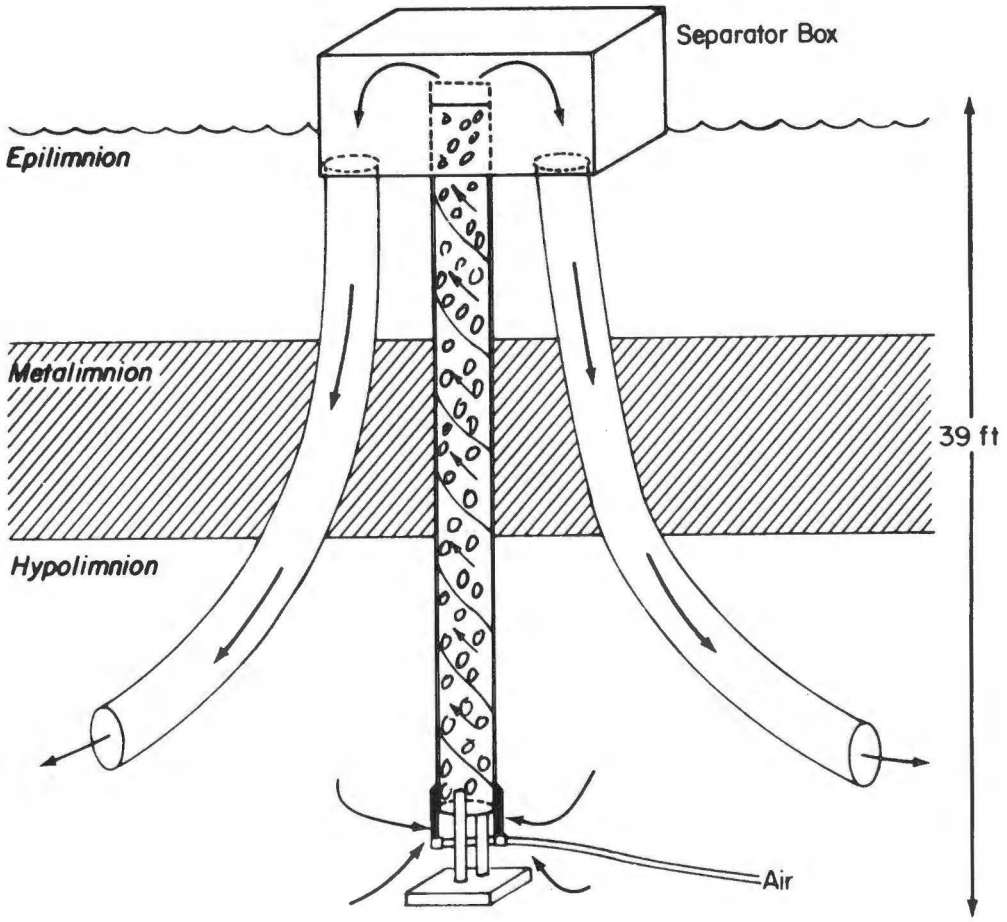


Fig. 52. Hypolimnetic aerator design used in Mirror Lake, Wisconsin (Smith et al. 1975).

modification of "U-tube" aeration for hypolimnetic aeration. The design offers some advantages, but verifications of its utility have not been made. The system combines both downflow air injection and air-lift features. The efficiency is increased because some energy expended in the downflow tube is recovered in the upwelling tube (Fig. 53). Fast and Lorenzen (1976) reported a variation of Speece's downflow air injection system. Their system did not incorporate a modified U-tube, and made no use of potential wasted gas energy. Instead, the waste gases were vented to the surface. This venting may promote the efficiency of pumping of hypolimnetic water to the epilimnion.

Several oxygen-injection hypolimnetic oxygenators have been proposed. The first system proposed and tested was the side stream pumping system. Water was drawn from the hypolimnion to shore through a pipe, and then returned to the hypolimion under pressure. The oxygen was injected into the pressurized return pipe and almost completely dissolved before the water was released. The system had a 5-horsepower water pump and a maximum oxygen capacity of about 50 lb per day (Fast et al. 1975). The side stream pumping

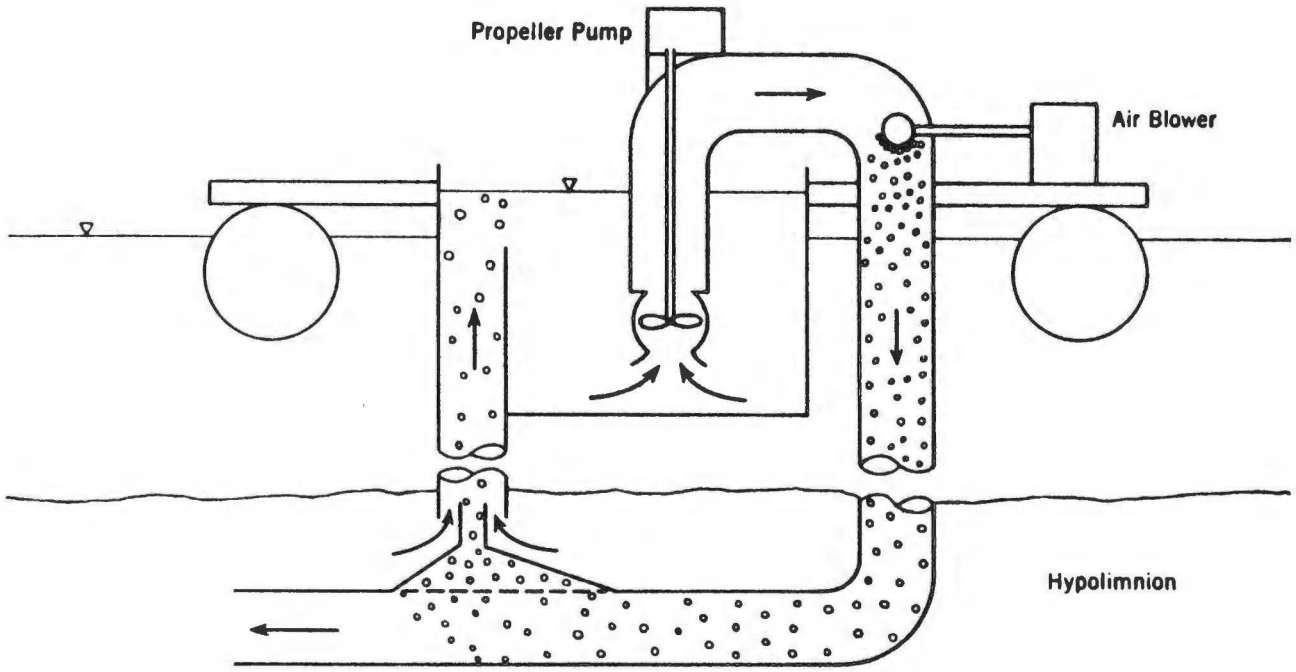


Fig. 53. U-tube hypolimnion aeration (Speece 1971).

system was successfully used at Ottoville Quarry, Ohio (Overholtz et al. 1977), but it repeatedly caused destratification of Attica Reservoir, New York (Haines 1974). Destratification can be prevented in shallow reservoirs and lakes only if pumping rates are greatly reduced (Haines 1974).

Speece (1971) proposed a deep-water, oxygen-bubble injection system, based on the premise that, if oxygen is injected at a sufficient depth in the impoundment, it will completely dissolve before it leaves the hypolimnion. The technique requires that the hypolimnion be at least 60 ft below the surface.

Speece (1971) also proposed a downflow bubble contact aerator for hypolimnetic oxygenation that consisted of an open-bottomed, conical hood equipped with a motor-driven propeller to draw in large volumes of water. Oxygen was injected through a dispenser located below the propeller. The hood was designed to retain gas bubbles until their oxygen composition was similar to that of air. The bubbles were then washed out due to "crowding" as more

oxygen was injected.

Various techniques have been applied in attempts to provide relief from potential winterkill conditions in northern lakes. Many techniques have failed (Wirth 1970): chopping holes in the ice, pumping water onto the ice, applying carbon or lamp black on snow-covered ice, snowplowing wide strips, aerating the water with small air compressors and perforated hoses, partly drawing down impoundments, and augmenting the lake water with oxygenated water. However, destratification and hypolimnetic aeration techniques, when properly carried out have been effective (Fast 1973; Halsey and Galbraith 1971; Schierholz et al. 1976; Smith et al. 1975; Wirth 1970).

Treatment of winterkill lakes by destratification techniques can be approached by two methods: Destratification can be implemented before ice formation to increase the lake's oxygen reserve and reduce the amount of oxygen or a consuming, decomposable organic matter (Fast 1973); or a destratification apparatus can be used during ice formation with the intent of maintaining large holes in the ice that will facilitate surface aeration and provide strong mixing currents that will circulate oxygen throughout the water mass (Wirth 1970). Smith et al. (1975) demonstrated that a hypolimnetic aeration device could be used to prevent winterkill conditions without creating hazardous conditions of open water and weak ice.

If winterkill lakes are in remote areas, where electrical and gasoline power sources are unavailable or where their installation is uneconomical, wind-powered aeration devices may be a viable alternative. Although primarily in the developmental phases, such devices have been built and successfully used (Rieder 1977; Schierholz et al. 1976). Schierholz et al. (1976) stated that a wind-powered, artificial aeration system must possess certain basic qualities.

> "First, and most important, is that the system must be relatively cheap. In order for wind-power to be an economical energy alternative, the system must be available at a low price. The goal of this design is to bring the manufacturing cost below $2,000. In order for this to be accomplished, the design must be simple and it must be constructed out of inexpensive and readily available components. Since the system will be installed at remote lake sites, it must be easy to transport and easy to erect. This means that the system must be simple to assemble and disassemble. The prototype must be structurally and mechanically able to withstand high winds and low temperatures with only a minimum of maintenance. The system must also be environmentally acceptable. These qualities have been incorporated into the design of this wind-powered aeration prototype."

A prototype designed by Schierholz incorporated an American Wind Turbine that directly operated a rotary blower equipped with a two-stage spur gear system. The system achieved an overall gear ratio of 30:1, which produced high compressor speeds at slow turbine speeds, through a 5:1 ratio of turbine shaft to spur gear and a 6:1 ratio of spur gear to blower. The turbine, gears, compressor, and governor were supported on a single 18-ft steel pipe tower. The tower stood on a 6-ft cross-beamed base supported by five guy cables. A more detailed discussion of the components was given by Schierholz et al. (1976). Rieder (1977) provided a detailed assessment of commercially available components that can be used to help build an optimum design.

3.2.3. Supplemental Instream Aeration

Supplemental instream aeration can be provided by using any of several devices and techniques. Mechanical and diffuser aerators have been used successfully in rivers (Hoskings et al. 1977; Whipple et al. 1970; Whipple et al. 1972), as have U-tubes located at dams (Bouthillier 1974; Wirth et al. 1970); aeration by hydroelectric turbines has also been successful (Amberg et al. 1969). Aeration by hydroelectric turbines is only applicable in certain special situations (Whipple et al. 1970). However, destratification and hypolimnetic aeration in the vicinity of turbine penstocks show promise as means for aerating turbine discharges (Dortch and Wilhelms 1978). Destratification and hypolimnetic aeration techniques are similar to those described previously, but efforts are concentrated in the zone adjacent to the penstock orifice. Turbine discharges are directly oxygenated by injecting pure oxygen in front of the penstock orifice or directly into the turbine (Nelson et al. 1978).

A U-tube aerator consists of two tubes or pipes, one of which is suspended inside the other; water flows down through the inside pipe and up between it and the surrounding pipe. Air is injected about 2 ft below the surface of the incoming flow (Bouthillier 1974). A U-tube of such design was installed at a dam on the Red River in Alberta, Canada. The tube was 40 ft long and consisted of a pipe 5 ft in diameter placed inside one that was 8 ft in diameter. Air was supplied by a positive blower but it is likely that entrainment of air by a Venturi aspirator would have yielded better results (Mitchell and Lev 1970).

Mitchell and Lev (1970) performed extensive analyses of U-tube designs. Although their efforts were focused toward sewage treatment applications, the information developed should be generally applicable to instream aeration. Wirth et al. (1970) described a modification of the U-tube concept that was installed at Twin Valley Lake, Wisconsin. The structure, which also served as the lake outlet, was designed to draw cold water from the hypolimnion and aerate it before it was discharged to the receiving stream. The discharge tumbled 33 ft to a concrete floor and rushed out a concrete tube 200 ft long to the stream channel (Fig. 54).

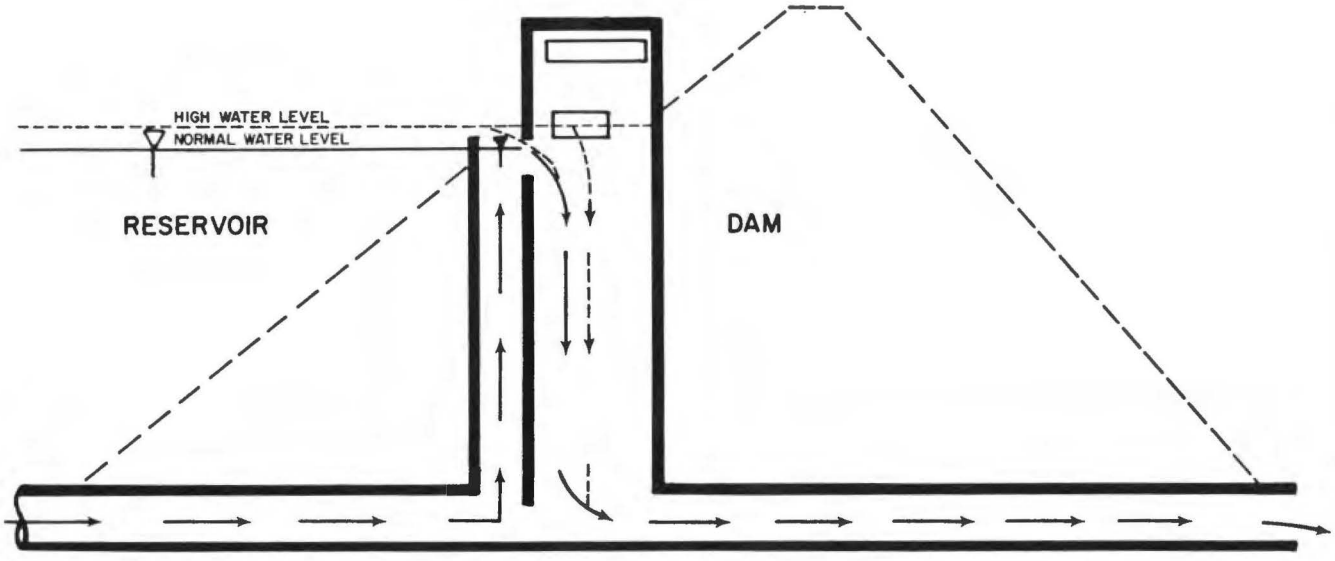


Fig. 54. Outlet structure on Twin Valley Lake, Wisconsin (Wirth et al. 1970).

Two aerator designs have been used for instream supplemental aeration--mechanical aerators and diffuser aerators. Both types are commonly used in waste treatment facilities (Whipple et al. 1970).

The mechanical surface aerators most commonly used have an impeller that draws water to the surface and casts it out by centrifugal force. A zone of intense turbulence is created to entrain and absorb air. The maximum efficiency rate is usually about 4 lb of oxygen dissolved per horsepower-hour (Whipple et al. 1970).

Diffuser aerators are similar to those used in destratification assemblies. The headers are usually perforated pipes placed parallel to each other in the stream bed perpendicular to the flow. The size of the device needed depends on the concentration of oxygen-demanding wastes in the stream and the characteristics of the site.

Supplemental aeration systems have been designed for large river systems

(Imhoff and Albrecht 1978; Whipple et al. 1972). Combinations of surface and diffuser aerators, and oxygen diffusion systems have been used. Whipple et al. (1972) designed a system for the Delaware River. Wind and wave action, tidal cycle, and navigational needs were considered. Although only a single test unit was installed, the authors speculated that a complete system would require about 50 units. Surface aerators would be used where navigation was not a factor and diffusers would be used along the perimeter of extensive port and anchorage areas.

Imhoff and Albrecht (1978) reported on a supplemental instream aeration system installed on the Ruhr River, West Germany, in which surface aerators, turbine aeration, side stream pumping systems, and diffusers were incorporated into the network. An oxygen monitoring system controlled aerator operation. Appropriate aerators were started when the dissolved oxygen concentration decreased to 4 ppm, and stopped when it exceeded 4.5 ppm upstream from the aerator.

Hoskings et al. (1977) developed a design that incorporated a side stream oxygenation system to maintain 4 ppm dissolved oxygen in the Houston Ship Channel (Fig. 55). The primary components were an oxygen source, pump station, pipeline contactor, pressure control valve, and distributor header.

Dittman and Lothan (1975) reported on investigations into packed column water oxygenators as a method for supplemental stream aeration. The countercurrent packed gas absorption columns used were capable of producing water with a dissolved oxygen content of 30 ppm or more. Thus, pumping requirements of such a system would be small.

31.3. IMPACTS ON THE ENVIRONMENT

Oxygen is vital to all metabolic processes of aquatic communities and organisms; consequently it is one of the most significant chemical substances in water (Reid 1961). Logically, the manipulation of the oxygen content of lakes, reservoirs, and streams can have a profound effect on their chemistry and biota. Therefore, adverse or beneficial effects, other than the improvement of habitat for fishes, may result from destratification, aeration, and oxygenation management techniques.

The principal adverse effects of destratification are related to the mixing action of the technique. Destratification transforms a lake into a nearly isothermic water mass, with a temperature close to the normal surface water temperature. If the surface water temperature is too high, coldwater fishery habitat will be eliminated (Fast 1973). Moreover, the resultant temperatures may be unsuitable for domestic and industrial uses (Fast et al. 1975; Jennett et al. 1972; Lorenzen and Fast 1977).

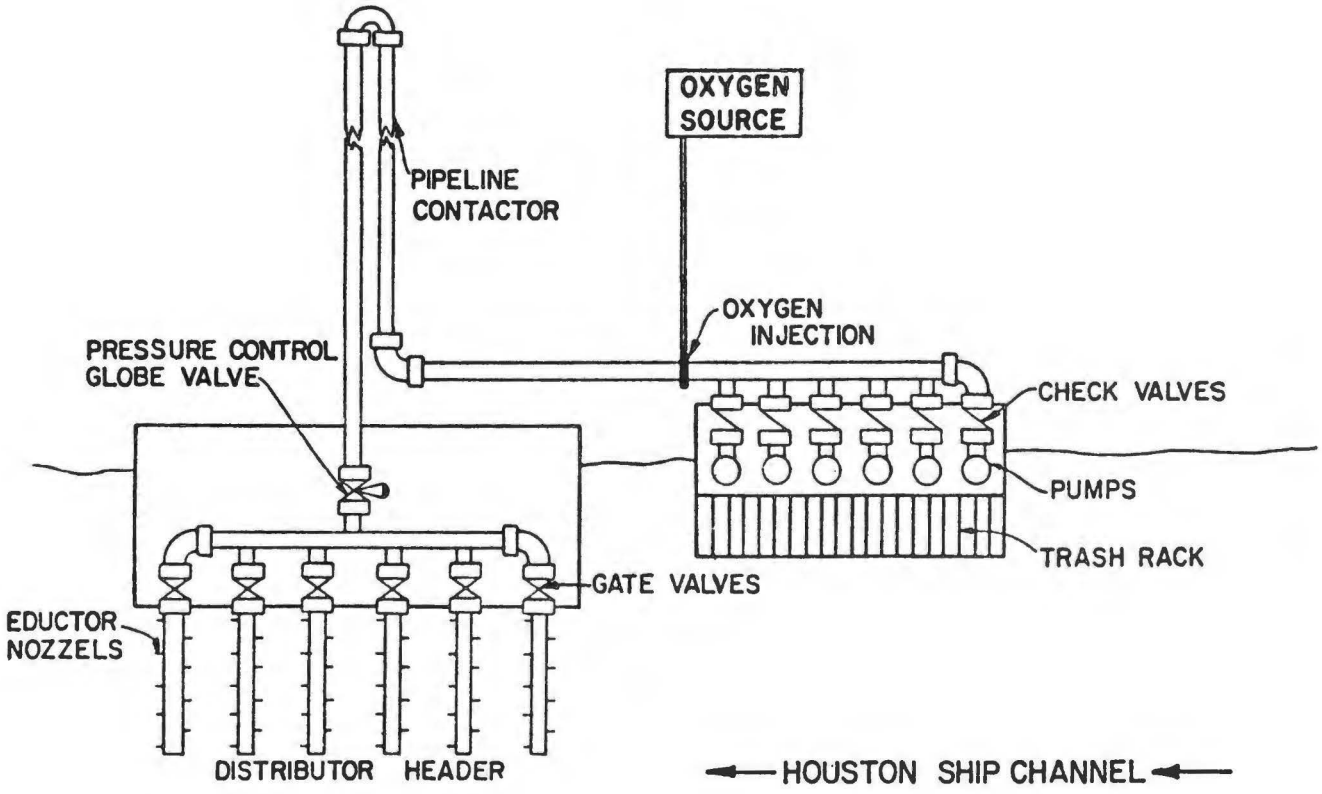


Fig. 55. Side stream oxygenation system developed by Hoskings et al. (1977) that maintained 4 ppm dissolved oxygen in the Houston Ship Channel.

Turbulence created by the destratification processes may cause resuspension of bottom sediments. If the sediments that are resuspended exert a particularly high oxygen demand, dissolved oxygen depletion may result--especially if the destratification equipment is inefficient and cannot compensate for the increased oxygen demand. If the destratification is improperly timed in relation to algal blooms, existing oxygen deficiencies can be aggravated (Pastorok et al. 1982).

Hypolimnetic aeration is more limited in controlling algal blooms than those realized by whole lake mixing, but the risk of adverse effects is less. Provided that the equipment used is properly designed, possible nitrogen supersaturation and resuspension of toxic contaminants are the only potential adverse effects that may result from hypolimnetic aeration. Although nitrogen saturation data are sparse, Fast et al. (1975) reported 150% nitrogen supersaturation after 80 days of hypolimnetic aeration in Lake Waccabuc. Fast

(1979) reported 140% nitrogen supersaturation in Lake Casitas, California, as the result of incomplete destratification. These concentrations are probably lethal to fish (Blahm et al. 1976; Rulifson and Pine 1976).

Some physical hazards to humans may be associated with aeration efforts. Extensive open-water areas that result from most winterkill prevention techniques create a danger, especially to snowmobilers (Wirth 1970). Mechanical aeration devices can be a hazard to swimmers and boaters. The impellers on mechanical agitators can severely injure swimmers, and the presence of such devices can obstruct navigational lanes (Whipple et al. 1970).

Dittman and Lothan (1975) listed the following problems or disadvantages associated with instream aeration systems now used:

1. The equipment may be damaged by storms.

2. The equipment may be a navigational hazard to boats, especially in fog.

3. Claims for personal injury may be filed under the "attractive nuisance" theory, even though the persons involved may have been trespassing on the equipment at the time of the injury.

4. Claims may be made for damage to boats.

5. Aeration equipment may be damaged maliciously.

6. Surface-type aerators may be damaged by debris drawn up into the impeller by the strong currents that are generated. (This type of occurrence has already been reported at existing installations.)

7. Underwater diffuser headers may be damaged by ships and anchors.

8. Any pathogens that might be present in the water can become airborne by the action of surface aerators.

The authors claimed that if oxygenation systems consisting of countercurrent packed columns were used, instead of the systems now used, none of these problems would arise.

Destratification and hypolimnetic aeration provide many benefits to water quality, in addition to improving the quality and quantity of fishery habitat. Both techniques effectively reduce concentrations of hydrogen sulfide, iron, and manganese associated with anoxic conditions (Fast 1979). The techniques

also help to reduce phosphorus loading by oxygenating anoxic sediments and, in turn, alter the release rates of phosphorus in sediments (Mortimer 1941, 1942). However, increased sediment temperatures and greater water movement near the sediment interface may increase phosphorus dissolution rates (Fast 1979). Enhanced populations of zooplankton and benthic macroinvertebrates may also result from aeration, and these may promote phosphorus removal (Davis 1974; Pastorok et al. 1982).

Short-term increases in fish growth and yield have been observed as a result of improved food sources and habitat, but long-term observations are unavailable (Pastorok et al. 1982).

Destratification can lead to a reduction of algal standing crops and cause shifts in composition of the algal community (Shapiro 1979; Toetz et al. 1972). If a lake undergoing destratification has sufficient depth relative to its euphotic zone, increases in algal production may be limited because the algae will be redistributed below the euphotic zone, where light conditions are not favorable (Bella 1970; Murphy 1962). Concentrations of blue-green algae may be reduced because their gas vacuoles rupture if subjected to rapid changes in pressure (Robinson et al. 1969). Destratification can also promote changes in carbon dioxide concentrations and in pH, which in turn may cause a shift in algal species composition from the less desirable blue-green algae to the more desirable green algae (Shapiro 1979; Pastorok et al. 1982). Algal abundance may also be reduced by grazing if zooplankton populations increase (Shapiro 1979). Zooplankters can thrive in the dimly lit, newly aerated, deep portions of the lake, where they can escape predation more effectively (Fast 1979).

Maintenance of a cold hypolimnion is a beneficial effect that is unique to hypolimnetic aeration systems. Cold hypolimnetic water not only provides a coldwater fishery, but also develops a more acceptable source of water for municipal and industrial water supplies.

A novel beneficial effect can be realized from a dual purpose hypolimnetic aeration device developed by Fast (1979). The device not only aerates hypolimnetic water, but it can also serve as a salmonid rearing system. He theorized that the fish reared in the system would feed almost entirely on zooplankton and that nutrient removal would occur when the fish were harvested.

31.4. COSTS

The selection process for determining the best type of aeration system to be used is described in Fig. 56. Lorenzen and Fast (1978) also presented guidelines for design and size selection, and provided generalized

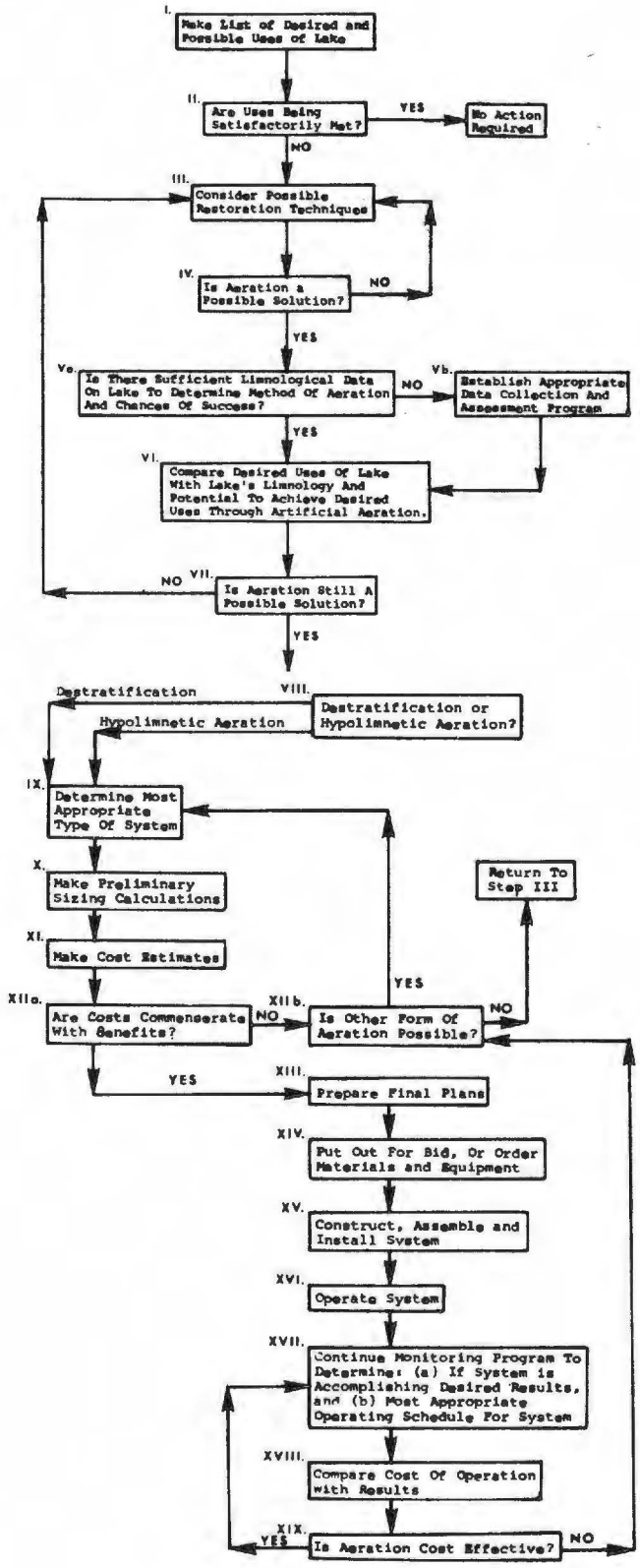


Fig. 56. The decision-making process for consideration of artificial aeration as a lake restoration technique (Fast 1979).

guidelines for cost estimates of hypolimnetic aeration and destratification.

The major capital costs associated with a destratification system are air compressors, supply lines, and diffusers. Two complete air compressors, motors, and associated gear to deliver 1200 ft^3 of air per minute would cost about $50,000-$60,000; the supply lines and diffusers would add another $5,000; power costs would be about $31,000 per year (all values in 1977 dollars).

The "Garton pump" is an inexpensive destratification system. A single assembled pump unit of this type costs about $1600 for equipment and material (Garton et al. 1979). The total cost would depend on the number of pumps employed. Estimates of costs in relation to efficiency were not reported.

The major cost items for hypolimnetic aeration systems are the compressor, the air-supply lines, and diffusers. Capital costs for a simple upwelling-downwelling pipe may be as much as $200,000. Various commercial systems can be used, but local suppliers may be able to custom-build a system at a lower price. Operating costs will be primarily for electricity. A system that uses a 115-horsepower motor that is operated 6000 h each year will consume about 575,000 kilowatt-hours. At $0.03 per kilowatt-hour (1977 prices), operational costs would be $15,000 per year.

Fast et al. (1976) presented a comparison of cost and efficiency for three hypolimnetic aeration or oxygenation systems used in San Vicente Reservoir, California (Table 11). A full air-lift system was the most cost-effective technique.

Speece (1971) estimated the cost of his U-tube hypolimnetic aerator to be $8700. Amortization of the cost over 5 years at a 6% interest rate, yields an amortized yearly cost of $2000. Assuming maintenance costs of $1000 per year and power costs of $810 ($0.015 per kilowatt-hour), the total annual cost (in 1970 dollars) would be $3810.

Wirth (1970) estimated that the initial cost of a winterkill management aeration system in Fox Lake, Wisconsin, was $7230. The power cost at 1970 prices was about $5 per day.

As stated previously, the wind-powered aeration system in remote locations, described by Schierholz et al. (1976), which may be useful, cost less than $2000 in 1975. The authors provided unit costs of materials in their description of the device.

Cost-effectiveness is one of the principal benefits of instream aeration

Table 11. Cost comparisons of three proposed hypolimnetic aeration and oxygenation systems for San Vicente Reservoir, California (modified from Fast et al. 1976).

System	Estimated costs[a] (thousands of dollars)		Total horsepower requirement	Efficiency (oxygen dissolved per kilowatt hour)	
	Capital	Yearly operation		Pounds	Kilograms
Side stream pumping system	$166	$80	150	1.4	0.64
Limno	>300	50.4	500	1.2	0.64
Fuel air lift					
Bernhardt	250-280	21.5	200	2.4	1.09
Fast	120-150	21.5	200	2.4	1.09

[a]Estimated power costs all based on $0.0188 per kilowatt-hour.

systems. It has been demonstrated that the cost of instream aeration can be less than one-third as much as the cost of upgrading waste treatment facilities that already have a high level of removal of biochemical oxygen demand, i.e., >79% (Hunter and Whipple 1970; Whipple 1969; Whipple et al. 1970). Cost differentials will probably increase as methods for optimizing system designs are developed (Lin 1977; Longman 1976; Olgac et al. 1976).

Cost estimates for construction, operation, and maintenance for a range of hypothetical alternatives are provided for mechanical surface aerators and diffuser aerators in Table 12 (Whipple et al. 1970).

Dittman and Lothan (1975) demonstrated that countercurrent packed column oxygenation requires less power per unit oxygen absorbed than do surface aerators and diffusers. Moreover, reduced capital costs would be realized as the size of the unit increased.

31.5. EVALUATION FOR USE ON UMRS

Of the many aeration techniques discussed in this chapter, supplemental instream aeration and winterkill prevention may be those most immediately applicable in UMRS. Supplemental instream aeration may be a

Table 12. Costs (thousands of dollars, in 1978) of mechanical surface and diffusion aeration systems (modified from Whipple et al. 1970).

Aeration system	Construction costs			Annual operation and maintenance		
	Equipment	Contingencies and engineering at 20%	Total	Personnel etc.[b]	Capital recovery cost (6% in 20 years)	Total annual costs
Mechanical surface aeration[a]						
Electric aerator, 75 hp						
Case IA, 3 units	$110	$22	$132	$30	$11.5	$ 41.5
Case IB, 6 units	219	44	263	50	22.9	72.9
Case IC, 9 units	326	65	391	68	34.0	102.0
Electric aerator, 50 hp						
Case IIA, 4 units	133	27	160	30	13.9	43.9
Case IIB, 8 units	255	51	306	50	26.7	76.7
Case IIC, 12 units	369	74	443	70	38.6	108.6
Diffusion aeration[b]						
Electric drive, 80 hp						
Case IIIA, 4 units	170	34	204	37	17.8	54.8
Case IIIB, 8 units	340	68	408	63	35.5	98.5
Case IIIC, 12 units	510	102	612	88	53.4	141.4
Diesel drive, 80 hp						
Case IVA, 4 units	168	34	202	37	17.6	54.6
Case IVB, 8 units	335	67	402	68	35.1	103.1
Case IVC, 12 units	500	100	600	98	52.3	150.3

[a]Equipment for mechanical surface aeration includes mechanical aerator (material only), installation of aerator, electrical equipment and installation, excavation, shelter, and miscellaneous. Equipment for diffusion aeration systems includes blower and driver unit, diffusion system, electrical equipment and installation, excavation, shelter, air diffuser nozzles, and miscellaneous.
[b]Annual operation and maintenance cost for surface aeration includes personnel, electrical power, removal of aerator and reinstallation, maintenance, and miscellaneous. Parallel costs for diffusion aeration systems include personnel, electric power, removal of aeration piping, maintenance, and miscellaneous.

particularly important management alternative if significant increases in organic loading occur within UMR basin. Winterkill prevention techniques can

probably be put to immediate use.

Whipple et al. (1970, 1972) demonstrated that, even with advanced waste treatment, some streams experience low dissolved oxygen due to nutrient loading. Untreatable, nonpoint inputs may constitute the major sources of biochemical oxygen demand. Such conditions are expected to increase as human activity increases within UMRS. Substandard dissolved oxygen concentrations already occur at a few locations in UMRS (Simons et al. 1981a). Future consideration should be made of integrated instream aeration systems such as those described by Imhoff and Albrecht (1978) and Whipple et al. (1972).

Destratification and hypolimnetic aeration may have limited value on UMRS. However, if hydroelectric facilities are developed at the navigational dams, or if modifications of dams are made in conjunction with the development of a deeper navigational channel, the river system might be altered to the point that some degree of thermally induced density stratification occurs. If oxygen depletion results, the use of remedial destratification or hypolimnetic aeration systems may be required.

CHAPTER 32. CONTROL OF NUISANCE AQUATIC PLANTS

32.1. SITUATION TO BE MITIGATED OR ENHANCED

Nuisance populations of aquatic vegetation generally develop in response to an environmental perturbation. However, some aquatic systems develop overabundant aquatic vegetation without human involvement. The factors that are most often the primary causes of nuisance growths of aquatic vegetation are eutrophication, accelerated and excessive sedimentation, and introductions of exotic aquatic plants.

Eutrophication from cultural practices promotes nuisance aquatic plant growths by increasing the productive potential of a given body of water. Spectacular blooms of algae are often stimulated by heavy nutrient loads, especially of phosphorus compounds. Moreover, excessive vascular plant densities can develop because competition for available nutrients is greatly reduced by the abundant enrichment.

Accelerated and excessive sedimentation encourages nuisance rooted aquatic plant growths in two principal ways: (1) Accumulating sediments often provide a more favorable substrate than the existing underlying strata. For example, since sand and gravel are poor substrates for rooted aquatic plants, nuisance stands are not likely to develop on them. However, if those substrates become overlaid with silt or silt-clay sediments, a much more suitable substrate for rooted plant growth is formed and dense stands of plants are likely to develop. (2) Sediment accretion may promote rooted aquatic plant growths by filling deep, subphotic zone areas in a body of water, thus raising the bottom into the photic zone where rooted aquatic plants can become established.

Exotic plants often become nuisances because factors that prevented rampant growth in their native habitat are not present in the new environment. Without such controlling factors, exotic plants may outcompete valuable native species and clog or otherwise limit the use of waterways.

Most methods of aquatic plant control are generally symptom-directed. Some of them, however, may be truly remedial actions, provided they are applied in conjunction with actions that eliminate poor land use practices, improper waste treatment, and poor waste disposal practices. Bringing exotics under control through biological means, in effect, establishes a new ecological status quo. The pest species remains, but not in objectionable quantities.

Aquatic plants are essential components of every aquatic ecosytem. Their

primary function is the conversion of sunlight into energy forms usable by other living organisms. As such, aquatic plants provide the energy base in most aquatic environments. Aquatic plants also contribute to the habitat necessary for various fish and invertebrates. They protect shoreline from wind and wave erosion, provide wildlife with food and nesting habitat, and provide quality fishing locations for anglers. The blossoms of some aquatic plants, such as American lotus, are valued for their aesthetic contribution. On the basis of these and other considerations, the elimination of all plants in an aquatic system is never desirable (Dillard 1975).

Only when aquatic plants are considered weeds or nuisances should control measures be considered. King (1966) concluded that there are 10 characteristics common to weeds: they (1) are growing where they are not wanted; (2) are competitive and aggressive; (3) have wild and rank growth; (4) are persistent and resistant to control or eradication; (5) consist of large populations and extensive growths; (6) are useless, unwanted, and undesirable; (7) are harmful to man, animals, or crops; (8) grow spontaneously, appearing without being sown or cultivated; (9) have high reproductive capacity; and (10) are unsightly and disfigure the landscape. It is clear that the designation of a plant as a "weed" is based on the degree to which the plant inhibits man's use of a resource. Thus a plant may be regarded as a weed in one situation but not in another (Mitchell 1974).

Excessively dense growths of aquatic vegetation can interfere with the commercial, recreational, and aesthetic uses of waterways. Such growths can also create health hazards to humans and domestic animals (Applied Biochemists, Inc. 1976). From a fishery management perspective, overly abundant aquatic plants can adversely affect dissolved oxygen concentrations, make angling difficult, and upset the balance of the fish community by providing too much cover for small fish (Klingbiel et al. 1968).

The control of nuisance populations of aquatic plants is substantial and should first be directed toward the primary cause--eutrophication of aquatic environments (Blackburn 1974). Uncontrolled drainage from farmland, discharges of inadequately treated domestic and industrial wastes, and drainage from garbage dumps all contribute nutrients to a body of water. The control of aquatic weeds is often only temporary, but is necessary if man is to use water resources to the fullest extent.

Considerable effort has been directed toward the development of tools or management techniques for aquatic plant control. Chemical, biological, and mechanical controls and habitat manipulation are management approaches that have been investigated and applied. A variety of approaches have been developed for use in the many types of ecological situations because effectiveness differs in different situations, and individual techniques often have only limited applicability.

32.2. *DESCRIPTION OF TECHNIQUES*

Aquatic vegetation can be categorized according to morphological differences. Algae are unicellar, filamentous, or colonial plants, either planktonic or attached to a substrate. Vascular plants can be submergent, floating-leaved, free-floating, or emergent. The present discussion is limited to the control of algae and submergent, free-floating, and floating-leaved vascular plants. (For information on the control of emergent vascular plants, see Chapter 38.)

32.2.1. *Chemical Control*

Control of aquatic plants with herbicides is the simplest and least expensive control method (Walsh 1981; Applied Biochemists, Inc. 1976; Blackburn 1974), but herbicides may have undesirable effects such as lack of specificity, toxicity to nontarget organisms, and (occasionally) persistent residues.

Herbicides and plant growth regulators are relatively non-persistent in the environment, but cause significant changes in aquatic ecosystems. Their impacts must be judged in relation to (1) toxicity to the target species, (2) relative toxicity to nontarget species, (3) fate of residues and their significance to water, fishes, crops, livestock, and foods, (4) environmental factors that affect toxicity, efficacy, and persistence, and (5) synergizing or antagonizing activity of carriers, formulations, metabolites, degradation products, or other pesticides (Gangstad 1978).

A number of herbicides have been used to control aquatic plant populations but only seven are now registered for use in food-fish environments: chelated copper, copper sulfate, 2,4-D, diquat, endothall, glyphosate and simazine.

Specific information on herbicides provided in this guide was extracted from the Weed Science Society of America (1979), FWS (1979b), EPA Compendium of Registered Pesticides, Volume I (EPA 1974), and Applied Biochemists, Inc. (1976). Information on the seven herbicides approved for aquatic use in food fish environments is given here.

1. Copper chelate (Copper II alkanolamine complex)

   Names of commercial products: Cutrine-Plus, Algaetrol-76, Mariner A, Stockrine Algaecide, and others.

   General information: Copper chelate is registered for use as an

aquatic algicide. It is effective against a broad range of algal species. A granular formuation is especially effective against muskgrass and nitella. Copper chelates appear to be photosynthetic inhibitors that weaken cell membranes. These compounds are generally nontoxic to fish and wildlife unless applied in very soft water (i.e., < 50 ppm $CaCO_3$).

Vegetation controlled: Planktonic and benthic algae.

2. Copper sulfate (Cupric sulfate pentahydrate)

Names of commercial products : Agway Copper Sulfate, Algimycin PLL-C Slow Release, Diamond Copper Sulfate Bluestone, Mariner M, and others.

General information: Copper sulfate has the same mode of action as copper chelates. However, it is a far more corrosive compound and readily precipitates as copper carbonate in hard water.

Vegetation controlled: Planktonic and benthic algae.

3. 2,4-D [(2,4-dichlorophenoxy) acetic acid]

Product names: Aqua-Kleen, Rhodia, 2,4-D, Riverdale 2,4-D Granules, Transvall Weed-Rhap, Vegatrol A-4D, Visko-Rhap 2D, Weedtrine II.

General information: Used on agricultural land, rangeland, forestland, and on aquatic sites for control of emergents, submergents, and floating plants.

This herbicide is nontoxic to mammals but gives a phenolic taste to water that may last for many months. The chemical acts as a plant hormone that stimulates growth and kills plants by having them outgrow their food supply. It imparts an unpleasant flavor to fish.

The label of 2,4-D restricts the use of water in treated areas. Swimming is restricted for 1 day and other uses, such as public drinking water, stock watering, and irrigation, are restricted for 3 days. These restrictions apply only to the treated area and to a relatively small marginal or buffer zone around the treated areas.

The chemical is not harmful to people, livestock, or wildlife but drift can damage crops for miles downwind. Amine formulations of 2,4-D have less drift from volatilization. For best results, foliage must be thoroughly wetted. Repeat applications

may be required.

Because it is very difficult to wash 2,4-D out of spraying equipment, a separate sprayer should be used only for 2,4-D to insure against accidental damage to crops or ornamental plant losses.

Vegetation controlled: Broadleaf weeds, brush, and aquatic emergents.

4. Diquat (9,10-dihydro-8a, 10a-diazoniaphenanthrene-2A)

Product names: Diquat Water Weed Killer, Diquat 2 Spray, Ortho Diquat, Reglone, Weedtrine-D, Aqua-Quat

General information: Diquat is a contact herbicide used as a noncrop weed killer, a general aquatic herbicide, and "top killer" for agricultural use. An important and unique property of diquat is its rapid and complete inactivation by soil. Diquat is a quick-killing herbicide that is absorbed by plant tissue. It is most efficient on plants without an extensive root system. Treated water should not be used for human or animal consumption, spraying, or for overhead irrigation within 14 days after treatment or until chemical analysis shows that the water does not contain more than 0.01 ppm of diquat (EPA 1982). It should not be applied to muddy water.

Vegetation controlled: General weeds, filamentous algae, and submerged and floating aquatic vegetation.

Specific comments: Experiments by Barrett (1981) indicated that diquat can achieve localized control of aquatic vegetation in fast flowing water when it is used with a carrier, like sodium alginate, that forms a viscous solution which sticks to the plants treated.

5. Endothall (3,6-endoxohexahydrophthalic acid)

Names of commercial products: Aquathol formulations, Hydrothol formulations

General information: Endothall is formulated as a dipotassium salt and as a di(N,N-dimethylalkylamine) salt of endothall. It is a contact herbicide that interferes with vital enzyme activity. Treated water should not be used for irrigation or domestic purposes within 7 days after application.

Vegetation controlled: Pondweeds, burreed, hornwort, watermilfoil, naiad, and mudplantain.

6. Glyphosate - (N-(phosphonomethyl)glycine)

Product name: Roundup

General information: This herbicide is used for relatively nonselective weed control. It is relatively nonpersistent in soil. Its effectiveness may be reduced by rainfall within 6 h after application, and negated by heavy rainfall within hours after application. Not for use with aerial spray equipment. Aquatic area uses: banks of small water impoundments, irrigation ditchbanks, or drainage ditchbanks. Glyphosate has a temporary registration for use in food fish areas.

Vegetation controlled: Broadleaf weeds, grasses, and floating aquatic plants

7. Simazine (2-chloro-4,6-bis(ethylamino)-*s*-triazine)

Product names: Princep 80W, Princep 4L, Princep 4G; Aquazine 80W Algicide, Algimycin GLB-X, Gesatop, Primatol

General information: Simazine can be used for control of aquatic weeds. Toxicity to mammals is low, however, even though treated water must not be used for irrigation, livestock watering, or human consumption for at least 12 months after treatment. The chemical is a temporary soil sterilant and acts through the roots and foliage of plants. Its use near crops or valuable plants should be carefully controlled. Meyer (1966) noted that simazine seemed to be less effective for aquatic plant control than other available chemicals.

Vegetation controlled: Planktonic algae, filamentous algae, and submergents.

Specific Comments: Linde (1969), who reported on the use of simazine for grass and sedge control, stated that the treatment was so effective that residual effects (2 years later) prevented the growth of planted barnyardgrass.

In the following vegetation list, effective herbicides for each plant are noted. No specific application volumes, mixtures, or rates are provided because there are wide differences in site-specific characterisitcs and in the concentrations of commercial products. The labels of most herbicides provide application information required for control of a specific plant species. The plants are listed by common name, but the generic names are also provided to avoid confusion. A much more extensive list of plants effectively controlled by herbicides was published by DeVaney (1967). In the present list, each plant name is followed by the names of the herbicides effective in its control.

Algae

1. Planktonic algae (various species): copper sulfate, copper chelate, simazine

2. Filamentous algae (benthic, various species): copper sulfate, copper chelate, simazine, diquat, endothall

3. Muskgrass and nitella: copper sulfate, copper chelate, simazine, endothall

Submerged plants

1. Bladderwort: diquat, 2,4-D

2. Buttercup: diquat

3. Common hornwort: diquat, endothall, simazine, 2,4-D

4. Fanwort: endothall, simazine, 2,4-D

5. Hydrilla: diquat

6. Naiad: diquat, endothall, simazine, 2,4-D

7. Pondweed: diquat, endothall, simazine, 2,4-D

8. Water chestnut: 2,4-D

9. Watermilfoil: diquat, endothall, simazine, 2,4-D

10. Waterweed: diquat, endothall, 2,4-D

Floating-leaved and free-floating plants

1. Burreed: endothall, 2,4,-D

2. Cowlily: endothall, 2,4-D, glyphosate

3. Duckweed and wolffia: diquat, simazine, 2,4-D

4. Lotus: endothall

5. Pennywort: diquat, 2,4-D

6. Salvinia: diquat

7. Water hyacinth: diquat, 2,4-D, glyphosate

8. Water lettuce: diquat

9. Waterlily: 2,4-D, glyphosate

10. Watershield: 2,4-D

11. Waterstar mudplantain: diquat, endothall, 2,4-D

Specific precautions to be observed for the safety of fish, wildlife, and humans were discussed by Rollings and Warden (1964) and Applied Biochemists, Inc. (1976). (Precautions are also listed in Chapter 38.)

Herbicides are provided in a variety of formulations, including solutions, emulsions, oil solutions, suspensions, slow-release pellets, and granules (Burkhalter et al. 1974). Herbicides can also be formulated with polymers, plastics, elastomers, and waxes to provide drift control (Walsh 1981). The various formulations provide flexibility in uses to fit site-specific application needs (Steward 1981).

Liquid formulations can be applied by several methods. The chemical may be metered or injected into the water from booms trailing behind the boat or from a boat bailer connected to a tank of chemical. Herbicides may sometimes be applied as a spray over the water surface. In rapidly flowing canals, the chemical may be injected into the water from booms attached to a tank truck. Slow-release pellets and granular formulations are conducive to applications by hand, with a broadcast spreader, and by air. (Equipment care and calibration are discussed in Chapter 38.)

32.2.2. Biological Control

Biological control methods have been advocated as having great potential for effective, economical, and permanent control of nuisance aquatic plants (Walsh 1981; Schuytema 1977). The advantages of biological controls are that they provide relatively low-cost, perpetual control (Bennett 1974).

Biological control organisms used or proposed for aquatic plant control fall into three categories: plant pathogens, invertebrates, and herbivorous fish. The pathogens include viruses, bacteria, and fungi. Invertebrates include insects, mites, snails, and crayfish. Fishes that show potential as biological control agents are the grass carp and the tilapias. Turtles, waterfowl, and mammals have also been investigated as potential biological control agents, but their utility was judged to be limited by Schuytema (1977) who published a comprehensive review of aquatic plant control organisms.

Exotic weeds are considered good candidates for biological control, the inference being that their natural enemies have not accompanied them; however, it is possible that certain native weeds may also be controlled by similar methods (Bennett 1974).

Biological controls are not intended to eradicate nuisance plant species, but instead to try to reduce species to a non-nuisance density. Control is successful if the predator (control) and prey (nuisance plant) reach a state of quasi-equilibrium and balance is restored to a level that existed before the appearance of the nuisance (Schuytema 1977).

The following statement was suggested by Walsh (1981) as indicating an appropriate attitude toward the development of biological controls:

> "Researchers in biological control of aquatic plants have a tremendous responsibility to environmental protection because of the complexity of aquatic ecosystems. Any intentional alteration of these systems involves the risk of undesirable consequences. The risk is compounded when the modification is irreversible, as is typically the case in introduction of non-native species that subsequently reproduce. Nevertheless, potential benefits from introduction of organisms for control of nuisance aquatic plants can outweigh the risks if strict guidelines are followed. Suggested guidelines include: (1) the need for an introduction must be clearly established; (2) the organism must have a desirable ecological and economic impact; (3) the species must have minimal niche overlap with native species; (4) it should cause minimal reduction of non-target species; (5) field releases should be studied and ecological impacts determined; (6) disease interrelationships should be carefully examined, and (7) methods for control of the introduced species should be established prior to large scale introduction."

Other information on theory and techniques for biological control was given by Andres and Bennett (1975), Anonymous (1968), Balock et al. (1972), Dean (1969), Fowler and Robson (1978), Freeman (1976), Freeman et al. (1973), Lembi and Ritenour (1977), Magnuson (1976), and Osborne and Sassic (1979).

22.2.3. Mechanical Control

Mechanical control of nuisance aquatic plants has been practiced for centuries (Robson 1974). The technique involves collection of plants, followed by subsequent treatment and return to the water, or by removal from the infested body of water (harvest method). Usually plants are harvested by machine and transported to shore, where they are either deposited or transported elsewhere for disposal or use.

Types of machinery used for harvesting aquatic weeds were described by Livermore and Wunderlich (1969). Nichols (1974) listed manufacturers of weed harvesting equipment (Table 13). The choice of equipment, such as harvesters, transporters, and weed ploughs depends on several factors: (1) the type of plant to be harvested; (2) the type of water body; (3) debris or other foreign matter encountered; (4) the characteristics of the shoreline; (5) prevailing weather conditions; (6) the harvesting concept used; and (7) the plant disposal method contemplated. Other important factors related to the objectives of management plans are cost, results, and ecological implications (Walsh 1981).

The effectiveness of mechanical aquatic plant harvesting and harvester systems were evaluated by Culpepper and Decell (1978), Koegel et al. (1978), Koegel et al. (1974), and Livermore et al. (1975).

32.2.4. Habitat Manipulation

A fourth approach to aquatic plant control is habitat manipulation. The objective of habitat manipulation is to limit plant growth by altering one or more of the physical or chemical factors critical to growth. These factors include light, bottom type, water, temperature, wind, dissolved gases, and nutrients. Bottom types and wind affect the location of plants; the other factors influence physiological processes (Nichols 1974). Because it is possible to control plant growth through the limitation of any one of these factors, many techniques have been developed, including shading; dredging; overwinter drawdowns; flooding; nutrient limitation; and blanketing with sand, gravel, and fiberglass.

Shading can be done by using light occlusive dyes or installing opaque plastic sheeting. Both techniques reduce or eliminate the light needed for active photosynthesis. The use of these techniques is generally restricted to small areas. A dye treats the whole pond, whereas the opaque plastic sheeting (which is suspended on floats) can be used to treat individual, separate areas (Dawson and Kern-Hansen 1979; Mayhew and Runkel 1962).

Dredging, to be effective, must lower the lake bottom beyond the limit of light penetration. It then eliminates the light needed for plant growth. Shallow-water dredging has little utility for plant control; however, deep dredging can be an effective long term aquatic plant control technique (Nichols 1974). Pierce (1970) reviewed small-scale dredging machinery and costs and Peterson (1981) provided a comprehensive review of dredging techniques.

Bottom blanketing can be done with vinyl coated fiberglass or with a 6- to 8-in. layer of sand or gravel. Sand and gravel blanketing is often

Table 13. Manufacturers and selected specifications of weed harvesting equipment (modified from Nichols 1974).

Company and address	Model	Cutting bar (feet)[a] Width	Depth	Cutting speed (mph)	Removal method
Air-Lec Industries 3300 Commercial Ave. Madison, Wisconsin	(Boat mounted)	3.5	3.5	3-6	8-ft rake available for raking shore
American Waterweed Harvesting Company 14901 Minnetonka Industrial Rd. Minnetonka, Minnesota	Harvester	16	6	3	Cutter unit loads onto attached 50 ft self-unloading barge
	Shore Line Cleaner	7	4	3-6	10 ft rake available for raking to shore
Aqualogy Products Corp. P.O. Box 505 Downers Grove, Illinois	Aqua-Beach-Comber	7[b]	6	<1	Rake available for raking to shore
Aqua-marine 1116 Adams St. Waukesha, Wisconsin	650	8	5	1.5	Aqua-trio includes self-unloading harvester, transport barge, and shore conveyor
	Sawfish	8	5	1.5-2	L-shaped front end loading rake
Hockney Co. 913 Cogswell Dr. Silver Lake, Wisconsin	HC-10	10	5	4	Rake attachment for raking to shore
	HC-7 (Boat mounted)	7	4	4	Raking attachment for raking to shore
Taussig Assoc. 1625 Eye St., N.W. Washington, D.C.	Water Witch	8[b]	10	10	None

[a]Width = width of cut; depth = maximum depth of cut
[b]Machine has a hydraulic uprooting system, not a cutting bar.

installed over sheets of perforated black plastic. The plastic reduces nutrient transport from covered sediments and may prevent mixing of the blanket material with the covered sediments (Nichols 1974). Perkins et al. (1980) evaluated the use of vinyl coated fiberglass mesh for the reduction of watermilfoil in Lake Washington, Washington. Though only experimental, the screens (400 apertures per square inch) appeared to be well suited for the improvement of small areas suffering from nuisance growths of aquatic plants.

Overwinter drawdowns expose plants to freezing and desiccation. It is an effective method of control for certain species, but may promote the growth of others (Table 14). A prerequisite to applying this technique is the ability to control water levels on the problem lake. If a water control structure (i.e., dam) is not present, pumping facilities may have to be substituted, provided the lake is not too large. Beard (1973), Lantz et al. (1964), and Nichols (1972) applied winter drawdowns successfully. (For more information on this technique see Chapter 28.)

Table 14. Selected references on the influence of drawdowns[a] on aquatic plant species (modified from Nichols 1974).

Species[b]	Source			
	Nichols (1972)	Nichols (1974)	Beard (1973)	Lantz et al. (1964)
American bulrush			U	
American wildcelery	U		U	
Bladderwort	C			C
Bur marigold			I	
Canadian waterweed			U	
Common arrowhead			U	
Common bladderwort			U	
Common cattail	I		U	
Common ducksmeat			U	
Common hornwort	U	C	C	
Common pickerelweed	C			
Cowlily	C	C	C	
Duckweed			U	
Flatstem pondweed			U	
Floatingleaf pondweed			U	
Floating knotweed	I			
Grassleaf pondweed	I			
Greenfruit burreed			U	
Hemlock waterparsnip	I			
Largeleaf pondweed	C		C	
Leafy pondweed	I			
Marsh cinquefoil	C			
Marsh knotweed	I		U, I	
Needle spikerush	C		U	

Table 14. (cont.)

Species[b]	Source			
	Nichols (1972)	Nichols (1974)	Beard (1973)	Lantz et al. (1964)
Northern mannagrass	I			
Ribbonleaf pondweed	I		U	
Rice cutgrass	I			
Richardson pondweed	I		U	
Robbins pondweed		C	C	
Sandbar willow	I			
Schreber watershield	C		U	C
Slender naiad	I		I	
Softstem bulrush	I			
Stiff wapato	C			
Swamp milkweed	C			
Sweet flag	I		U	
Waterlily	C			C
Watermilfoil			C	
Waterthread pondweed			I	
White buttercup			U	

[a]C = controlled; U = unaffected; and I = increased.
[b]Common names largely follow Scott and Wasser (1980).

Flooding has been used to control the common cattail, (McDonald 1955); it may control submergent aquatic plants as well (Robel 1962), though its utility for this purpose is limited.

Nutrient limitation is another useful habitat manipulation technique. The two methods used involve inactivation or dilution (Nichols 1974). Nutrients can be inactivated by precipitation with alum, fly ash, or clay. Peterson et al. (1973) described nutrient inactivation procedures used successfully on Horseshoe Lake, Wisconsin. Dilution methods simply involve diluting a nutrient-rich lake with increased water flows from a nutrient-poor source (Born et al. 1973).

32.2.5. Integrated Pest Management

Integrated control is a new concept that involves the use of all aquatic plant control methods to achieve effective, long-lasting effects. The following statement on integrated control is from Walsh (1981):

"The integrated control method involves use and coordination of

several methods (chemical, mechanical, biological) to achieve desired vegetation densities within aquatic systems. By integrating several control methods, the most desirable aspects of each method can be utilized. For example, chemical and mechanical methods remove vegetation rapidly, whereas biological organisms remove weeds more slowly, are longer lasting, and less costly. The advantage of integrating methods is that vegetation can be managed more precisely than when a single method is used. After initial control is achieved, biological organisms can be stocked in fewer numbers in order to maintain vegetation at the desired density, and the extent of treatment with other methods may be decreased. Biological control with grass carp alone is promising, but this fish can completely remove all vegetation from the system and eventually affect emergent plants that are important for wildlife and fishery benefits. If stocking rates are decreased and only regrowth is removed after prior treatment, this problem will be eliminated."

Six types of integrated approaches were described by Walsh (1981): (1) herbicide treatment followed by stocking herbivorous fish; (2) herbicide treatment followed by the introduction of pathogens; (3) mechanical harvesting followed by stocking with herbivorous fish; (4) mechanical harvesting, destruction, or both, followed by introduction of pathogens; (5) introduction of insects followed by introduction of pathogens, and (6) mechanical or chemical treatment followed by the introduction of competitive or allelopathic plants. In all these methods, the first treatment is designed to either facilitate the second or reduce its intensity.

22.3. IMPACTS ON THE ENVIRONMENT

Chemical, biological, and mechanical applications that control aquatic vegetation are themselves significant environmental perturbations. As such, the potential for adverse effects, as well as for beneficial impacts, is great. Methods of habitat manipulation for aquatic vegetation control embody similar potential effects.

22.3.1. Chemical Control

Chemical methods of aquatic plant control may have these undesirable effects (Walsh 1981; Dillard 1975):

1. The chemical may lack target-plant specificity.
2. The chemical may be toxic to nontarget organisms.
3. Chemical residues may persist and limit water uses until the compounds degrade.

4. Chemical treatment leaves the killed plants in the water; dissolved oxygen in the water can be dangerously reduced when excess nutrients are released upon decay.

5. The chemical may be potentially hazardous to the applicator.

On the other hand, chemical treatment offers these significant advantages (Walsh 1981; Nichols 1974; Blackburn 1974):

1. Chemicals can be very effective.

2. Large areas can be easily and rapidly treated.

3. Costs are comparatively low.

4. Registered herbicides are environmentally safe when applied at prescribed rates.

32.3.2. Biological Control

The major reservation expressed about biological control of aquatic plants is the potential for permanently altering ecosystems in a negative way (Walsh 1981). Considerable time and effort are required to test the host specificity and environmental compatability of possible control organisms. Even so, that compatability can seldom be ensured. Nevertheless, biological control holds significant promise as a permanent and effective control technique.

32.3.3. Mechanical Control

Mechanical control methods have several drawbacks. No substantial mechanical control programs have been initiated by either private enterprise or governmental agencies for three reasons: (1) they are too expensive in terms of money, labor, and fuel; (2) control over large areas is much slower than that exerted by chemical control; and (3) they are inflexible--i.e., each piece of equipment, or configuration of equipment, is designed to work at a specific site under limited environmental conditions. Mechanical control is difficult because of the size and cumbersomeness of the equipment, the need for trained personnel, the volume of plant biomass involved, the requirement of permits for easements and disposal, and the extensive support logistics needed for fuel and transportation of personnel (Walsh 1981).

The method has some positive attributes, which were listed by Nichols (1974):

1. When harvested, the plants are removed. If sprayed with an herbicide or treated with a pathogen or insect, they persist in a decomposing state for some time.

2. No potentially harmful substances are added to the water during harvesting and the method is generally considered to be environmentally acceptable.

3. In some instances, nutrient removal by removal of plants is beneficial to the aquatic system. However, algal populations have sometimes been stimulated.

4. Mechanical removal of some aquatic weed species may allow recolonization by other, less pestiferous species.

A significant advantage of mechanical harvest control is the potential use of plants as animal feed and as a soil conditioner. Nichols (1974) discussed these uses in detail (Fig. 57).

32.3.4. Habitat Manipulation

Habitat manipulation techniques vary considerably in their approach to the control of nuisance aquatic vegetation. The potential environmental impacts also vary.

Shading has few adverse effects but is temporary, at best. The method is restricted in application and easily controlled. The use of dyes and black plastic sheeting may be aesthetically undesirable.

The principal drawback of dredging is its cost. Otherwise, deep dredging is an effective long-term aquatic plant control technique. It expands the available space for fish and may provide additional spawning habitat by uncovering quality spawning substrates.

Blanketing with sand and gravel is difficult, costly, and may limit the production of benthic invertebrates (Born et al. 1973). However, gravel blanketing may provide desirable spawning substrate for some fishes and sand blanketing may create quality swimming areas.

Overwinter drawdowns provide two ancillary benefits: They help to reduce overcrowded populations of small fish by making them more susceptible to predation, and they may promote consolidation of sediments. This consolidation, in turn, provides more space for fish and a better substrate for benthic invertebrates (see further discussion in Chapter 28). Principal

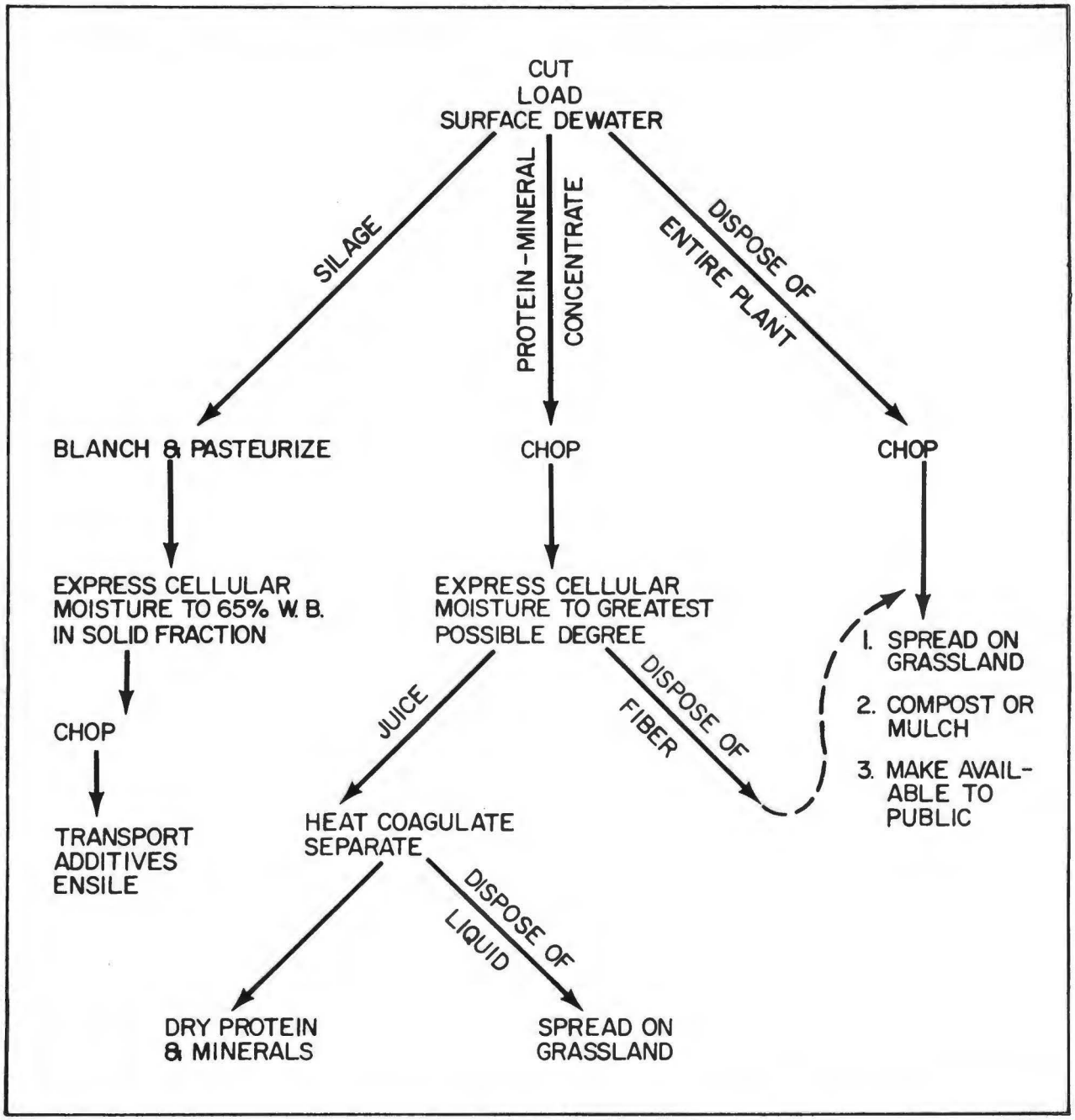


Fig. 57. Processing methods for aquatic vegetation (Nichols 1974).

disadvantages of overwinter drawdown are related to the loss of water and possible stimulation of the growth of unwanted plant species.

Nutrient limitation is a promising technique, especially for algal control. Peterson et al. (1973) listed the following benefits of nutrient precipitation with alum:

1. Total phosphorus in the lake decreased during the summer after treatment.

2. No large increase in total phosphorus occurred in the hypolimnion during the following two summers.

3. Some increase in the transparency of the water was apparent during the summer after treatment.

4. Water color decreased for a short time.

5. Nuisance planktonic algal blooms that had been common in previous years did not appear.

6. Dissolved oxygen conditions improved markedly, particularly during the following few winters.

7. No adverse ecological consequences were observed.

32.4. Costs

The costs of chemical applications vary with the chemical used and the size of area to be treated. Updated price information on herbicides may be obtained from local chemical suppliers. Prices vary with brand names and active chemical concentrations. For example, simazine applied at 1.7 to 3.4 lb per acre-foot for algal control costs $6.30 to $12.60 per acre-foot, and submergent control (3.4 to 6.8 lb per acre foot) cost $12.50 to $25.00 per acre-foot (1982 prices). Copper sulfate costs $55 to $110 per surface acre to control algae. Free-floating plants could be controlled by 2,4-D at a cost of $11.50 to $23 per acre in 1982.

Although biological controls, are relatively inexpensive when established (Schuytema 1977), the research and testing procedures leading to their approval may be very costly (Freeman et al. 1973). Walsh (1981) stated that the cost of introducing insects is very high; that finding suitable species, quarantine, and testing can take from 8 to 10 years; and that the process may cost several million dollars to complete.

Mechanical harvesting costs are high. Nichols (1974) presented a budget

calculation showing that costs per acre varied with the rate of operation (Table 15).

Habitat manipulation techniques are also expensive. However, the usual long-term benefits of such measures must be considered. Black plastic sheeting (4 mils thick) is very costly. Nichols (1974) stated that the cost was $275 per acre in 1974 dollars. No costs were available for light-occlusive dyes. Dredging is also very costly. Carline and Brynildson (1977) stated that the cost of dredging in small spring ponds ranged from $0.01 to $0.06 per cubic foot of dredged material. Overwinter drawdown costs are reviewed in Chapter 28. Born et al. (1973) presented a cost analysis of the Marion Millpond restoration project (Table 16). Costs of sand blanketing, sediment manipulation, and stump removal were included. A summary of manpower, basic equipment, and costs of alum precipitation procedures, shown in Table 17, was presented by Peterson et al. (1973). Total cost estimates were not included.

32.5. EVALUATION FOR USE ON UMRS

The usefulness of several habitat manipulation techniques described appears to be limited for controlling aquatic plants in large river systems. Nutrient inactivation, which limits growth only in nonrooted species (e.g., algae, duckweed), is unsatisfactory for reservoirs such as the pools above the locks and dams. The long-term utility of sand blanketing is questionable and its application would be confined to areas with only limited siltation problems. Shading with black plastic sheeting and light-occlusive dyes would be applicable only to small bodies of water, such as ponds.

Because navigation is the prime consideration in management operations on UMRS, overwinter drawdowns for submergent aquatic plant control have only limited applicability. (For a more complete evaluation of drawdowns, see Chapter 28.)

Mechanical harvesting of submergent and floating-leaved aquatic vegetation would have little value as a fish management practice on UMRS. It is far too costly for application on large river systems and may be physically impossible in some situations. It would, however, be useful for improving boat access and movement in certain weed-choked areas.

None of the biological controls that have been developed are now suitable for application on UMRS. If exotics should become established, pathogens and insects may be the most acceptable biological control organisms. Most problem plants are endemic species and many are valuable as wildlife food. Biological control of such plants would probably be too extensive, and might interfere with wildlife requirements.

Table 15. Typical harvesting budget calculation sheet for mechanical control of aquatic vegetation (modified from Nichols 1974).[a]

I.	Capital investment for equipment		
	Harvester	$28,900	
	Shore conveyor	7,200	
	Mobilizing assembly	1,805	
	Freight	687	
		$38,592	
	Annual depreciation $38,592 ÷ 10 years		$ 3,860
II.	Leased truck and hauling expense 200 miles per day; 5-day week; 66-day season		
	Leasing fee - $290 x 3 months	$ 870	
	Mileage cost - 200 miles x 66 days x $0.10	1,320	
	Gasoline - (200 miles x 66 days x $0.10) ÷ 10 miles per gallon	264	
			2,450
III.	Labor 8-h day; 66 days; 2 men @ $4 per man-hour (includes fringe benefits): 8 h x 66 days x 2 men x $4 per hour		4,224
IV.	Harvesting, operating, and maintenance expense		1,200
V.	Contingencies (10%)		1,162
	Annual estimated operating cost		$12,900

VI. Summary of cost per acre

Acres cut per hour (8 h per day for 66 days)	Acres per season	Cost per acre
1	528	$24.25
1/2	264	48.50
1/3	176	73.00

[a]Figures were provided by Aquamarine Corporation, are based on the use of their equipment, and apply to costs in 1973.

Table 16. Budget for rehabilitation of Marion Millpond, Wisconsin (from Born et al. 1973).

Expenditures and sources of funds	Amount
Expenditures	
Modification of dam	$ 4,800
Stump removal	
Labor, mechanical (summer)	2,000
Stump cutting (year-round)	1,200
Removal by heavy equipment and hauling (winter)	14,000
Flotation, removal by boat and disposal	5,600
Sediment manipulation	
Dragline--shore and pond bottom	20,000
Dragline--sediment drainage program	3,000
Bulldozing--sediment removal and grading	14,000
Spoils removal, shoreline "trimming"	5,000
Bottom treatments	
Plastic sheeting (about 25 acres)	4,600
Placement on pond bottom (winter)	1,200[a]
Placement on cleared ice (winter)	8,000[a]
Placement, including rip-rapping, along shore	6,700[a]
Total expenditures	90,100
Sources of funds	
Inland Lake Demonstration Project	82,000
Community of Marion (cash disbursements)	8,100
Community of Marion (donated equipment and labor)	11,000
Approximate total costs	$101,000

[a]Includes cost of materials, equipment, and labor.

Table 17. Summary of manpower, basic equipment, and costs for nutrient inactivation by chemical precipitation (from Peterson et al. 1973).

Cost item	Costs[a]
Sampling[b]	$ 40
8 man-hours per trip @ $5 per hour	19
270 miles round trip @ $3 per day + $0.06 per mile	
Analyses[b]	
12 samples per trip @ $30 per sample	360
Staff	
One professional	13,000
Overhead	7,300
Chemicals	
12 tons alum @ $60 per ton	720
Delivery to site	180
Labor for treatment	
12 man-days @ $40	480
Expenses	100
Equipment list	(Essentially all equipment was on loan)
2 Workboats, 18 ft	
2 Barges, 10 X 20 ft	
4 Outboard motors, 18-25 horsepower	
1 Amphibious truck, 2 1/2 ton	
4 Gasoline driven pumps	
1 Generator, 4,000-watt	
2 Electric pumps	
3 Electric mixers	
4 Slurry tanks, 55-gallon	
2 Slurry tanks, 200-gallon	
Piping, valves, hose, plastic tubing, marker flags, gasoline. plastic tarp, rope, dust masks	

[a]Many of the costs associated with this treatment depended almost entirely on local salary levels, distances to site, sampling plan, magnitude of treatment, and local availability of equipment. In essence, treatment costs must be estimated for each specific situation.

[b]A total of 38 sampling runs are included in this report, which would yield a total cost of about $15,900 for sampling and analysis--not including the 1966 data.

Chemical herbicides are usually efficacious and economical. Consequences of using such compounds are not always understood and their applicability is often limited. Only registered products should be used. Impacts of herbicides are usually temporary and some compounds can be used selectively if properly applied. If the resulting effects are not those sought by managers, no lasting ecological damage is likely to occur. Given an appropriate situation, chemical treatment may not only be more effective than mechanical control, but can also be far less expensive. Extensive investigations have demonstrated the safety of herbicides registered for aquatic use.

CHAPTER 33. MANIPULATION OF FISH POPULATIONS

33.1. SITUATION TO BE MITIGATED OR ENHANCED

All of the subjects discussed thus far in Part VII (Fishery management techniques) have, in general, been focused on one central theme: Given that man has altered a pristine riverine environment through his activities, what can be done to make the "altered" environment more amenable to the requirements of fish populations? In this chapter, however, we consider a second and related theme: If the river ecosystem is suitable for the production of fish for food and recreation, what can be done to enhance these fish populations? The answers are varied and not easily established. They must deal with two questions, the answers to which are essentially subjective: What is a quality food fish? and What qualities must a fish population have to provide quality angling?

Within most fish communities, competition (both interspecific and intraspecific) for food and space plays a major role in defining the character of the fishery. Combined with the effects of predation and reproduction, competition influences fish growth rates and numerical composition by species and year classes (Bennett 1970). Under ideal conditions, the success of these forces interact to produce a fish community that is in a "balanced" condition: the growth rates of all species are satisfactory and the relative abundance of predator and prey remains fairly constant. However, these ideal conditions are rare, especially when human influences are present.

The specific factors that negatively affect fish communities and population balance are numerous and varied. The impacts of anglers on the fishery resource are of particular concern. Once imbalanced, a fish community often remains so, even though the causative factors have been removed (Bennett 1970).

Man disrupts the ideal balance through the removal or addition of fish. As an angler, man asserts himself as an inefficient and selective predator (Bennett 1970). He tends to remove large predator fish of certain species. If fishing pressure on the predators is excessive, an overabundance of prey results. If overabundant, the prey will be slow growing, and may even suppress the predator species and prevent its recovery (Bennett 1970).

Man can influence the characteristics of interspecific competition by introducing exotic fish species. Such introductions may be of fish from other continents (e.g., brown trout into North America) or from other watersheds (e.g., rainbow trout into waters east of the Rocky Mountains). These introductions may have an extremely negative effect on desirable endemic populations. The introduction of the common carp into North America is a

clear example. Because it has no natural enemies of consequence, is highly adaptable, and has great reproductive capacity, the common carp has become intensely competitive with native species throughout its range in North America (Scott and Crossman 1973).

Water pollution can also have negative effects on the fish population balance. Intense eutrophication can lead to an overabundance of aquatic vascular plants that provide prey species with such extensive cover that they cannot be effectively cropped by predators. Excessive turbidity interferes with the capture of prey by sight-feeding predators.

Partial winterkills favor an overabundance of species that are tolerant of low dissolved oxygen; most often these are undesirable rough fishes. Such conditions can result from pollution, but winterkills can be independent of anthropogenic influences (Schneberger 1972).

Destruction of predator spawning habitat also affects fish community balance and is usually the result of human activities.

In the development of fishery management as a science, two management concepts have evolved (Larkin 1980): maximum sustainable yield (MSY) and optimum sustainable yield (OSY). The first of these refers to a maximum poundage of fish that can be removed on a continuing basis, and OSY includes considerations of quality aspects of the fishing experience.

Although OSY approaches MSY in many fisheries, managers should consider values other than physical yield. As such, OSY has gradually replaced MSY as a theoretical goal in the management of recreational fisheries (Roedel 1975). MSY represents an average of the highest potential surplus that is likely to be produced by a given fishery stock. The concept of MSY as a management gool starts to break down as user and allocation conflicts develop (Wallace 1975). As we stated previously, the quality of sport fishing is related to more than total pounds of harvest. Indeed, the quality of sport fishing not only relates to the catching of fish, and size of fish taken, but also to aesthetic experiences of the event (e.g., the environmental situations in which fish are found). The concept of OSY best accommodates the elusive but very important element of "quality" in recreational fishing (Stroud 1975).

Anderson (1975) stated that balance in fish communities and populations affects OSY:

> "The pyramid of production in an aquatic ecosystem or portions of the pyramid representing the fish community can be considered [to be] balanced or imbalanced. A balanced fish community has the capacity to provide a satisfactory and sustained harvest of fish of

desirable size in proportion to the productive capacity of the system. The term 'balance' does not describe a state of static equilibrium; it has an artistic connotation. A balanced fish community or aquatic ecosystem is like a work of art in that critics can be complimentary in their evaluation and response. The state of balance relative to management of objectives has a strong influence on how close we can approach optimum sustainable catch, harvest, and yield."

The primary objective of fish population manipulation methods is to restore or maintain balanced fish populations. "Balance" as used here connotes a partial fulfillment of OSY objectives (Anderson 1975). Although the techniques described are decidedly oriented toward the benefit of anglers, the methods would be of benefit to inland commercial fishermen in situations where a fishery is underexploited by sport fishermen.

33.2. DESCRIPTION OF TECHNIQUES

If, for various reasons, a fishery loses its "balance" and no longer produces satisfactory yields to the fisherman, several optional management techniques can be initiated to influence the fish populations directly and to restore the balance. These options encompass techniques of controlled removal or addition of fish. Four discrete selective fish removal methods can be used: (1) imposition of angler harvest regulations that restrict the catch of an overabundant species can be relaxed or removed; (2) mechanical removal, generally in the form of netting, can be encouraged; (3) reproductive failure of certain target species can be induced by properly timed water level drawdowns; and (4) fish stocks can be partly or completely removed by the use of toxicants. Additions involve the stocking of either predator or prey species. In each situation, the species chosen can be either endemic or exotic, depending on niche availability (Anderson 1975). Often a combination of removal methods followed by, or concurrent with, stocking is most effective.

33.2.1. Fishing Regulations

Recreational angling exerts a tremendous influence on the fish community structure. If angling pressure is excessive, the integrity of the fishery may be jeopardized. To prevent overexploitation of fishery resources, governmental regulations have been instituted. Such regulations control the method of angler harvest, the rate of angler harvest, the size of fish that can be creeled, and the geographic boundaries of angling activity.

Fish populations can be manipulated by either tightening or relaxing controls on angler harvest. If regulations are made more restrictive, the

effect will be similar to an addition to the fish stock, because it encourages the development of a larger year class and facilitates the carryover of a year class to the succeeding year. Where the threat of an overabundance of prey fishes occurs, it is usually desirable to maintain predator populations with an abundance of large individuals. Minimum or "slot" size limits may promote such a population structure (Johnson and Anderson 1974). Relaxing regulations encourages the opposite effect. Bennett (1970) presented a graphic representation of the effects of angling on fish populations (Fig. 58). The effectiveness of regulations in meeting fish management goals is usually limited to reducing harvest. Several authors have discussed the theory of harvest regulation as it relates to common riverine game fishes (Bennett 1970; Cooper 1980; Funk 1972; Kendall 1978; Noble 1980).

When the regulation of fishing effort fails to remedy population imbalances characterized by overabundant, slow-growing, or stunted sport species, or by overabundant, repressive populations of various species of rough or coarse fish, several other removal techniques may be applied. The techniques include mechanical removal, water level drawdowns, and removal with toxicants.

33.2.2. Mechanical Control

Mechanical removal is typically characterized by some method of netting, but electroshocking methods have also been used (Snow 1967). Types of nets that have been used include trawls, gill nets, hoop nets, trammel nets, trap nets, and seines (Hacker 1975; Sullivan 1967; Priegel 1971; Miller et al. 1969; Churchill 1949; and Jester 1971).

Buchanan et al. (1974) and Headrick et al. (1975) evaluated the effects of mechanical thinning (removal) on panfish and nonpanfish species, respectively. An evaluation of physical thinning projects (including angling) revealed a 42% success rate when physical thinning operations were directed at panfish, and a 53% success rate when the technique was directed at nonpanfish species.

A particularly good example of successful mechanical rough fish control is that used in Lake Winnebago, Wisconsin. The operation was directed at freshwater drum, but other rough fishes (common carp and suckers) were also removed. In 1955-66, 35.5 million lb of rough fish were removed, of which 33.4 million lb were freshwater drum. As a result, existing populations of walleyes, saugers, and white bass increased, and marginal populations of yellow perch and black crappie developed (Priegel 1971). This management effort was accomplished chiefly by commercial fishing. However, as populations were reduced, commercial fishing became economically less attractive. Some private fishing crews dropped out of business and state crews were assembled so that the fishing pressure could be maintained (Hacker 1975).

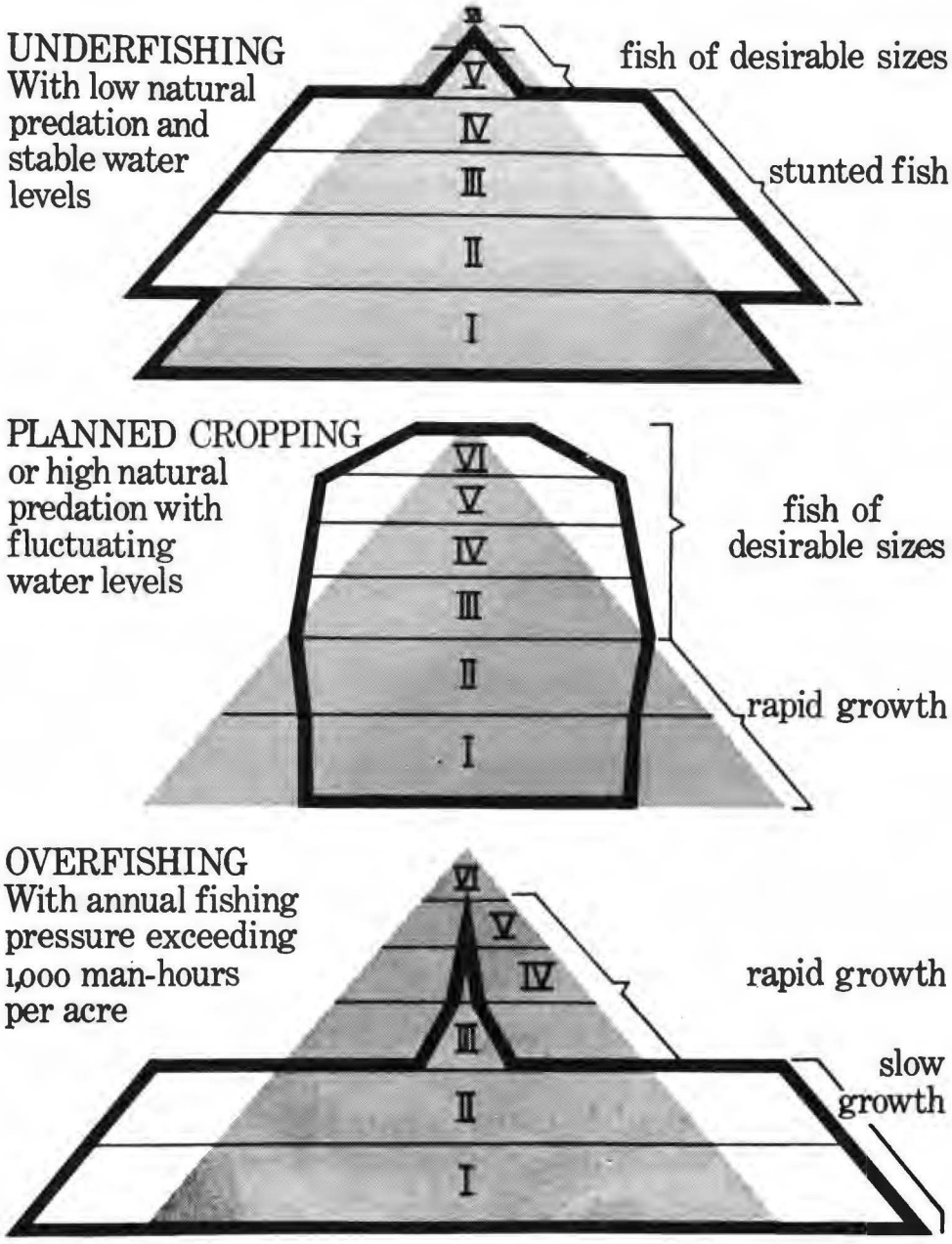


Fig. 58. Diagrams representing theoretical fish populations (underfished, planned cropping, and overfished) superimposed on segmented triangles representing the first six year classes of fish populations reduced (spaced) on a 50% mortality rate (Bennett 1970).

33.2.3. Drawdowns

Bennett (1970) stated that R. W. Eschmeyer first noted in 1947 that

fluctuating TVA impoundments provided better fishing than pools with a permanent or stable water level. He suggested that the "winter drawdown apparently limits the abundance of rough fish (by limiting their food) without serious injury to the gamefish populations." Since then, controlled water level fluctuations have become a common fishery management practice (for discussion of management of water levels, see Chapter 28).

It is readily apparent that this technique can be practiced only on reservoirs or lakes with water level control structures. Bennett (1970) stated that effective fall-winter drawdowns must reduce the lake surface area by more than 25% to force fish from the protection of beds of aquatic plants.

Drawdowns are generally instituted for the control of rough fish and overabundant forage species (e.g., bluegills). A drawdown functions in two ways. It kills directly by stranding fish and fish eggs, or causes increased predation on forage fish by forcing them out of protective cover into the proximity of predator species.

Common carp and bluegills have been primary targets for selective thinning through drawdown techniques (Beard 1971a; Beard and Snow 1970; Bennett et al. 1973; Heman et al. 1969; Hulsey 1956; Lantz et al. 1964; Pierce et al. 1963; Shields 1957, 1958). Success has usually been limited (Buchanan et al. 1974; Headrick et al. 1975).

33.2.4. Chemical Control

Fish toxicants have been used for thousands of years. Natives in Asia and South America, as well as American Indians, have used plant extracts to capture fish for food in freshwater and saltwater (Lennon 1971). Piscicides are routinely used in fishery management for the control of pest species, as well as for management of out-of-balance fish populations.

The practice of reclaiming streams, rivers, ponds, lakes, and reservoirs has grown rapidly in the past 40 years. The development of more effective compounds has promoted mono- and bi-species management of food and game fishes (Lennon 1971; Lennon et al. 1970). Such development led Prevost (1960) to remark that the reclamation of water with fish toxicants is the best available management tool. Lennon et al. (1970) presented the following rationale for an expected increase in reclamation by the use of toxicants:

1. There is a growing need for intensive management of food and game fishes to meet increasing demands in the face of shrinking water resources.

2. Selective exploitation, unwise stocking of native or exotic

fishes, or alterations in water quality are contributing to frequent imbalances in wild populations, with undesirable fishes suppressing or excluding desirable fishes.

3. Improved toxicants, specific to fish or to selected fish species, are becoming available.

4. More and better-trained people are entering the field of fishery management.

Although more than 40 substances have been used as fish toxicants (Lennon 1971; Lennon et al. 1970), only 4 are currently registered for use as piscicides (Meyer et al. 1976; Schnick et al. 1979): antimycin, rotenone, Bayer 73, and TFM. Registered compounds are accepted as safe for the intended uses, and adverse effects on the environment are minimal (Threinen 1972).

Two compounds show promise as candidate piscicides. Squoxin (1,1'-methylenedi-2-naphthol) is a chemical selectively lethal to northern and Umpqua squawfish. It reportedly is 3 to 100 times more toxic to squawfish than to salmonids (MacPhee and Ruelle 1969). Marking (1972) concluded that Salicylanilide I (2',5-dichloro-3-tert-butyl-6-methyl-4'-nitrosalicylanide), a compound related to Bayer 73, has potential as a general piscicide. The compound has broad spectrum activity, kills bullheads, and is inexpensive. Moreover, it effectively kills fish at similar concentrations in water that is soft or hard, cold or warm, or acid or alkaline.

Lennon et al. (1970) presented the following technical data on two of the four registered fish toxicants. The other two piscicides, Bayer 73 and TFM (3-trifluoromethyl-4-nitrophenol), are used as lampricides in both Canada and the United States in lotic and lentic waters of the Great Lakes system (Schnick 1972; Hamilton 1974; Gilderhus and Johnson 1980). The compounds are used to kill larval sea lampreys and can be applied only by governmental agencies.

Antimycin

Alternative name:		Fintrol-5, Fintrol-15, and Fintrol-Concentrate.
Chemical formula:		$C_{28}H_{40}N_2O_9$
Formulation	:	Controlled-release coating on sand grains, and as water-soluble liquid.
Primary use	:	Registered fish toxicant in United States and Canada.
Secondary use	:	Fungicide; miticide.
Safety hazard	:	May cause conjuctivitis; protect eyes with safety glasses.
Persistence	:	Non-persistent in environment

Rotenone

Alternative name:		Nox-Fish, Pro-Noxfish, Nusyn-Noxfish Chem-fish Regular, Chem-fish Special, Fish-Tox, Derris, Cube, Derrin, Nicouline, Tubatoxin, Timbo Powder.
Chemical formula:		$C_{23}H_{22}O_6$
Formulation	:	Liquid, synergized liquid, and powered plant roots.
Primary use	:	Insecticide.
Secondary use	:	Registered fish toxicant in United States and Canada.
Mode of action	:	Inhibitor of cellular respiration.
Safety hazard	:	Inhalation of powder can cause headaches, sore throats and other cold symptoms, and sores on mucous membranes; contact can cause irritation of eyes and rash on skin. Protective clothing is advised when using powdered root. Use of wettable powder or liquid formulations reduces risk to safety and health.
Persistence	:	Seldom persists in environment longer than 2 weeks; longer in very soft water.

Rotenone and antimycin can be used to manipulate fish populations. Selective thinning, as well as complete reclamation of lentic and lotic systems, has been attempted (Hacker 1971; Hooper and Crance 1960; Johnson 1975). Libey and Holland (1980) described a method for selectively thinning larval bluegills by making periodic applications of rotenone at low concentrations. Greenbank (1941) demonstrated that rotenone could be used selectively to kill warmwater species and to spare salmonids in a thermally stratified lake. Various formulations of antimycin can be used to produce similar results. Fintrol-5 and Fintrol-15 are formulated to release the toxicant in the first 5 and 15 feet of water, respectively (Lennon et al. 1970). A sand grain carrier releases the toxicant as it sinks through the water column.

Reviews of the current literature on fish toxicants were given by Hamilton (1974), Lennon (1970), Lennon et al. (1970), and Schnick (1972, 1974a, 1974b). Buchanan et al. (1974), Headrick et al. (1975), and Spitler (1970) also reviewed the effectiveness of chemical treatment projects.

Lennon et al. (1970) noted that total reclamation involves a complete kill of the existing fish population followed by a restocking of desirable species. They presented a series of steps that constitute the methodology for aquatic reclamation projects:

1. Demonstration of need.
2. Selection of a method or methods for the solution of the problem.
3. Selection of a toxicant.
4. Selection of application methods.
5. Pre- and post-reclamation assessments.

Lennon et al. (1970) traced the evolution of principles and methods for the reclamation of streams. They cited 31 references covering the period from 1954 to 1969.

The difficulties of reclaiming streams led to the preparation of technique manuals. McCoy and Ratledge (1967), who compiled a manual for the reclamation of mountain trout streams in North Carolina, discussed in detail the following elements of pre-reclamation investigations: (1) the need for an adequate assessment of fish populations in the project area; (2) the mechanics of time-motion studies of stream flow and establishment of the rate of longitudinal mixing; (3) determination of a linear relation between specific conductance and known salt concentrations at a constant temperature; (4) rotenone toxicity studies to determine the concentration of toxicant and duration of exposure required to kill target species; and (5) detoxification of rotenone with potassium permanganate. They also presented a plan of operation that included personnel, equipment, and supplies.

Fernholz and Slifer (1967), in outlining procedures for the chemical reclamation of soft-water trout streams in Wisconsin, listed 15 steps involved in a stream reclamation project:

1. Conduct a biological survey to determine the need for a reclamation project.

2. Conduct a public relations program to win general support for the project.

3. Obtain written approvals from riparian landowners, sportsmen clubs, civic groups, and the public service commission as necessary.

4. Set a tentative date for the project.

5. Prepare an outline map of the project area, including all access points, streams, tributaries, backwaters, and toxicant stations.

6. Establish stations for application of the toxicant about 1 mile apart.

7. Measure volume of stream flow at each station.

8. Establish a bench mark at every fifth station at the time the flow measurements are made.

9. Conduct salt-resistivity tests at each station, above and below the points of salt introduction.

10. Calculate toxicant requirements for each station from reference

table in the manual.

11. Calculate the volume of any impoundments present and the amounts of toxicant needed to compensate for the additional volume in these areas.

12. Establish a detoxification station if required.

13. Establish stations for live-cages of test fish in treated area and untreated areas downstream.

14. List manpower and equipment needs.

15. Establish post-treatment survey procedures.

Procedures and techniques for stream reclamation were discussed by Slifer (1970), who covered such topics as the salt-conductivity relation, station location, toxicant selection, application rates, project timing, equipment, fish barriers, and detoxification.

33.2.5. Integrated Pest Management

Various combinations of control methods can be incorporated into an integrated pest management program. Meyer and Schnick (1980) described the integrated pest management concept as follows:

> "Integrated pest control is a management concept that involves the systematic application of multiple techniques in a way that will exert maximum impact on a target organism. To the greatest degree possible all available information on the biology of the pest species is used against itself, including such diverse elements as susceptibility to parasites or pathogens, susceptibility to toxicants, vulnerability of various life stages to habitat changes, potential usefulness of attractants and repellents, susceptibility to trapping, and the possibility of using sterilization techniques to reduce or eliminate reproduction. This information is then used to combine the various control techniques in a program that will affect as many life stages of the target species as possible, will attack the organism at the most vulnerable stage in its life history, or will reduce the amount of chemical required without a decrease in efficacy."

The potential exists for integrated pest management to manipulate fish populations. For further discussion on the concept of integrated pest management, see Chapter 32.

33.2.6. Stocking

Stocking fish represents one of the oldest methods of fish population manipulation. In North America, Theodatus Garlich published a treatise on artificial propagation in 1857. By 1870, about 200 private persons were practicing fish culture (Thompson 1970) and common carp had been brought from Germany and were established in inland waters of the Pacific coast. Before 1936, stocking and angling control were the only fish management methods used (Bennett 1970).

Stocking is far from being a cure-all. Bennett (1970) stated that accumulated evidence suggested that successful stocking is limited to the following situations:

1. Interim stocking of trout large enough to be caught immediately.

2. Stocking in newly constructed and filled artificial lakes and reservoirs.

3. Stocking in reclaimed or renovated lakes or streams after the indigenous or stocked fish population has been removed.

4. Introducing a new species to improve the ecosystem, either for sport fishing or as a "fill-in" for the food chain. Such an introduction should be preceded by a partial poisoning of the present fish population to insure that competition for food and space is reduced before the new fish are released.

5. Stocking where conditions for growth are favorable, but reproduction is uncertain (e.g., when channel catfish are released in ponds containing mixed populations of fishes) or subject to predictable failure (as in shallow lakes subject to complete winterkill).

Some notable fishery management successes and failures have been associated with the stocking of exotics. Introduced species can improve ecological efficiency, enhance production, and increase angling opportunities in optimum sustained yield management. Such introductions must be preceded by research and evaluation to determine the ecological, social, and economic benefits and costs (Anderson 1975). Notable successes include the establishment of coho salmon, chinook salmon, and other introduced salmonids in the Great Lakes; and the establishment of striped bass and its hybrids (striped bass x white bass) and threadfin shad in southern reservoirs. The most notable disaster has been the introduction of the common carp.

Kerby and Joseph (1978) decided to investigate the potential stocking of

the striped bass x white perch hybrid in estuaries because of the success of the striped bass x white bass hybrid stocking in freshwater impoundments. These hybrids were hardier, more adaptable, and have more rapid early growth rates than striped bass. The striped bass x white perch hybrids also grow much faster and to a larger size than resident white perch. Apparently, the striped bass x white perch hybrid could be stocked in estuaries as a supplement to natural populations of striped bass and white perch.

Many descriptions of stocking methodologies have been published. It is apparent that no standard methodology has been established and that many variables influence procedures. Fry, fingerlings, and adults have all been used, and the rates at which fry and fingerlings are stocked in large systems often depends on availability. Moreover, angler catches of edible-size fish resulting from plantings of fry in lakes where the species stocked are already established are often indeterminable (Klingbiel 1971a). Fingerlings of different sizes can be used, but survival often depends on the abundance of food and predators (Klingbiel 1971a; Paxton and Day 1979).

Considerable attention has been given to the management of largemouth bass, particularly in farm ponds and reservoirs. Wenger (1972) reviewed the works of H.S. Swingle, G. W. Bennett, H. A. Regier, and others. Much of his discussion of new or reclaimed farm pond and reservoir stocking procedures revolved around the time of stocking, size of fish, type of fish, and predator-prey ratios. Good, recent, evaluations of stocking procedures for black basses, bluegills, and catfish were presented by Muncy and Bulkley (1971) and Paxton and Day (1979). Fleener et al. (1974) discussed the effects of stocking smallmouth bass in the Big Piney River, Missouri.

Coolwater species, such as esocids and percids, are often stocked to increase recruitment (Johnson 1975; Klingbiel 1971a). Although stocking success in waters with established fish populations varies, the stocking of walleyes in new reservoirs and reclaimed lakes has been consistently successful. Survival of stocked fingerling muskellunge is highly variable, and there appears to be an inverse relation between the size of the walleye population and the percentage of stocked muskellunge that survive (Klingbiel 1971b). Information on percid and esocid stocking techniques and evaluations was provided by Carlander et al. (1960), Carlander and Ridenhour (1955), Erickson (1972), Kendall (1978), and Muncy and Bulkley (1971).

33.3. IMPACTS ON THE ENVIRONMENT

If the angler harvest is properly regulated, no adverse effects on the fishery should ensue from angling. Problems sometimes arise because angling regulations are often statewide or area wide and do not consider the unique characteristics of individual bodies of water.

Tailoring regulations for each body of water would, of course, be biologically ideal. However, such regulations cannot be properly written without adequate population and environmental information. For states such as Wisconsin and Minnesota, which contain thousands of lakes, such a task would be nearly impossible because of fiscal constraints. The size and complexity of the book of regulations that would be required would cause anglers to rebel. The effects of underfishing and overfishing have already been discussed (see, e.g., Fig. 58).

Depending on the type of gear used, mechanical removal of fish may produce adverse effects on nontarget populations. Gill nets often severely injure or kill fish that are caught, and are generally selective for size. Species selectivity depends on the time of fishing, mesh size, and placement of the nets. However, habitats used by different species overlap and nontarget fishes are often caught.

In view of the success of some mechanical rough fish removal projects (Miller et al. 1969; Priegel 1971), direct damage to nontarget species is probably insignificant. The benefits to sport fish populations from the large-scale removal of dominant rough fish species should outweigh any direct damage to nontarget populations.

The primary adverse effects of drawdown techniques involve the loss of aesthetic values and losses of water that may be needed by offstream users. Spring and summer drawdowns may be especially unpleasant aesthetically, because odors released by decaying vegetation and dead fish are offensive. Inasmuch as water impounded for irrigational purposes is at a premium at that time of year, instituting a drawdown may be difficult (see Chapter 28). Losses of nontarget populations, particularly of invertebrates, may also occur (Kaster 1976).

Beneficial effects of drawdowns, in addition to the intended objectives, include compaction and aeration of sediments (Nichols 1974) and certain desirable changes in plant communities (see Chapter 32).

The recommended concentrations of rotenone and antimycin are generally safe for nontarget organisms. Although most fish toxicants are also toxic to aquatic invertebrates, the effect is temporary; usually the populations rapidly rebuild to pretreatment levels (Lennon 1971; Schnick 1974a, 1974b, 1972).

An advantage of rotenone not directly related to fishery resource manipulation is its usefulness in fish population sampling during survey work (Crandell et al. 1976; Holder 1975; Masnik et al. 1978; Provine 1976; Timmons et al. 1978). The principal advantage of antimycin, in comparison with

rotenone, is that its presence is not sensed by fish (Lennon et al. 1970). Because antimycin cannot be detected by fish, it may be the best substance for stream reclamation and other projects where avoidance by fish may result in unwanted survival.

In certain situations, the stocking of fish can adversely affect endemic fish populations. Dilution of high quality, wild stock gene pools, as well as immediate stresses due to crowding, have been observed in some waters (Schwiebert 1977). Kerby and Joseph (1978) reported that no evidence has been obtained to demonstrate adverse effects on gene pools from striped bass x white bass hybrid stocking. Competition could be a problem, however, between the striped bass x white perch hybrid and striped bass and white perch in estuaries. The potential effects of stocking exotics are seldom fully realized ahead of time because the effects of introductions may not be manifested until several years after the fish are introduced.

Stocked fish can help to reduce fishing pressure on native stocks and can be used to provide a fishery in waters where natural reproduction fails. Such fish can also provide diversity for anglers in an optimum sustained yield fishery by giving them an opportunity to catch species that otherwise would not be available.

33.4. COSTS

The development of angling regulations should not be considered an extra cost item in fishery management, since it is a primary tool of fishery managers. Indeed, the development of effective regulations is a part of overall management plans and reflects the application of fishery management as a science.

Mechanical removal of fish is a time-consuming, costly procedure. Costs are primarily associated with labor and equipment and are similar to costs for net-type sampling techniques. Commercial fishing is preferred whenever feasible because marketing of the captured fish reduces state operating costs. A problem often encountered by commercial fishermen is that of unprofitability as fish removal rates approach effective fish management levels and catch rates decline (Hacker 1975; Priegel 1971).

Drawdown costs (analyses are presented in Chapter 28) are related to the value of the water for other uses, if any.

Fish toxicants are generally expensive. The cost of antimycin in April 1980 was $85 per unit. An application rate of 10 ppb then cost $21.78 per acre-foot of water. The two rotenone formulations Nusyn-Noxfish and Noxfish

cost $15.20 per gallon and $21.70 per gallon, respectively. At an application rate of 2 ppm, Nusyn-Noxfish would cost $10.03 per acre-foot and Noxfish $14.32.

The cost of stocked fish varies from region to region and species to species, and among different rearing methods. Local hatcheries can be consulted for current price estimates. Costs are generally provided as a price per pound of live-weight. Costs of producing salmonids range from $0.40 to $1.90 per pound (Nelson et al. 1978).

33.5. EVALUATION FOR USE ON UMRS

Mechanical harvesting and spot removal with toxicants seem to be two fish population manipulation measures that have immediate applicability on UMRS. Rough fish, especially common carp, are prevalent in UMRS, and a commercial fishery directed toward rough fish has operated for many years. Efforts should be made to facilitate the effectiveness of commercial fishermen. Helping them locate productive fishing grounds and improve their techniques might be appropriate. If localized concentrations of rough fish are not exploited by commercial fishermen, spot removal with toxicants would be useful. However, the need for spot removal should be justified on a case by case basis.

Because fish communities are not static, the possibility that undesirable fish species may become dominant is always present in populations subjected to heavy angling pressure. Integrated pest management should be applied to use all means of control available. The use of attractants could draw undesirable species into areas where a selective toxicant could be used effectively with little effect on the rest of the community. Selective removal techniques have been developed (Libey and Holland 1980), and prospects for the development of more selective toxicants and techniques are good (Lennon et al. 1970). Future uses of fish toxicants in the management of fishery resources of UMRS should not be ruled out.

Stocking would probably not enhance the fishery of UMRS. If quality habitat can be protected or improved, game fish populations should respond positively. Considering the success of striped bass and their hybrids in some landlocked reservoirs in the United States, these forms may warrant investigation as possible introductions.

PART VIII. WILDLIFE MANAGEMENT TECHNIQUES

Wildlife management is the science and art of changing the characteristics and interactions of habitats, wild animal populations, and men to achieve specific human goals (Giles 1969). The maintenance and manipulation of wildlife habitat is a major factor in wildlife management. Yoakum et al. (1980) stated that wildlife objectives should include maintenance of quality habitat as it exists in a natural system and provision for quality habitat where it has deteriorated or where a specific habitat component is lacking.

Wildlife and wildlife habitat associated with large river systems have been greatly affected by man-induced changes. Factors that affect wildlife habitat are critical because they also directly affect wildlife populations. Navigational, industrial, municipal, agricultural, and recreational developments alter the wildlife habitat of river systems. These changes may have adverse, neutral, or beneficial impacts, but many of the current multiple uses of river systems have adverse effects on wildlife.

The wildlife management techniques identified in this guide were chosen on the basis of their possible application to large river systems according to two criteria: (1) value in mitigating impacts on wildlife, or (2) enhancement of the existing wildlife resources. All techniques discussed deal directly with maintenance and manipulation of wildlife habitat.

CHAPTER 34. ARTIFICIAL NEST STRUCTURES

34.1. SITUATION TO BE MITIGATED OR ENHANCED

Artificial nest structures are used to improve or replace nesting habitat for target species and to mitigate losses caused by timber harvest, snag removal, agricultural clearing, channelization, or inundation. River riparian zones are frequently affected by these activities. The loss of bottomland forests adversely influences tree-nesting raptors, colonial birds, songbirds, cavity-nesting birds, and denning mammals. Inundation reduces available habitat for ground-nesting birds. Lock and dam construction can adversely affect rookery sites of colonial-nesting birds because they are dependent on shallow-water feeding areas and such construction usually results in an increase in the proportion of deep water depths. Activities to maintain navigation channels, including the clearing of riparian vegetation and disposal of dredged material may also destroy valuable wildlife habitat.

The loss of suitable avian and mammalian habitat has created a need for increased use of artificial nest structures. Bird houses have been used around the world for many years, but the development of nesting platforms for waterfowl and raptors is relatively new. Many waterfowl that normally nest on the ground also nest in other sites, including trees, over-water structures, and elevated artificial structures. The use of artificial structures should be a secondary technique after the existing habitat has been protected, but man-made structures are sometimes the key to the survival of a species (Yoakum et al. 1980). Artificial nest structures can compensate for a deficiency of natural sites in otherwise suitable habitat (Yoakum et al. 1980). Many species have benefited from the development and use of artificial structures.

34.2. DESCRIPTION OF TECHNIQUES

34.2.1. Nest Boxes

Nest boxes properly built, placed, and maintained can be more effective than natural cavities in increasing the production of wood ducks (McGilvrey 1968). Two plans for wood duck houses, vertical wood and vertical metal, were developed by Bellrose (1976). A third type, horizontal metal, was developed by McGilvrey and Uhler (1971). This horizontal house was developed to deter starlings, which are serious competitors for nest boxes throughout much of the breeding range of wood ducks. Horizontal cylinders proved 100% effective in preventing starling nesting in Massachusetts (Heusmann et al. 1977). Grabill (1977) described another successful European starling deterent that involved placing a small starling nest box next to an existing wood duck box. Numerous plans for duck nest boxes have been published (Bellrose 1976; U.S. Forest Service 1969; Webster and Uhler 1964; Yoakum et al. 1980).

Griffith and Fendley (1981) described the use of 5-gallon plastic buckets as wood duck nesting structures. The ducks accepted and used the plastic buckets as readily as conventional nest boxes in the United States; however, Norman and Riggert (1977) found little use of 5-gallon plastic buckets by nesting Australian waterfowl.

Bellrose (1976) developed the following guidelines for use in designing a wood duck nest box program:

1. Although wooden boxes are more acceptable to wood ducks than metal boxes at the outset, the high success rate of metal boxes may contribute to a higher occupancy rate of metal than of wooden boxes in a few years, as wood ducks become conditioned to nesting in boxes. Rough lumber or other rough surfaced material must be placed inside the box and below the opening for ducklings to use as a "ladder" when they leave the box.

2. Nest boxes should be made predator-proof, either by special mounting to exclude predators, inverted metal cones on the supporting pole, or with entrances that exclude raccoons. Predator protection is essential wherever groups of boxes are placed.

3. A 3- to 4-in. layer of sawdust, wood chips, or shavings must be provided in the box to cover the eggs during the laying period.

4. Houses placed in groups of two to four per acre ultimately have the highest use because of the homing of successfully nesting ducks and their offspring.

5. Wood ducks use nest boxes on poles in water at a higher rate than houses placed in the woods. Nest boxes in the woods should be close to water and placed 10 to 20 ft above ground. The openings should face the water or flyway.

A low occupancy of nest boxes by wood ducks may not necessarily indicate an abundance of natural sites. It may reflect a low breeding population or improper construction or placement of the nest boxes (Bellrose et al. 1964). Strange et al. (1971) found that wood ducks preferred man-made nest boxes, even in areas with abundant natural cavities.

Standard wood duck boxes and others with slightly modified designs have also been used by other cavity-nesting waterfowl. Bolen (1967) and McCamant and Bolen (1979) reported that nest boxes were used by black-bellied whistling-ducks in Texas. The use of nest boxes by buffleheads was noted in Alberta and California by Erskine (1972) and in British Columbia by Yoakum et al. (1980). Hooded mergansers use wood duck nest boxes in many parts of the United States (Bellrose 1976), particularly those nearest the water (Morse et al. 1969).

Griffee (1958) reported that common mergansers and barrow's goldeneyes used nest boxes in Oregon. McGilvrey (1968) suggested the use of a 5-in. entrance hole in areas where goldeneyes may nest. Other nest box modifications and nest box use by goldeneyes were reported by Johnson (1967) and Eriksson (1979).

Wood duck boxes have also provided nest sites for Eurasian kestrels and Eastern screech owls. Hammerestrom et al. (1973) concluded that nest boxes can markedly increase Eurasian kestrel populations where available nest sites are the limiting factor. Boxes placed on transmission towers increased local breeding populations of Eurasian kestrels in Colorado (Stahlecker and Griese 1979). Detailed nest box plans for Eurasian kestrels were provided by Yoakum et al. (1980). Artificial nest boxes have been used as a feasible method for maintaining or increasing local populations of common barn-owls in areas where nest sites are scarce (Marti et al. 1979).

Additionally, wood duck nest boxes have served as nest sites for passerine birds and woodpeckers. Nesting reports have been documented for northern flickers, house wrens, and Carolina wrens by Brown and Bellrose (1943), Doty and Kruse (1972), and Strange et al. (1971); purple martins and great crested flycatchers by McGilvrey and Uhler (1971); bluebirds and tufted titmice by Strange et al. (1971); and tree swallows and red-winged blackbirds by Doty and Kruse (1972).

Kalmbach et al. (1969) provided many designs for songbird nesting structures. Yoakum et al. (1980) also provided designs and dimensions for bird house structures. Each house must be designed and constructed to meet the needs of the target species. Declining populations of the eastern bluebird have become increasingly dependent on artificial nest houses because natural sites have been destroyed or lost through competition with European starlings and house sparrows (Zeleny 1977). Tree swallows also readily adapt to bluebird houses (Yoakum et al. 1980).

Artificial den boxes have also increased the carrying capacity for gray squirrels (Barkalow and Soots 1965a; Burger 1969). Detailed plans for squirrel nest boxes were given by Barkalow and Soots (1965b), U.S. Forest Service (1969), and Yoakum et al. (1980). Sanderson (1975) provided a guide for management of gray squirrel den trees, including an option for the provision of artificial dens. Nest boxes are a proven means of attracting gray squirrels to new habitat (Hesselscherdt 1942). McComb and Noble (1981) compared nest box use with the use of natural cavities by various birds and mammals in three habitat types of southern forests.

Other mammals reported to have used nest boxes include flying squirrels, Virginia oppossums, raccoons, and deer mice.

Carey and Sanderson (1981) noted that routing can be used to accelerate tree-cavity formation and has potential as a habitat management technique for cavity-nesting wildlife, but that further research is necessary.

34.2.2. Nest Baskets

Artificial nest baskets for ducks have been developed as a method of increasing nesting success. Bishop and Barratt (1970) reported an average of 33% use by ducks, primarily mallards, over a 6-year period in the prairie region of Iowa. Similar results were noted by Doty et al. (1975) in the prairie pothole region of North Dakota. A significantly higher success rate was found for basket-nesting than for ground-nesting mallards. On the other hand, Doty et al. (1975) noted that less than 1% of the baskets located in the forested wetlands of Minnesota, Wisconsin, and North Dakota were used. The authors attributed these differences to negative responses to open top structures, to avoidance of the flax straw used for nesting material, and to unknown factors.

Nest baskets used by Bishop and Barrett (1970) and Doty et al. (1975) were cone-shaped molds made of galvanized hardware cloth or fiberglass, supported by metal posts. The Iowa baskets were lined with prairie cordgrass or mixed tall-prairie grasses and brome. A number of hay types were used by Doty et al. (1975), who found that sixrow barley straw and smooth brome grass were preferred over flax straw. Detailed construction plans for nest baskets were published by the U.S. Forest Service (1969) and Yoakum et al. (1980).

Cylindrical wire baskets (3.9 ft in diameter and 3.9 ft tall) filled with rocks have been used to improve nest sites for Canada geese on basalt rock islands that were devoid of depressions and unable to retain nest material. Small rocks and gravel were placed on the top of the structure to prevent loss of nest materials and the depression in the rocks was lined with soil and grass. The structure was located where the top of the basket would remain above the pool level (Fielder 1979).

Bishop and Barrett (1970) and Doty et al. (1975) agreed that the location and height of nest baskets were important factors involved in site selection by the hens. Nest baskets elevated 3 to 4 ft above the water level and placed in openings in stands of emergent vegetation were most readily accepted. Doty and Lee (1974) reported that a high percentage of surviving successful basket nesters returned to the original site in succeeding years.

Nest failure because of human disturbance was slight, except when nesting hens were captured for marking in North Dakota (Doty et al. 1975). Loss to predators was reported as insignificant by Bishop and Barrett (1970) but bird predation increased in certain high-density, open-basket areas in North Dakota

(Doty et al. 1975). In an attempt to discourage bird predators (primarily gulls), Doty (1979) developed and compared several types of covered cones, baskets, and cylinders with open baskets. Mallards used covered cones at much higher rates than cylinders. Use of open baskets declined despite a decline in bird predation. Behavior of nesting females and overhead concealment of eggs may both have been important factors. Truncated metal cones can be used to protect the baskets if mammalian predation becomes significant.

A few waterfowl of other species have been reported using the nest baskets: redheads, canvasbacks, gadwalls, northern pintails, blue-winged teal, and Canada geese.

Burger and Webster (1964) noted that American black ducks and mallards in Maryland frequently used offshore duck blinds as nesting sites. Nesting ospreys shared the blinds with ducks. Coulter and Miller (1968) described an artificial nest structure patterned after a nesting roll designed by Francis Uhler. It consisted of a hollow cylinder about 4 ft long made from hay supported by poultry netting. These structures were readily accepted by island-nesting American black ducks in Vermont.

34.2.3. Platforms

Canada geese readily accept many types of artificial platforms as nest sites. The major types of artificial goose nesting structures that have been described and evaluated follow.

1. Tree platforms--shipping pallets or similar structures placed in trees (Craighead and Stockstad 1961).

2. Washtubs, 55-gallon drum ends (split and half drums), or tires--placed on elevated platforms, in trees, or on support poles (Brakhage 1965a; Dill and Lee 1970; Rienecker 1971; Saul 1972; Yocom 1952).

3. Nest structures consisting of an iron pipe supporting the end of a fiberglass tank (Atkins and Fuller 1979).

4. Nest structures consisting of a single pole supporting a crate-type nest box (Will and Crawford 1970).

5. Dill platforms--wire baskets 4 ft square, braced with angle iron and supported by steel legs (Rienecker 1971).

6. Haystack platform--17 hay bales stacked four layers high and fenced (Rienecker 1971).

7. Floating platform--various types of nest boxes placed on

anchored floating structures (Brenner and Mondok 1979; Dill and Lee 1970; Rienecker 1971; Will and Crawford 1970).

Diagrammatic plans for artificial nesting platforms were provided by Dill and Lee (1970) and Yoakum et al. (1980).

Basic criteria for construction and placement of artificial nesting platforms for use by Canada geese include the following:

1. Placement in favorable nesting locations strongly influences platform use. Nest sites over water are preferred over land-based platforms. Ideal placement is 50 to 300 ft from shore and 200 ft apart (Rienecker 1971). If platforms are too close together, site selection may be adversely affected, and territorial stresses may cause desertion.

2. Water level fluctuations, water depth, and weather-related factors should all be considered in selecting platform locations. The water should be deep enough to discourage land predators. The platform should be high enough to prevent accessibility to predators in shallow water, and strong enough to resist damage caused by wave action, strong winds, or shifting ice.

3. Nest material of hay, wood chips, or sawdust must be supplied in the nest box structure.

4. Large platforms are preferred initially but use of smaller structures increases as Canada geese are conditioned to artificial sites. Platform use usually increases each year after placement, indicating a normal process of learning by Canada geese.

5. Gander loafing sites should also be considered when establishing platform locations. If no natural stands such as stumps, logs, rock piles, or islands are within 100 ft of the nest site, they should be provided. Chaining a log to the platform creates a loafing site, reduces territory size, and increases the attractiveness of open-water sites (Brakhage 1965a).

Rienecker (1971) noted that the presence of special landing platforms did not affect the selection of nesting structures by Canada geese. On the other hand, Saul (1972) reported that an adequate perch that allows the nesting pair of geese to become familiar with the nest site may be important to the use of the structure.

Floating nest platforms provide an alternative to elevated structures in situations with unsuitable shorelines or highly fluctuating water levels. In

Colorado, the success rate of floating nest platforms was similar to that of elevated platforms (Will and Crawford 1970). The anchors used in that study provided stability in winds in excess of 80 mph. Dill and Lee (1970) suggested using floating structures where ice action might destroy stationary platforms. Waterfowl nesting rafts were successfully used in Pennsylvania strip mine pools where severely fluctuating water levels had previously reduced nesting success (Brenner and Mondok 1979). The rafts were used primarily by mallards, but blue-winged teal and Canada geese also used the structures. No structural damage by ice occurred to two platforms left out over three winters. Rienecker (1971) noted that rafts did not justify their cost and maintenance compared with stationary platforms, even though they were durable under rigorous conditions.

Man-made nest platforms for raptors have been developed to help declining breeding populations and to offset the lack of suitable elevated nesting sites. In areas where previously occupied osprey nest sites had been damaged or destroyed, Reese (1970) placed 4 X 4 ft platforms on existing elevated structures. Those platforms received almost 100% use and other platforms placed in new areas also attracted nesting ospreys. The number of young ospreys per active nest over a 5-year period was 1.5 (Rhodes 1977). Frier (1980) successfully moved osprey nests from active utility lines and channel markers to nearby 4 X 4 ft platforms erected on slightly higher poles. The new sites were always accepted by the nesting pair. Similar osprey platforms have been used successfully in north-central Wisconsin (Eckstein et al. 1979), Maryland (Rhodes 1972), and California (Kahl 1972). Kennedy (1977) advocated undertaking large-scale programs to install artificial nesting platforms for ospreys along all river systems in Virginia. Platforms should be in open, shallow water, from 50 to 200 yards offshore, and on predator-proof aluminum poles.

Navigational markers and hunting blinds have become unintentional nesting platforms for osprey, particularly in Chesapeake Bay. Reese (1981), who compiled reproductive success data on osprey in the Choptank River, Chesapeake Bay, found most of the nests were on marine navigational aids and offshore waterfowl hunting blinds. During the 8-year study, the authors observed that the 1972-79 mean percentage of accessible nests with eggs was 92%, with nestlings was 69%, and with fledgings was 66%. The average number of young per nest with fledgings in both accessible and inaccessible nests with known outcome ranged from 1.7 to 2.2 annually and averaged 1.95. These numbers were comparable to or above fledging broods (1.4-2.0) in other areas of eastern United States. Reese (1977) also studied the nesting success of ospreys in Talbot County, Maryland, and found that ospreys seemed to prefer and use most successfully nest sites on channel markers and offshore duck blinds even though trees suitable for nesting remained plentiful in proportion to their actual use by ospreys. Apparently, human disturbance and other factors have not influenced lack of nesting success (1.0 fledgings per active nest) as much as environmental contaminants have.

Several other species of raptors have used and benefited from artificial platforms. A pair of bald eagles accepted a reconstructed nest when their nest sites collapsed in a storm (Dunstan and Borth 1970). Bohm (1977) successfully erected nests for red-tailed hawks in Minnesota. Use of man-made nests has also been noted by great gray owls (Nero et al. 1974), ferruginous hawks (White 1974), great horned owls (Bohm 1977; Scott 1970), and snail kites (Sykes and Chandler 1974).

Nelson and Nelson (1976) developed a powerline platform for various raptors that reduced power outage problems and bird electrocutions. Observations by Stahlecker and Griese (1979) in Colorado indicated that raptor platforms would not be used by birds if they were placed in the lower portions of transmission towers. Extensive research on raptors nesting on power poles has been done by the Electric Power Research Institute (D. Gebken, personal communication). Descriptions and plans for raptor structures were detailed by Bohm (1977), Eckstein et al. (1979), Frier (1980), and Yoakum et al. (1980).

Artificial nest platforms can also be used as an improvement technique for encouraging colonial birds. Great blue herons have used channel markers in Oregon (Henny and Kurtz 1978) after the loss of former nesting trees by inundation. Suitable nest sites could be provided by artificial structures. Wiese (1976) observed great egrets using platforms in Louisiana. Double-crested cormorants have used nest structures in areas where suitable trees are scarce. The Wisconsin Department of Natural Resources has had considerable success in inducing cormorants and black-crowned night-herons to nest on artificial platforms (D. Gebken, personal communication). Meier (1981) found that platforms constructed with a lath surface and with additional perching space were the most successful of the designs tested. Cormorant production on artificial platforms was generally greater than on natural nesting sites. Yoakum et al. (1980) described an artificial nest tree designed for cormorants that consisted of 12 platforms on a utility pole.

34.3. IMPACTS ON THE ENVIRONMENT

Man-made nest boxes and platforms are durable, and if they are properly constructed, erected, and maintained, they are more successful than many natural sites. Artificial structures are most beneficial when natural sites are limited but also can improve nesting habitat conditions in areas where natural sites are abundant. Range expansion or increased total productivity may sometimes occur where suitable nest sites were formerly lacking. Nest boxes are useless, however, unless adequate food sources and resting areas are available nearby.

Artificial nest structures can have several deficiencies or adverse effects:

1. Structures may be virtually ignored by the target species, with a resultant low occupancy.

2. Nest sites may be vulnerable to predators unless properly protected. Total productivity may actually decrease due to the vulnerability of the artificial structures.

3. Competition from less desirable or nuisance species may limit use of artificial sites by the target species.

4. Human interference or vandalism may occur if the structures attract attention.

34.4. COSTS

Few cost estimates for nesting structures are available. Costs are often reduced by donations of materials and labor by local conservation groups, service clubs, or youth organizations.

Plastic "pre-fab" wood duck houses were marketed for $13 each (1979 price) by the Minnesota Waterfowl Association (L. Marking, personal communication). Five-gallon plastic buckets for wood duck nest structures are sometimes available free, but usually they cost about $0.50 each (Griffith and Fendley 1981).

The cost of wire duck nest baskets was estimated to be $17 each (1974 prices) excluding cutting, welding, and other labor costs (Doty et al. 1975). Maintenance over a 20-year period was estimated at $60 per basket.

Brenner and Mondok (1979) reported that floating, nesting rafts could be constructed and installed for $9.75 each. No maintenance was required over a 3-year period and costs per duckling fledged were subsequently reduced. A wire and rock elevated structure designed as a Canada goose nesting site requires less than 0.5 man hour and $2.75 for wire (Fielder 1979).

In three of the elevated goose platforms used by Rienecker (1971), the 55-gallon steel drums that were used as basic material could be obtained at little or no cost. Construction and maintenance costs were low for all of the drum-type platforms. Maintenance requirements for the Dill platform were extensive due to weather-related damage. Haystack platforms required little maintenance, but initial costs were high because fences were used to bind the bales together. Floating platforms were considered too expensive to maintain.

34.5. EVALUATION FOR USE ON UMRS

Many of the nest structures discussed have direct application to UMRS. Although extensive bottomland clearing has not occurred in the UMRS basin as compared with riparian zones of the Lower Mississippi River and some other large rivers, increased navigational, commercial, agricultural, and residential development may reduce riparian habitat in the future. The lock and dam systems inundated large expanses of the riparian bottomland in the past and may do so in the future if water levels are raised to help accommodate increased commercial traffic.

The UMRS is an important wood duck production area in the Mississippi flyway and nest box programs have greatly improved nesting habitat.

Nest baskets and platforms show a strong potential for improving waterfowl nesting conditions along UMRS. Usually high densities of mallard nests found on suitable areas (those with sufficient cover and below high water) of UMRS may indicate a possible shortage of these nesting sites (Fernholz 1979). Continued habitat loss and adverse effects of high water in spring suggest that artificial structures could significantly contribute to waterfowl production. Although Doty et al. (1975) reported little use of available duck baskets in the forested areas of Wisconsin and Minnesota, the open wetlands of UMRS may be more acceptable, especially when ground sites are limited. Nesting Canada geese could benefit from artificial structures, but propagation releases may be necessary to establish a significant local breeding population at the outset.

Raptor platforms in the UMRS basin would attract nesting birds but may not affect the overall population if nesting sites are not a limiting factor. An active osprey nest was observed on a power line structure in Pool 6 of UMRS (L. George, personal communication). The use of this only marginally suitable location may indicate a shortage of suitable elevated nest sites. One management possibility would be to design channel markers with an acceptable nesting platform that did not interfere with the marker's original purpose.

Cormorant nest structures warrant further investigation for UMRS applications. Platforms could help stabilize declining populations of double-crested cormorants, a species listed as endangered in Wisconsin, Illinois, and Missouri. The current active colonies in UMRS floodplain contain a sizable fraction of the entire breeding population in Illinois and Wisconsin (Thompson 1977). Double-crested cormorants use artificial structures along UMRS on the Upper Mississippi River Wildlife and Fish Refuge in Wisconsin (C. Korschgen, personal communication) and on refuges in Illinois (Kleen 1975).

Other colonial-nesting birds, including great blue herons, great egrets, and black-crowned night-herons may benefit from the availability of artificial platforms on UMRS.

In all artificial nesting structure programs, the extensive commercial and recreational boat traffic and related activity that occurs on UMRS must be taken into consideration. Structure placement proposals must consider each species' relative tolerance of human activity and disturbance.

CHAPTER 35. ISLAND CREATION OR DEVELOPMENT

35.1. SITUATION TO BE MITIGATED OR ENHANCED

Island creation and habitat management are designed to mitigate habitat losses from mainland or river-bottom development. Islands provide new nesting, feeding, and loafing areas for waterbirds and furbearers. Open-water areas in impoundments have developed increased turbidity due to wind-driven waves that resuspended sediments (see Chapter 17). Islands act as buffers to wave action, reduce shoreline erosion and turbidity, and provide productive substrates for plants and benthos (Kennedy et al. 1979). Dredged material used for island construction and maintenance is used beneficially, whereas the material might otherwise adversely affect other areas. Dredged material can be used to rebuild, improve, protect, or replace older islands that have been reduced or destroyed by erosion. New islands can be created away from heavily disturbed areas to increase the amount of available habitat for waterfowl and furbearers.

35.2. DESCRIPTION OF TECHNIQUES

Islands are considered important wildlife habitat areas because, as a rule, they are relatively predator-free and isolated. Their value has increased in many areas as a result of losses of mainland habitat. Man-made islands become increasingly important when natural islands are lost to erosion or development. Colonial-nesting waterbirds and waterfowl benefit most from island construction and development. The discussion of island creation in this chapter is divided between islands built of dredged material and generally smaller waterfowl islands because the two types are distinctly separated in the literature.

35.2.1. Dredged Material Islands

The U.S. Army Corps of Engineers Dredged Material Research Program (DMRP) evaluated dredged material islands in seven regional areas: the coastal waterways of New Jersey, North Carolina, Florida, Texas, Oregon and Washington; the U.S. Great Lakes; and UMRS. The areas were studied to document the use of dredged material islands by colonial waterbirds and compare bird use with several physical characteristics, such as island vegetation, presence of dikes, natural sites, and man-made sites. Soots and Landin (1978) noted that regional reports were filed for each area that provided recommendations and guidelines for management of existing and new dredged material islands. Soots and Landin (1978) estimated that 2 million colonial waterbirds nest on dredged material islands in the United States.

Dredged material island habitat in DMRP studies is considered to be "critical" for some colonial waterbird species but is relatively unimportant for others. The islands also provided nesting habitat for numerous noncolonial species. Two factors were given that determined the extent of use of dredged material islands by colonial waterbirds: (1) the species present and their abundance; and (2) the number of dredged material islands with suitable habitat compared with suitable natural sites available.

The extent of use by nesting waterbirds depended on five factors:

1. Degree of isolation of the island from ground predators and human disturbance.
2. Habitat diversity of the island.
3. Stability of the potential nesting substrate.
4. Behavioral characteristics of the nesting species.
5. Foraging requirements of the nesting species.

Soots and Landin (1978) recommended that, as a first management option, existing islands be managed to provide the desired habitat because the creation of new islands is not always the best alternative for habitat enhancement. Specific placement of dredged material on existing islands can increase habitat diversity. Planned disposal on older dredged material islands can be used to set back vegetation to a more desirable stage of succession (Smith 1978).

The most effective use of dredged material for upland habitat development appears to be island construction where target species are to be provided isolated breeding habitat (Lunz et al. 1978). Before the island is developed, several factors should be considered. The initial consideration should be the potential to attract the target species. Other important features of island development must include site location, timing of development, and physical design.

Isolation is widely considered to be one of the most important factors in determining site selection. Distance from predator populations and excessive human disturbance greatly affect the wildlife value of islands. Whenever possible, areas that are already important habitats for other wildlife or fish should be avoided. Material transport distances and the energy regime (e.g., currents and prevailing winds) of the site are also important considerations in the selection of a site for island development.

Timing of the development is important because spring dredging activity may disturb nesting birds. Fall or winter were considered ideal, to allow for initial sorting of fine materials by wind and water (Soots and Landin 1978). Habitat development during this period can provide suitable substrate for nesting habitat in the following spring.

The physical design of dredged material islands should involve the following aspects:

1. Size. General guidelines given by Soots and Landin (1978) recommended areas of 5 to 50 acres. Larger islands may support predator populations and be difficult to manage. The authors noted that smaller islands were acceptable for least terns. Smith (1978) suggested that individual islands generally should not exceed 20 to 25 acres, and that a pattern of several small separate islands was most desirable. Dames and Moore (1977) concluded that the smaller a confined disposal area is, the more rapidly the ecological development of the site will occur.

2. Configuration. An evaluation of wave action, water currents, and water surface elevation is mandatory when one is attempting to determine island configuration to reduce erosion potential. Steep slopes should never be constructed (Soots and Landin 1978). Dikes have been shown to be beneficial in creating feeding and loafing areas but they can be detrimental because they disrupt potential nesting sites (Landin 1978a). Smith (1978) suggested that dikes not be built on habitat development islands. The North Carolina DMRP regional study provided further information on diking related to bird use (Parnell et al. 1978).

3. Substrate. Substrate preferences vary with the particular bird species, but coarse material generally makes better nesting substrate than fine material because of its greater stability (Soots and Landin 1978). Hunt et al. (1978) provided guidelines that can be followed in placing the desired substrate (Table 18). (Substrate modification techniques are discussed in Chapter 40.)

4. Elevation. The elevation should be high enough to prevent flooding of the colony area but not high enough to be subjected to heavy wind erosion. The optimum height was considered to be 3 to 10 ft above the high water level (Soots and Landin 1978). Kennedy et al. (1979) recommended a height that would allow 90% of the island to remain above the high water line.

Island habitat development involves confined or unconfined disposal of dredged material in shallow water or on existing islands. Construction of dredged material islands seldom involves unconventional techniques or methodologies (Smith 1978). Construction equipment needed for habitat development listed by Hunt et al. (1978) is summarized in Table 19. The authors also discussed construction, placement, and containment guidelines for upland disposal practices. The actual dredging and disposal techniques are discussed in Part VI of this guide.

Table 18. Guidelines for operation of disposal areas[a] (from Hunt et al. 1978).

1. Position the discharge pipeline so that the coarse fraction of the dredged slurry will be deposited where it can be put to best use.
2. Facilitate material placement operations in water by using (a) additional pipeline flotation, (b) a spillbarge, and (c) a floating swing-discharge line.
3. Facilitate material handling operations on land by using (a) wye branches and waves with pipeline, (b) fill trafficability improvements, (c) a whooping crane, (d) low-ground-pressure vehicles, and (e) a dragline with deadman and pulley.
4. Lessen scouring during deposition by using energy dissipators such as baffle plates, bleeder pipes, and pipe distribution systems.
5. Maintain adequate retention time for sedimentation in confined disposal areas by using properly designed weirs with adjustable crest elevations, and cross and spur dikes, if required.
6. Divide confined disposal area into cells so that (a) flexibility in receiving incremental fill volumes is increased, (b) accuracy of settlement prediction in filled cells is improved, and (c) new habitat can be developed incrementally.

[a]Modified from Johnson and McGuiness (1975).

Vegetation on dredged material islands has mainly been used as a substrate stabilizer for erosion control, rather than as a method to increase attractiveness to wildlife. Management of vegetation has a direct effect on use of the islands by particular species because requirements of different species vary from bare substrate to a climax stage of forest plants. The target species, in each instance, determines the needed vegetational stage. Soots and Landin (1978) divided the classification of vegetation on dredged material islands into eight categories: bare substrate, sparse herb, medium herb, dense herb, herb shrub, shrub thicket, shrub forest, and forest. They provided breeding biology and nesting substrate and vegetation characteristics and preferences for the species of colonial nesting waterbirds found in DMRP regional studies. (Vegetation manipulation and propagation techniques are also discussed in Chapters 38 and 40.)

Deason and Sharpe (1978) described a dredging program begun on a Colorado River impoundment to improve marsh habitat for the endangered Yuma clapper rail. Islands and dikes were constructed in Topock Marsh. Although the developments had not yet been fully evaluated, early observations indicated

Table 19. Construction equipment needed for habitat development[a] (from Hunt et al. 1978).

Operation	Equipment used		
	On land	In shallow water	Offshore
Clearing foundation	Bulldozer, dragline	Dragline on timber mats	Floating dragline
Obtaining material	Bulldozer Dragline Truck transport from borrow area	Clamshell Dragline on pontoons Dragline on timber mats Hydraulic dredge and pipeline Truck transport from borrow area	Barged dragline Clamshell Hydraulic dredge and pipeline Barged transport from borrow area
Placing material	Dragline Bulldozer Hydraulic fill[b] End-dumping from trucks	Dragline on pontoons End-dumping from trucks Hydraulic fill	Bottom-dump scows Barge with conveyor Hydraulic fill[b] Barged dragline
Shaping and compacting[c]	Bulldozer Scrapers Haul traffic	Bulldozer Haul traffic Dragline	Bulldozer Dragline
Placing riprap	---	Clamshell	Barged clamshell

[a]Modified from Johnson and McGuinness (1975).
[b]Various hydraulic fill procedures have been used, including bleeder pipe (on land, shallow water); direct discharge (on land); spillbarge (on water), virgin clay source used; and floating swing discharge line.
[c]Compaction normally carried out on 1 ft added layers of fill on emergent portions of dike.

extensive use of the new habitat by clapper rails and many other animals.

Further information on specific waterbird species, situations, regional differences, and other factors were reviewed in an extensive bibliography of pertinent research prepared by Landin (1978b); Smith (1978) presented a selected bibliography of DMRP reports related to habitat development; and a literature review by Allen and Hardy (1980) covered impacts of navigational

dredging on fish and wildlife, including assessments of the impacts of islands constructed of dredged materials in coastal waters, in rivers, and in the Great Lakes. Other literature reviews concerning dredged material islands were given by Landin (1978a) and Soots and Landin (1978). Buckley and Buckley (1976) provided specific management guidelines for colonial nesting waterbirds.

35.2.2. Waterfowl Nesting Islands

Waterfowl nesting islands are considered important habitat because of the high nesting densities and nesting success associated with them. Loss of habitat and high predation have kept waterfowl production at low levels in many areas, especially in prairie pothole regions (Duebbert and Kantrud 1974). Heavy island use has been attributed to predator-free nest sites, a high ratio of water edge to land mass, and the proximity of water, food, loafing sites, and nesting cover (Hammond and Mann 1956).

Canada geese prefer nesting on islands (Craighead and Craighead 1949; Dill and Lee 1970; Dow 1943; Mickelson 1975; Miller and Collins 1953a; Naylor 1953; Vermeer 1970a; Yocom 1952). Nesting geese using gravel bars and sandbar islands in rivers preferred nest sites near driftwood (Craighead and Craighead 1949). Similar islands can be improved as nesting locations for Canada geese by placement of logs and driftwood (Yocom 1952). Frequently flooded gravel bars used as nesting sites by Canada geese on the Columbia River of Washington were successfully improved by the addition of elevated wire, rock-filled baskets (Fielder 1979). Rienecker (1971) suggested that islands may be more practical than elevated platforms as goose nesting habitat if heavy equipment is available and water areas can be drained. Although many authors noted that there was little predation on island goose nests, they found that crowded conditions near favorable sites frequently resulted in desertion because Canada geese are highly territorial.

Although several species of ducks use islands for nesting, gadwalls and mallards are inclined to nest on them in abnormally high concentrations (Drewien and Fredrickson 1970; Duebbert 1966; Johnson et al. 1978; Hammond and Mann 1956; Miller and Collins 1953b; Vermeer 1970b). The resultant high densities were attributed to high nesting success and subsequent homing by young birds. The literature indicated that hatching success is significantly higher on islands than on normal upland sites.

Jones (1975) provided guidelines for island placement and development during new reservoir construction and during maintenance of existing impoundments. He recommended a model island for small impoundments as being long, narrow, larger than 0.05 acre, and placed parallel to the shoreline or in a position that would avoid direct wave action from prevailing winds. Heavy equipment was suggested for constructing the island.

Various authors have discussed site location and physical characteristics for desirable waterfowl nesting islands. Islands should be separated from the mainland by several hundred feet if they are to remain free of predators (Hammond and Mann 1956). If they are closer to the main shoreline, a water depth of 1.5 to 2 ft deters most predators (Hammond and Mann 1956; Jones 1975; Keith 1961). The elevation should be 2 to 4 ft above the maximum high water level (Keith 1961; Uhler 1956). Small islands with low profiles are less attractive than others to predators (Johnson et al. 1978). Erosion can be reduced by natural vegetation, by placement of stabilizing materials, by selecting a sheltered location, or by placing islands close to each other. The proximity of food may be of greater importance to ducks than to geese (Hammond and Mann 1956). Islands generally vegetate naturally within a year (Johnson et al. 1978), but seeding may improve the desired nesting habitat (revegetation is discussed in Chapter 40). On islands where cover was sparse, American black ducks readily accepted artificial brush piles and hay nesting rolls (as discussed in Chapter 34) as nest sites (Coulter and Miller 1968).

Brush, hay, and earth islands have been used successfully on Wisconsin waterfowl areas (Linde 1969). Hay islands were attractive the first year but were no longer suitable in the following year. Brush islands were accepted by captive Canada geese and were expected to last several seasons, depending on the degree of ice action. Earth islands were used by loafing and nesting waterfowl. Most of the islands were constructed in winter by placement of material on the ice. Earth islands were constructed with bulldozers and draglines.

Islands created for colonial waterbird nesting sites are often attractive to other waterfowl. Vermeer (1968) found that island-nesting northern pintails and lesser scaup in Alberta were strongly associated with colonies of common terns. A high nesting density of ducks was also found among California gulls and ring-billed gulls, but fledging success was severely reduced by gull predation.

Mathisen (1969) reported that common loons used man-made islands in the Chippewa National Forest, Minnesota. Artificial islands provided preferred sites and probably would increase nesting success in otherwise suitable loon habitat where islands are lacking. Artificial islands were chosen by loons as readily as natural ones in another study of selection of man-made sites (McIntyre and Mathisen 1977). Islands used were constructed by anchoring sections of floating bog mats in open water. Cedar logs were also used successfully in place of floating bog mats on lakes without bog vegetation.

35.3. *IMPACTS ON THE ENVIRONMENT*

New islands provide colonial-nesting birds with nesting sites similar to those provided by older existing islands and traditional mainland locations. Islands offer protection from ground predators and generally reduce human interference. Upland areas of islands developed for waterfowl provide nesting sites and usually yield a high nesting success. Exposed sand bars, island edges, and the associated habitat benefit many species by providing loafing, feeding, and nesting sites. By manipulating the vegetation, an island's successional stage can be controlled to benefit a target species or to create general habitat diversity. Island habitat development may also benefit nontarget species, as evidenced by the use of DMRP sites by 56 nesting noncolonial species (Soots and Landin 1978).

The wind buffering capacity of islands enhances growth of submergent and emergent aquatic plants on at least one side of an island (Kennedy et al. 1979). The vegetation provides fish habitat and food; waterbird feeding areas, brood cover, and nesting sites; furbearer habitat; and bank protection. (This aspect, along with the impact of islands on the aquatic habitat, is discussed in Chapter 17.)

Island habitat development has the following additional advantages (Smith 1978): (1) a traditional disposal technique is used, (2) existing disposal areas are used, and (3) management of islands can be conductive to further disposal.

Allen and Hardy (1980) noted that turbidity, sedimentation, burial of organisms, changes in substrate composition, changes in bottom topography, blockage or filling of side channels, and releases of noxious materials and nutrients were potential adverse effects of the disposal of dredged material. Smith (1978) also listed three disadvantages of island habitat development: (1) interruption of hydrologic processes, (2) destruction of open-water or marsh habitats, and (3) injudicious placement of material or timing of disposal.

Indiscriminate placement of material, lack of erosion protection, or lack of containment may result in negative effects on benthic organisms and flows. Low elevation of dredged material islands may result in seasonal flooding that disrupts, destroys, or causes abandonment of existing or potential nesting locations. Another disadvantage of island habitat development is that it may increase the cost of a dredging project (Soots and Landin 1978).

Islands that attract recreational use during the bird breeding season have little value as nesting sites unless protective measures are taken to guard against human disturbance. Buckley (1978) and Buckley and Buckley

(1976) presented possible measures that can be taken to curb disturbances of colonial-nesting waterbirds.

Islands of riprapped dredged material encourage use by gulls, which compete with cormorants and terns for food and nesting areas (D. Gebken, personal communication). Gulls and common terns occupy bare sand substrates as nesting sites and increase competition with other birds that nest on bare substrate. Increased gull populations may also result in predation on the nests of other birds.

Hammond and Mann (1956) cited several instances where predator invasions of islands resulted in total destruction of waterfowl nests. Vermeer (1970a) reported increased predation by coyotes on Canada goose nests when nesting islands became accessible during a dry year. Ground-nesting colonial species are extremely vulnerable to land-based predators, and predator intrusion may result in complete destruction of a colony.

35.4. COSTS

Cost of dredged material islands varies with site-specific factors related to planning and construction. Wildlife habitat considerations and management of dredged material islands may also increase the cost of a project.

Planning costs increase if detailed research of potential sites is necessary and site selection problems occur. Two 20-acre sites in a DMRP project involved planning and engineering design costs of $45,000 and $35,000, but these costs were considered to be abnormally high. Planning costs are substantially lower for more conventional marsh development sites (U.S. Army Engineer Waterways Experiment Station 1978).

Construction costs depend on site access, distance between dredging and disposal sites, foundation and protective structures needed, characteristics, requirements, availability of equipment, and local labor rates (U.S. Army Engineer Waterways Experiment Station 1978). Construction costs of two DMRP projects, exclusive of actual dredging and vegetative propagation, were $288,000 and $167,500. The difference in costs of the two sites was due to the use of an expensive protective structure for one island.

The reported costs of small islands for waterfowl vary widely. Small islands averaging 0.006 acre constructed in dry, wetland basins averaged $50 per island (Johnson et al. 1978) when built with a D-7 Caterpillar tractor and dump truck. Rock was used to form the island foundation and marsh soil covered the surface. The life expectancy of 20 or more years for the islands

reduced annual waterfowl production cost estimates.

Jones (1975) reported expenses of $150 each for 0.5-acre islands but expenses for smaller islands (0.05 acre) did not exceed $60 each. These estimates were based on costs of construction with a dragline, scraper, and bulldozer.

Small earth islands can be constructed by dumping 4.5 cubic yards of fill on ice at a cost of $1.62 per island, according to Linde (1969); however, the author believed the islands should have been larger and somewhat higher. He estimated that hay islands cost $2 per island when 30 to 40 were constructed at a time. Since the usable life of hay islands is short (1 year), their initial costs must be justified by immediate use.

35.5. EVALUATION FOR USE ON UMRS

Thompson and Landin (1978) surveyed waterbird colonies along UMR and noted that no dredged material deposits were being used by colonial waterbirds as nesting sites. They attributed this non-use to the following factors:

1. The deposits lacked suitable vegetation for any of the breeding species within the study area.

2. More suitable natural areas were available for nesting.

3. The disposal sites were excessively disturbed by recreationists and nearby river traffic because they were close to the main channel.

Thompson and Landin (1978) suggested that the creation of bare isolated dredged material islands would benefit the least tern. This colonial waterbird no longer nests along UMRS and has been given endangered status. Other colonial nesting waterbirds may not benefit from island creation because of the abundance of suitable natural habitat.

The potential benefits of island creation for waterfowl, fish, and furbearers in the Weaver Bottoms area of UMRS were described by Kennedy et al. (1979). Islands may prove to be equally beneficial in other extensive open water areas of UMRS. New islands should be located well away from the main channel in relatively inaccessible and inconspicuous areas.

Flood-free upland habitat is lacking in the UMRS corridor, and is available mainly on the river bluffs some 300 ft above the water surface (Fernholz 1980b). High nesting densities of waterfowl found on suitable UMRS

islands indicate that suitable nesting habitat is scarce. Created islands with suitable vegetation should serve to increase duck production.

The few existing sandbars of Pool 7 of UMR receive heavy use by resting and feeding shorebirds (Lesher 1981). If suitable shorebird habitat is lacking in other UMRS areas, the creation of islands and sandbars may benefit these nongame species. Before UMR was developed for navigation, sandbars provided important traditional wintering habitat for Canada geese (Hanson and Smith 1950; Reeves et al. 1968). (Additional information on the applicability of island creation to UMRS is given in Chapter 17.)

CHAPTER 36. MARSH CREATION OR DEVELOPMENT

36.1. SITUATION TO BE MITIGATED OR ENHANCED

Marsh creation or development is a technique designed to offset wetland losses or to improve existing relatively unproductive wetlands. Natural vegetative succession and siltation have converted many wetlands to terrestrial habitats of reduced value to wildlife. In addition, development has sometimes caused either a direct loss or destruction of marshes so that their value as wetland habitat has been greatly reduced. The filling of backwater sloughs and lakes with dredged material is one cause of wetland destruction. Periodic inundation is one of the most important characteristics of wetland habitats that has been affected by large river-related water projects. The improvement of marshes has great potential as an enhancement measure because many marshes have reached low-production climax stages. Habitat diversity must be restored to make wetlands attractive to a wide variety of wildlife.

Wetlands typically are considered as areas that are inundated or saturated by surface water or groundwater and populated by plant associations or communities that tolerate permanent or periodic inundation or prolonged soil saturation (Lunz et al. 1978). Marsh creation or development can provide habitats for many wildlife species that depends on wetlands. Marshes are recognized as extremely valuable natural systems because of their importance in food production, fish and wildlife cover, nutrient cycling, erosion control, floodwater retention, groundwater recharge, and aesthetics (Smith 1978).

In this chapter we discuss marsh creation with dredged material, and marsh development with small impoundments, level ditching, and pothole construction. Large-scale impoundments are not discussed as a mitigation or enhancement measure, although some of the effects of reservoirs are noted. (Closely related techniques are discussed in Chapters 27, 35, 37, and 39.)

36.2. DESCRIPTION OF TECHNIQUES

36.2.1. Potholes

Low-quality wetlands that have filled in with vegetation and lack open water can be improved by creating potholes. Potholes are defined as small, shallow, open-water retention areas or basins with surface areas of usually less than 4 acres (Atlantic Waterfowl Council 1972; Yoakum et al. 1980). Artificially created potholes are sometimes referred to as pits, sumps, or dugouts, depending on their design and location. Potholes are of greatest value to waterfowl in areas where the birds are abundant and competing for

territorial sites (Linde 1969).

Potholes are usually constructed or improved with the following objectives (Atlantic Waterfowl Council 1972):

1. To furnish open water areas that attract waterfowl by providing areas for courtship activities, territorial sites, or brood-rearing areas.

2. To disperse waterfowl throughout a marsh and to provide improved loafing or feeding areas.

3. To provide dependable water sources during dry periods for marsh-dependent wildlife.

Bulldozers, draglines, and blasting are the methods most commonly used to create potholes. Potholes should have an area of one-quarter acre or larger, have an irregular shoreline, and a depth not exceeding 2 ft (Atlantic Waterfowl Council 1972). Potholes larger than 2 acres can be partitioned to reduce the size of territories and thus increase the number of breeding waterfowl that can be accommodated. Artificial islands (see Chapter 35) can be a beneficial addition to large potholes. In areas where wetlands are subject to severe summer droughts, proposed potholes should be located within 0.5 mile of suitable brood-rearing water (Atlantic Waterfowl Council 1972). If a number of ponds are being constructed on an area, the depth, size, and edge cover should be diversified among the units.

Linde (1969) commented that M. Hammond and C. Lacy "found the optimum size of potholes on their study area was 20 to 25 ft wide and 40 to 75 ft long with a water surface area of 500 to 2000 square feet." They recommended that the potholes have one or two gradually sloping edges so that there could be some use of bottom foods by dabblers. They did not feel that it was necessary to level spoilbanks. Increases in size within the above range gave proportional increases in use. They recommended 150- to 200-ft spacing between potholes. Potholes should have a depth of about 4 ft and a berm should be left between the spoil pile and the water to reduce silting. The pattern of pothole arrangement should be in block form and well within the daily duck pair's traveling range from a marsh and large breeding and brooding pond. On their area this was 0.25 mile or more.

Linde (1969) reported on the use of bulldozers and draglines to construct potholes in Wisconsin. Silted-in upland depressions were deepened with a bulldozer and the spoil was used to create adjacent tillable acreage. The estimated useful life of these potholes was 25 years and use by waterfowl and deer was heavy. In areas characterized by very wet soils, where a bulldozer cannot operate, it is necessary to use a dragline or to blast potholes.

Pits are basins excavated below ground level to create a small reservoir in areas where soil conditions are suitable for holding water. Spoil material can be spread out or can be stacked as small dikes to catch and retain natural overflows, thus further increasing water surface areas.

Blasting of potholes as a waterfowl management technique was once limited by the cost of dynamite. New developments that enable the use of ammonium nitrate, a common commercial fertilizer, as a blasting agent have increased the applicability of this technique (Burger and Webster 1964). The detonation with a dynamite primer of a mixture of ammonium nitrate (AN), and No. 2 fuel oil (FO), here termed ANFO, has proved to be effective for opening dense emergent vegetation in extensive marshes, providing open water, and creating favorable habitat for wildlife (Mathisen et al. 1964). The use of ANFO is considered to be the most expeditious and economical method for constructing most types of small potholes (U.S. Forest Service 1969). Dynamite is used where precision blasting is required; ANFO can be used where economy is the primary consideration (Atlantic Waterfowl Council 1972).

Dynamite was first used to create openings in marsh vegetation (Scott and Dever 1940). Provost (1948) detailed blasting techniques used to create potholes and discussed the possible benefits for waterfowl. When the potholes evaluated in that study were reexamined 21 years later by Strohmeyer and Frederickson (1967), they had remained effective in maintaining open water areas, but natural changes in water levels and the activities of muskrats had the greatest influence on the cover-to-water ratio. All blasted potholes had become nearly uniform in depth. The potholes were useful for marsh birds only during dry years, when marsh vegetation was dense. Overwintering muskrats used potholes in shallow marshes. If permanence of a pothole is desired, the original depth of the ditch is less important than the soil type in which it is constructed and the frequency with which water can be expected to fill it.

Mathisen et al. (1964) and Mathiak (1965) provided a detailed summary of methods in which ANFO is used as a blasting agent, and discussed all aspects of pothole blasting. Specific instructions, warnings, and dimensions of potholes blasted with ANFO (Table 20) were presented by Mathiak.

Linde (1969) noted that a disadvantage of blasted ponds concerns the extremely steep, almost perpendicular edges. In loose soils, sloughing and silting-in may result. Blasted potholes are less attractive to waterfowl than dug ponds, which can be constructed with gradual slopes that provide shallow water for dabbling ducks and edges for preferred loafing spots.

Blasted potholes at Delta Marsh, Manitoba, were evaluated for waterfowl use by Hoffman (1970). Greatest use of the ponds occurred during spring and early summer. In comparison with surrounding wetlands, there were greater

Table 20. Dimensions of potholes blasted with ammonium nitrate (modified from Mathiak 1965).

Weight of nitrate charge, and soil type	Potholes measured (number)	Pothole size	
		Depth (inches)	Diameter (feet)
Heavy (150 lb)			
Wet peat	1	48	39
Dry peat	1	96	33
Soft blue clay	1	72	29
Unweighted average		72	34
Moderately heavy (100 lb)			
Wet peat	4	48	26
Dry peat	5	57	32
Soft blue clay	4	76	24
Hard clay	14	69	22
Wet marl	1	36	41
Dry marl	1	84	24
Dry sand	2	49	23
Wet sand	3	45	25
Unweighted average		58	27
Intermediate (75 lb)			
Wet peat	9	52	25
Hard clay	6	58	21
Unweighted average		55	23
Light (50 lb)			
Wet peat	6	45	27
Dry peat	1	48	23
Hard clay	9	52	21
Wet marl	1	30	35
Dry marl	1	72	21
Dry sand	11	40	19
Wet sand	1	50	19
Unweighted average		48	24

fluctuations in annual abundance, less species diversity, and more breeding pairs per unit of shoreline on the ponds. Relations of the size and cost of blasted potholes to waterfowl use were studied in Colorado by Hopper (1972). He noted that, when given a choice, breeding and migrating ducks of several

species preferred potholes created by 75- and 150-lb ANFO charges over those those produced with 25- and 50-lb charges. Warren and Bandel (1968) discussed pothole blasting with ANFO charges on fresh and saline marshes in the Chesapeake Bay area of Maryland and presented information on the size and depth of potholes, sloughing of spoil, soil types, and plant invasions.

Bedish (1972) recommended that blasting not be done in peat soils unless a mineral soil is within 3 ft of the surface. In deep peat soils, the bottom is loosened by the blast and may float up to fill the pothole within a year.

Although current emphasis is on ammonium nitrate as a blasting agent (Mathiak 1965), dynamite is still useful because it offers great flexibility in the placing of small charges (Strohmeyer and Fredrickson 1967).

36.2.2. Level Ditching

Level ditching is the construction of ungraded ditches on lands having a high water table (Atlantic Waterfowl Council 1972). It is a technique often used to create habitat diversity for furbearers and waterfowl. Many marshes have filled in from the accumulation of vegetative matter or silt to the point where little or no open water is present, although a wetland still exists. Level ditching creates deep, open-water areas and upland spoil banks that upgrade the value of the marsh. This technique can increase the value of marginal wetlands to waterfowl and other wildlife and make them less susceptible to drainage for agricultural conversion.

Level ditches are constructed to achieve the following purposes (Atlantic Waterfowl Council 1972; Mathiak and Linde 1956):

1. To improve the distribution of water in marshes having dense, unbroken stands of vegetation.
2. To provide open water for waterfowl courtship and brood rearing.
3. To provide a stable water source during dry years for all marsh-dependent wildlife.
4. To furnish nesting and loafing sites adjacent to open water for waterfowl and den sites and shelter for furbearers.
5. To establish, increase or maintain aquatic food and cover plants for waterfowl and furbearers.
6. To provide access for harvest or management.

Soil scientists, hydrologists, and agricultural engineers should be consulted when one is considering level ditching. The practice is applicable only on wetlands where soils are suitable for the construction of ditches that require little maintenance for a long time. Peat, muck, clay, and silt soils are acceptable soils, whereas sand, sandy loam, and clays high in silt content are generally unsuited for level ditching, according to Atlantic Waterfowl Council (1972) and Yoakum et al. (1980), who gave the following specifications for level ditching:

1. Ditching is usually applied to wetlands larger than 2 acres.

2. Ditches must be laid out on contour levels if slopes exceed 0.5%.

3. Ditches should be spaced 200 to 400 ft apart and be 3 to 6 ft and 10 to 30 ft wide.

4. Level ditches are usually installed at right angles to natural channels; water control structures at the connecting point are used to allow flood waters in, or to regulate flows. The ditching pattern should avoid interception of natural channels.

Level ditches can be constructed with marsh plows, dredges, backhoes, draglines, or by blasting. Draglines are the most common construction tool, largely because of their advantage over blasting. Blasted ditches are shallower, more susceptible to erosion, and lack high spoil banks (U.S. Forest Service 1969).

Spoil material from level ditching should be stacked 10 ft from the ditch edge in piles alternated from side to side at 50-ft intervals (Atlantic Waterfowl Council 1972). When alternation of the spoilbanks is impractical, a 10-ft break should be left at intervals (Linde 1969). Such breaks between spoil piles help to reduce nest predation by breaking up predator travel lanes. The spoil provides den sites for muskrats and nesting areas for waterfowl.

Ditches are usually constructed in straight lines except in large flat marshes where zig-zag patterns can be used. Mathiak and Linde (1956) recommended cutting no more than 300 ft of ditch in a straight line. Alternating patterns assist in reducing wave action caused by high winds. Linde (1969) cited two studies of duck nesting density that related to ditching patterns: H. Mendall found that zig-zag patterns increased the nesting of ring-necked ducks but M. Hammond and C. Lacy reported that puddle duck nesting densities in straight ditches was equal to that in ditches with zig-zag patterns. Detailed modifications of ditching designs were given by Mathiak and Linde (1956) .

Anderson (1948) observed that level ditching on three private Wisconsin marshes was beneficial to muskrat populations and substantially increased trapping revenues. Mathiak and Linde (1956) found that ditching projects provide about 6 years of maximum muskrat production before heavy tunneling in the spoil bank causes rapid siltation. Even so, the ditches were still useful for waterfowl after their value for muskrats had declined (Linde 1969).

36.2.3. Impoundments

Artificial impoundments are commonly used to improve existing marshes or create new ones. The objective is not merely to flood an area, but to control water levels after impoundment as a method of managing food and cover (U.S. Forest Service 1969; Yoakum et al. 1980). (See Chapter 39 for discussion of dikes and associated structures used to impound water.)

Many large water projects have been designed to serve multiple functions, including irrigation, flood control, navigation, power generation, and recreation. Some of the effects of large impoundments are discussed here, but the creation of large reservoirs is not presented as a wildlife enhancement technique.

Marsh management implies the development of dry or nearly dry land into a shallow-water environment and the manipulation of that habitat to benefit wildlife (Cook and Powers 1958). Such management involves site selection, water level control, and control of physical or chemical factors that influence plant growth.

Linde (1969) provided the basic information needed to select a site for creation of a small marsh impoundment. The preflooded cover helps indicate potential productivity because plants are good indicators of fertility. Soil and water analyses are recommended before an impoundment site is selected. Good agricultural soils are generally productive for desirable wetland plants. Marsh environments surrounded by good quality agricultural soils should have more favorable chemical characteristics than areas receiving drainage from degraded soils (Cook and Powers 1958). Highly acidic waters with low alkalinity are generally unproductive.

Relatively flat basins with a gradient of less than 1% provide the best impoundment sites (Atlantic Waterfowl Council 1972). Low-fertility soils should be flooded to shallower depths than fertile soils. To obtain maximum use by dabbling ducks, 75% of the flooded basin should be 2 ft deep or less. Cook and Powers (1958) noted that the topography of an impoundment site should be nearly level, with widely spaced marginal contours to provide additional vegetated edge habitat.

An ideal source of water is one that will maintain desired water levels at all times and reflood an area within a few weeks after a drawdown has occurred. The most desirable arrangement consists of flooded areas of emergent vegetation alternated with open water (Linde 1969). Cook and Powers (1958), in discussing biochemical changes in the soils and waters of impoundments in New York, reported that, in areas where woody vegetation was submerged and killed by flooding, water transparency tended to be low and woody material on the marsh floor reduced the area of substrate available for plant growth.

Although almost all large reservoirs provide resting space for waterfowl, they usually do not have adequate food supplies. Small protected subimpoundments are much more beneficial to waterfowl than large impoundments because water level fluctuations and food supplies are more easily managed in small units. Subimpoundments can be used to increase the value of a nearby large reservoir but construction of small impoundments is not recommended in areas where the potential sites have undesirable features (Linde 1969).

Impoundments created by beavers serve the same functions as artificially created potholes. Properly managed beaver populations can create small impoundments at a small fraction of the human construction costs (Atlantic Waterfowl Council 1972). Maintenance of individual beaver ponds is not as important as the rotation of favorable habitat elements within the entire area of beaver influence (U.S. Forest Service 1969; Yoakum et al. 1980). The available food supply and local beaver populations determine the life expectancy of a beaver pond. Beaver populations can be controlled and managed by trapping. "Beaver pipes" are used to control water levels on beaver-created impoundments if they cause flooding problems (Atlantic Waterfowl Council 1972; Yoakum et al. 1980). A beaver pipe is a wooden tube, 25 feet long, with one solid end and a wire mesh bottom (Fig. 59). The tube is set on top of or through a beaver dam with the wire side down and the solid end extending out into the pond. It is secured by steel posts, and water flows freely through the bottom of the pipe out through the dam. The pipe can be set at almost any water level and the beavers' effort to stop the flow are usually futile (Yoakum et al. 1980).

36.2.4. Marsh Creation with Dredged Material

The use of dredged material as a substrate for marsh development is often a feasible alternative to traditional operations for disposal of such materials. When additional marsh habitat is desired, dredged material can be used to create or improve it. Marsh habitat development involves the confined or unconfined disposal of dredged material on aquatic sites. An increase in elevation or change in substrate can change a deep-water habitat into a shallow-water wetland. The desired elevation is achieved by regulating the amount of dredged material deposited on the site.

Fig. 59. "Beaver pipe," a device used to control water levels in beaver ponds (Yoakum et al. 1980).

Six major dredged material marsh developments were researched by the DMRP and summarized in a report by the U.S. Army Engineer Waterways Experiment Station (1978). Most of the following information concerning marsh creation with dredged material comes from that report. Other marsh development uses for dredged material were discussed by Smith (1978), and further detailed information on planning and engineering aspects of potential sites was

provided by the U.S. Army Engineer Waterways Experiment Station (1978).

The following criteria should be considered in choosing sites for marshes to be created with dredged material:

1. Low wave energy, shallow-water sites are most desirable. If low energy sites cannot be located, protective structures may be required.

2. Sandy dredged material is the ideal substrate (Smith 1978). Significant amounts of sand are often available during dredging, even in projects that involve primarily fine-grained material. In some situations, it will be possible to stockpile sand and then use it as a protective top dressing over finer substrates, or to use the sand to construct a protection dike or breakwater, if needed.

3. Highly productive areas should be avoided, even though they are often well suited for marsh development.

4. Cost factors become significant if long transport distances are involved. The cost and the availability of suitable transport equipment determine what transport distances are acceptable.

If the sediments to be dredged contain fine-grained material, a retention structure may be required to prevent the loss of material and excessive turbidity during placement. Several retention and protective structure types are technically feasible for use in marsh habitat developments (Fig. 60). The two most commonly used containment structures are sand dikes and fabric bags. Considerations in the selection of containment structures include the nature of the dredged material, maximum height of dredged material, required degree of protection from waves and currents, permanence of the structures, foundation conditions at the site, and the availability of structure material.

Retention structures used to confine substrates must provide a means for releasing carrier water from the disposal site. This is best accomplished by placing a weir within the substrate containment structure. The weir structure must be designed to provide selective withdrawal of the clarified upper layer of pond water within the containment without excessive resuspension and withdrawal of settled solids. Weir designs were described by Walski and Schroeder (1978).

Elevation of the substrate is important because it determines the amount of material that can be disposed of and the biological productivity of the new habitat. Settlement and consolidation both occur before the dredged material substrate reaches a final stable elevation. Consequently, tests of sedimentation and consolidation provide information on the expected behavior

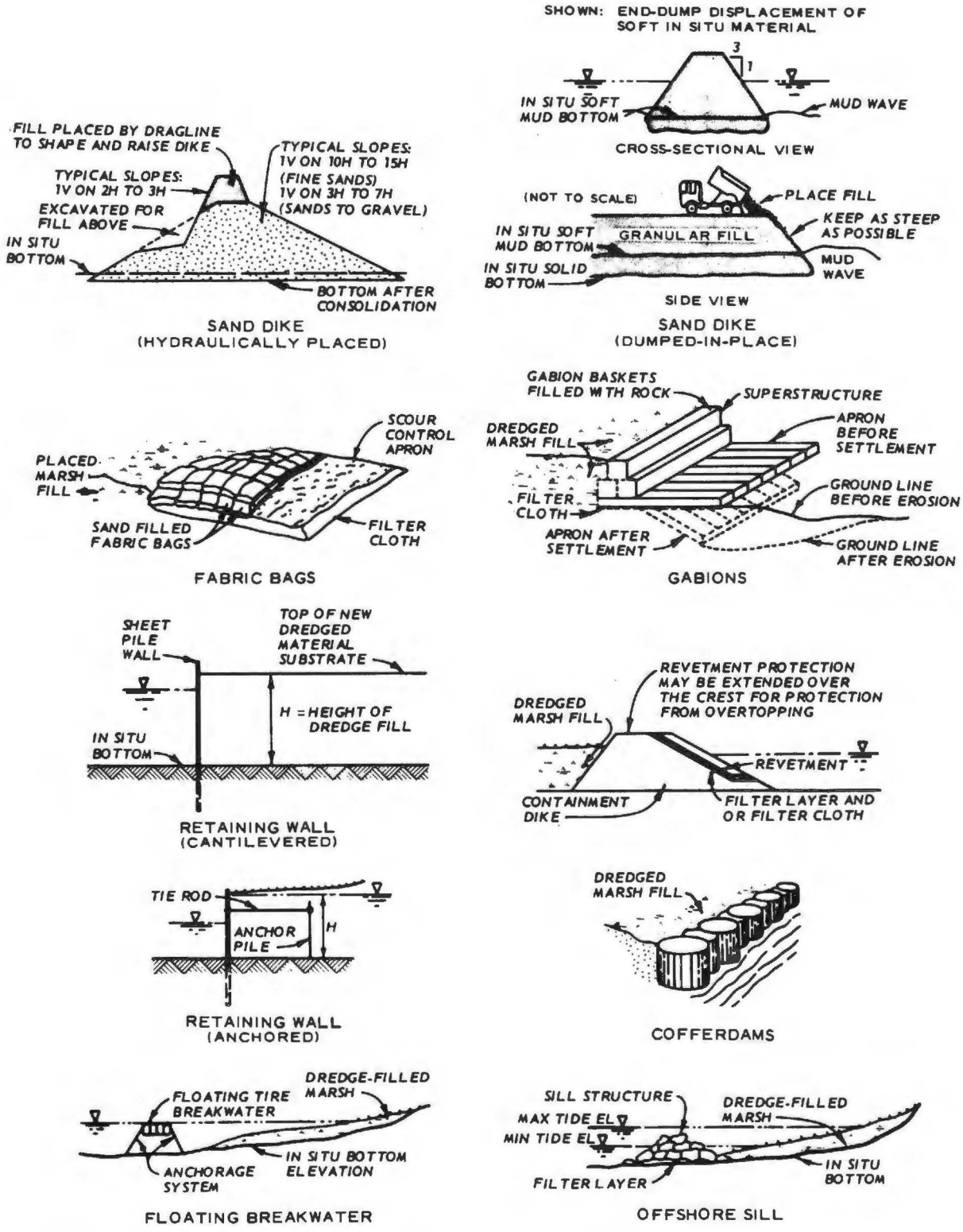


Fig. 60. Different types of marsh containment and protection structures (U.S. Army Engineer Waterways Experiment Station 1978).

of fine-grained sediments placed within confined areas. Detailed descriptions of procedures and equipment for such tests were given by Palermo et al. (1978). If the substrate is to consist of coarse-grained material, such tests need not be performed.

Salt marshes are generally most productive when they are within the upper third of the tidal range. Freshwater marshes should generally be flooded to a depth of 0.3 to 3.3 ft. Determination of final elevation is critical and should be based on precise knowledge of the elevational requirements of the expected plant community. Variations in topography produce habitat diversity and should be encouraged, provided that most of the area is within the desired elevation. The development of maximum vegetative cover within the first year requires that the dredged material be in place and have a relatively stable surface elevation at the beginning of the growing season.

The marsh should be shaped and placed to minimize possible adverse effects on drainage or flow patterns, and to blend into the surrounding environment. Size depends on the capacity of the disposal area and the amount of dredged material available. The area may be filled by using one-time, incremental, or cellular patterns. Low elevations that develop in the marsh can be raised subsequently with additional dredged materials, and overfilled areas can be reworked later. Guidelines for dredged material placement and surface shaping operations were provided by the U.S. Army Engineer Waterways Experiment Station (1978).

Most of the research done on marsh creation or development with dredged material has been conducted in tidally influenced coastal habitats. Although some of the information is not applicable to large river systems, many of the guidelines, planning, and engineering features can be related to freshwater projects. The U.S. Army Engineer Waterways Experiment Station (1978) listed references concerning six regional marsh development projects. Additional references include Lewis and Bunce (1980), Coastal Zone Resources Corporation (1976), Garbisch (1977), Johnson and McGuinness (1975), and Lunz et al. (1978).

36.2. IMPACTS ON THE ENVIRONMENT

Marsh development is generally beneficial because it improves or creates a desirable biological community, unless it is done at the expense of good fishery habitat. Shallow wetlands provide habitat for waterbirds, furbearers, and upland wildlife species. Specific beneficial aspects provided by marsh development include deep water in the winter; interspersion of cover types and waterfowl foods; and nesting and loafing sites for various wildlife species.

Level ditching increases habitat diversity for waterbirds and furbearers,

provides food and cover for wildlife during dry periods, and facilitates access for management or recreation purposes. In addition, spoil banks can be used to provide dry resting and feeding areas and shelter for muskrats during flood stages. In the construction of ditches, excavation is superior to blasting because blasted ditches are more susceptible to erosion and have no spoil banks for nest or den sites.

The creation of small marshes by impoundment of water increases available habitat for all wetland wildlife. An adverse effect associated with impoundments--especially large impoundments--is the inundation of valuable terrestrial habitat. Small impoundments may actually enhance surrounding terrestrial habitat if large open water reservoirs are associated with nearby ample food supplies (largely grain farming areas). Such impoundments may delay southward migrations of waterfowl, alter migration routes, or create new stopovers (White and Malaher 1964). These changes can create other serious resource problems related to artificial concentrations of waterfowl, disease, or abandonment of traditional wintering areas.

Pothole blasting has many of the benefits of marsh development previously mentioned. Mathiak (1965) reported that blasted potholes were used by a variety of wildlife, including deer, ring-necked pheasants, mink, and cottontails. He noted that soft soils in potholes may be hazardous for livestock and discussed the dangers of using explosives. An ANFO blast will not cause a fire but concussion from the blast may break nearby windows (Mathiak 1965).

Smith (1978) listed four advantages associated with the creation of marshes: a desirable biological community is created; dredged materials are used beneficially; newly created marshes can be used to replace or improve marsh habitats; and the additional cost above that of normal project dredging operations is small. He also listed four disadvantages: appropriate sites are scarce; other habitats are lost; toxic contaminants are potentially released; and the site is lost for subsequent disposal.

Marsh development may improve fish habitat, provided that suitable access for fish is available. Newly created deep-water areas in marshes are of little benefit to fish if the areas are surrounded by heavily vegetated shallow water. Level ditches can be beneficial if they are built into a circulating system that would prevent the accumulation of stagnant water with low dissolved oxygen. Shallow-water marshes can provide additional fish spawning habitat if associated with deep water, nursery areas, and feeding areas. (For further information, see Chapter 24.)

36.4. *COSTS*

Linde (1969) provided detailed cost and use figures for pothole construction in Wisconsin by blasting, draglines and bulldozers. On the basis of cost per acre-foot bulldozing was cheapest, but on the basis of cost per pothole, blasting was, by far, the cheapest. This comparison thus indicated that if many small potholes are to be constructed, blasting is the most economical form of construction; if fewer and larger potholes are wanted, bulldozing would be more economical, providing that conditions are suitable for using heavy equipment. The following information (1969 dollars) on the costs of construction of potholes with a dragline and bulldozer was taken from Linde (1969).

Bulldozed potholes ranged in cost from $77 to $721 per acre-foot. Spoil was spread and leveled as it was removed during bulldozing operations. Conditions must be dry enough to allow efficient operation. The high cost of $721 per acre-foot of water was a result of poor operating conditions. The least expensive pond was a 1.44-acre pond costing $110 per acre-foot. A series of 10 ponds of various sizes were bulldozed at an estimated cost of $87 per acre-foot, but they were constructed by cleaning out some natural depressions and were not really comparable because less spoil was removed than would have been removed if they had been constructed in flat terrain.

The average cost for pothole construction by draglines on selected state management areas in Wisconsin was about $435 per acre-foot of water (range, $222 to $750). Costs were influenced considerably by weather and operating conditions. All costs quoted were those for actual construction and did not include final spreading of the spoil or seeding of the banks.

Many tests have shown that, for comparable results, the costs of blasting with ANFO were one-fifth to one-third those of dynamite (Burger and Webster 1964). Linde (1969) reported that ammonium nitrate costs only about $^{1}/_{10}$ as much as dynamite ($0.42 per pound for dynamite and $0.04 per pound for ANFO) and that the cost of a 50-lb charge of ANFO was about $3, complete with detonating charge, fuse, and cap.

The cost for detonating one ton of ANFO at two different types of locations in Maryland, according to Warren and Bandel (1968) was $460 in saline areas ($300 for labor and $160 for material) and $436 in freshwater areas ($231 for material and $205 for labor).

The amount of earth moved per ton of ANFO averaged about 1530 cubic yards, at a cost of about $0.30 per cubic yard. This compares favorably with a dragline, which costs a minimum of $0.50 per cubic yard. Volumes and costs of experimentally blasted potholes in Wisconsin are shown in Table 21.

Table 21. Volume and costs of experimental potholes blasted with charges of ammonium nitrate and fuel oil (ANFO) (from Mathisen et al. 1964).

Charge (pounds)	Distance apart[a] (feet)	Soil[a]	Pothole size (feet) Width	Length	Depth	Cost
2-50	12	clay	25	35	7	$11.00[b]
2-8	NA	peat	14	19	4	4.00
1-50	NA	peat	25	25	7	5.60
36-27	10	NA	60	120	8-10	50.00

[a]NA-data not available
[b]Labor included

Hopper (1972) reported costs of pothole blasting with ANFO in Colorado (Table 22). Materials included ammonium nitrate, fuel oil, plastic bags, dynamite, and electric caps; labor was charged at $2.50 per man-hour.

Table 22. Relation of cost and surface area of 84 potholes, based on size of charge of ammonium nitrate and fuel oil (ANFO) (from Hopper 1972).

Size of charge (pounds)	Average cost per pothole Materials	Labor	Total	Average cost per 100 ft
25	$ 2.12	$2.75	$ 4.87	$2.42
50	3.49	3.62	7.11	2.42
75	6.35	5.12	11.47	2.01
150	10.49	8.32	18.81	2.21

Linde (1969) noted that the cost of level ditching operations was associated with the size of the project. On the basis of cost per running foot of ditch, the larger the project, the lower the cost per unit. Working conditions and salaries of equipment operators also cause operational costs to vary. Lind (1969) also published the costs of various level ditching projects in Wisconsin (Table 23). The Atlantic Waterfowl Council (1972) estimated the cost of level ditching to be $3 to $5 per running foot of ditch. Although Nelson and Davis (1972) did not break down costs to per unit figures, they reported that the costs of level ditches 30 ft wide and 4 to 5 ft deep ranged from $172 to $5169, and averaged $659 for lengths that ranged from 71 to 1732 ft and averaged 229 ft.

Table 23. Dimensions and construction costs of level ditches constructed on State-owned areas in Wisconsin (from Linde 1969).

Location	Length (miles)	Ditch dimensions (feet)[a]			Cost of ditch[a] (per foot)	Capacity of dragline (yards)
		Width		Depth		
		Top	Bottom			
Crex Meadows Wildlife Area	2.5	V	V	V	NA	5/8
New Auburn Area Wildlife Area	.35	14	6	6	$0.45	3/4
French Creek Wildlife Area	.17	13	5	5	1.91	3/4
Jackson Marsh Wildlife Area	.75	12	5	5	0.25	3/4
Horicon Marsh Wildlife Area (experimental ditches)	2.5	13	5	5	0.18	3/4
Horicon Marsh Wildlife Area (post-experimental ditches)	6.0	13	5	5	NA	1/2
Yellowstone Wildlife Area	2.3	15	5	8	NA	11/2

[a]V=variable; NA=not available

The costs of planning and constructing a marsh development site with dredged material are based on many considerations. The U.S. Army Engineer Waterways Experiment Station (1978) provided cost variability factors of marsh development and cost information for two of their DMRP field projects. Planning and engineering design costs were $45,000 ($2250 per acre) at Bolivar Peninsula, Galveston Bay, Texas, and $35,000 ($1750 per acre) at Windmill Point, James River, Virginia. Both sites are about 20 acres in area. The planning and engineering costs of these projects were increased by detailed research protocols and difficult site problems. Planning costs would be substantially lower at more conventional marsh development sites.

Construction costs are influenced by such variables as access to the

site, distance between the dredging and disposal sites, dredged material and foundation characteristics, energy regimes, cost of protective structures, availability of equipment, and local labor rates. Most of the construction costs encountered in marsh development are associated with conventional methods of confined dredged material disposal.

Construction costs, exclusive of actual dredging, were $288,000 ($14,400 per acre) at Bolivar Peninsula and $167,500 ($8375 per acre) at Windmill Point. These totals include dike construction and maintenance, post-construction grading and elevational changes, and other site preparation measures. The reason for the substantial cost difference was primarily the result of use of a more expensive protective structure (fabric bags) at Bolivar Peninsula. A temporary sand dike was used at Windmill Point.

36.5. EVALUATION FOR USE ON UMRS

Marsh creation and development techniques may have potential use on UMRS. Many backwaters have filled in with sediments and wetlands now lack diversity because vegetative growth crowds out open water. Increased diversity could improve habitat for all wildlife, particularly for waterfowl, furbearers, and fish.

Level ditching and pothole construction would benefit many backwater marsh areas that have filled from sedimentation or are choked with vegetation. Blasting, although not as desirable as dredging for the construction of potholes or ditches, may be a more practical method because of the difficulty of moving equipment in backwaters and wet areas. Blasting is also more economical. The deep water would benefit muskrats and fish by providing overwintering areas, and waterfowl by providing open water. Level ditching may also help increase circulation through wetlands areas.

Small impoundments with suitable water control structures may be developed within the existing wetlands. The water level control available in small impoundments would be used to maintain stable water levels during low water periods and provide waterfowl with food production sites.

Marsh creation with dredged material may have limited applicability on UMRS because of the lack of acceptable sites. Many wetlands may benefit from habitat improvement but open-water sites available for marsh creation are more suitable for island creation. Small marshes could be developed in association with islands.

CHAPTER 37. GREENTREE RESERVOIRS AND MAST MANAGEMENT

37.1. SITUATION TO BE MITIGATED OR ENHANCED

Greentree reservoirs are forested river bottomlands that are artificially flooded during the fall to attract migrating ducks (McQuilkin and Musbach 1977). Greentree reservoirs are created to make mast crops available to waterfowl by the shallow flooding of bottomland hardwoods. This habitat improvement technique does not interfere with proper timber management.

Fredrickson (1980) noted the past and continued demise of lowland hardwood wetlands as wildlife habitat and outlined the probable effects of water resource developments on lowland hardwood wetlands and wood duck habitat (Table 24). Only 5.2 million acres remain of the original 11.8 million acres of bottomland hardwood forests in the lower Mississippi River alluvial plain. By 1990 only 4.2 million acres may remain (Clark and Benforado 1981).

Table 24. Probable effects of water resource developments on lowlands and on wood duck habitat (from Fredrickson 1980).

Development	Effects on lowland hardwood wetland[a]		Effects on wood duck habitat[b]	
	Positive	Negative	Breeding	Wintering
Agriculture	1	2	8, 9,10	16
Channelization	1	2,3,4	9,10,12	16
Drainage	1	2,3,4	9,10,12	16
Levees				
Areas within	5	4	13,14	17
Areas outside	1	2,3,4	9,10,12	16
Upstream reservoirs	1	2,3,4	9,10,12	16
Greentree reservoirs	6	4,7	15	18

[a]Wetland effects: 1 = none, 2 = forests cleared, 3 = flooding reduced, 4 = composition of trees shifts toward less water-tolerant species, 5 = some forests remain, 6 = makes plant food available early in fall, 7 = static water levels.

[b]Habitat effects: 8 = no aquatic macroinvertebrates, 9 = fewer nest sites, 10= reduced cover, 11 = reduced flooding, 12 = fewer aquatic macroinvertebrates, 13 = deep water precludes feeding on many sites, 14 = turbidity reduced submergent plant growth, 15 = macroinvertebrate food available early, 16 = reduction in food resources and cover, 17 = flooding provides roosting areas, but foods are unavailable if water is too deep, and 18 = provides roosting and feeding sites for long period.

Many bottomland hardwoods flooded naturally before extensive flood control projects were undertaken. Currently, many large river systems have been impounded and channelized so that normal seasonal flooding no longer occurs. Protected areas outside the levees lack normal water fluctuations and lose their wetland character. Inside the levees, flooding occurs for longer periods and to greater depths, affecting the plant community (Fredrickson 1980).

In drought years, mast crops are generally unavailable to waterfowl. Greentree reservoirs improve waterfowl food availability when seasonal flooding is uncertain. Upstream reservoirs, drainage, channelization, and levees reduce spring flooding of areas where breeding wood ducks normally feed. Shallow flooding is essential to stimulate the production of invertebrates and to provide desirable feeding conditions before and during egg laying and during early brood rearing. If reservoir waters are released during dry periods, they cause lowland flooding out of the normal flooding cycle (Fredrickson 1980). Greentree impoundments for waterfowl and timber management also help prevent further losses from the clearing of bottomland by conversion to agriculture and benefit wildlife by reducing the impacts of flood control project.

The most obvious change in the Mississippi River delta has been the loss of lowland hardwoods and their conversion to row crops (MacDonald et al. 1979). Agricultural areas supply few of the requirements of wood ducks. Pesticides, herbicides, fertilizers, and suspended soil particles from agricultural runoff are serious problems and readily degrade natural wetland habitats (Fredrickson 1980).

37.2. DESCRIPTION OF TECHNIQUES

Flooded bottomland hardwood forests provide good habitat for certain species of ducks (Allen 1980). Flood control projects on many large river systems now prevent much of the normal seasonal flooding. When danger of flooding is reduced, bottomland hardwoods are often cleared and converted to agricultural use. Greentree impoundments may protect these bottomland areas from conversion to agriculture and benefit wildlife by reducing the impacts of flood control projects.

In greentree reservoirs, low dikes are used to impound water over flat bottomlands. The production of mast from various oaks and other tree species as a wildlife food source is the most important objective. Timber production is also considered an important management objective. Mallards and wood ducks are the principal target species, but greentree reservoirs also benefit wild turkeys, squirrels, deer, quail, furbearers, and many species of nongame mammals, birds, reptiles, amphibians, and fish (U.S. Forest Service 1969; Yoakum et al. 1980).

There are three main considerations in site selection for a greentree reservoir (U.S. Forest Service 1969; Yoakum et al. 1980):

1. The area should be flat and contain impervious clay soils. It should also be close to a low gradient stream in which the fall does not exceed 1 ft per mile, to prevent excessive diking costs.

2. There must be mast-bearing oak timber that can be flooded and is adapted to flooding.

3. There must be an ample and dependable seasonal water supply, which can be removed from the area before spring tree growth begins.

The U.S. Forest Service (1969) grouped common tree species with three categories (best, good, and poor) on the basis of their value as producers of waterfowl food:

Best: water oak, willow oak, nuttall oak, cherrybark oak, swamp red oak, pin oak.

Good: swamp chestnut oak, chinkspin oak, swamp white oak, overcup oak, blackgum tupelo, common hackberry, black locust, common honeylocust, baldcypress, tupelo, water locust.

Poor: elm, ash, American sycamore, poplar, hickory, beech, birch, red maple, boxelder maple, pine.

The rating by the U.S. Forest Service reflects the value of foods to wildlife in the fall. Elm, ash, and red maple--rated poor in the list--provide excellent sources of protein and lipids in spring (L. H. Fredrickson, personal communication).

The construction requirements for greentree reservoirs, including levees, borrow areas, water control structures, and spillways, are discussed in Chapter 39. The U.S. Forest Service (1969) and Yoakum et al. (1980) described three systems for flooding greentree reservoirs:

1. Retention of rainfall or flood waters is best adapted to low-gradient, flat-bottomed reservoirs and is dependent on rainfall at the proper season.

2. Diversion of inflowing streams requires a gate-type structure in the stream to permit diversion of the stream flow onto the diked area at the proper time. This method may be used where small streams enter terraced or well-drained bottomlands.

3. Pumping is used when groundwater is cheap and readily available

and where other water sources are unreliable.

Bottomland hardwoods can be flooded safely when the trees are dormant (McDermott and Minckler 1961; Merz and Brakhage 1964). Although the period of permissible flooding may vary with the latitude and timber type, it should not begin until after the first killing frost (Givens and Atkeson 1957). This is usually early October, or when the leaves begin to turn color. The period when water should be removed ranges from February in the south (Rudolph and Hunter 1964) to late March to mid-April in the north (Atlantic Waterfowl Council 1972; U.S. Forest Service 1969; Yoakum et al. 1980).

Complete drainage before the growing season begins is important because summer flooding may damage or kill desirable mast species (Rudolph and Hunter 1964; Merz and Brakhage 1964). Permanent flooding of tree root crowns may kill the trees (Green 1947; Hall and Smith 1955; Yeager 1949). Hall and Smith (1955) noted that all woody species were killed when root crowns were periodically flooded for more than 54% of the growing season. Whitlow and Harris (1979) summarized information on the flood tolerance of temperate woody plants and included a list of vegetation for each of the 10 U.S. Army Corps of Engineers divisions in the United States. The plants were categorized as very tolerant, tolerant, somewhat tolerant, or intolerant to flooding. The effects that water level fluctuations have on woody riparian and wetland communities were described by Tesky and Hinckley (1977a, 1977b, 1978a, 1978b). Spohrer (1975) provided an annotated bibliography on the effects of water fluctuation and sedimentation on bottomland hardwoods. Reed (1968) studied the effects of spring flooding of swamp white oak in a northern greentree impoundment. The area was flooded in March and a gradual drawdown began in July. No dead trees were noted, but the flooding caused considerable mortality of various shrubs. Green (1947) reported that permanently flooded swamp white oak maintained fair growth through 2 years of inundation.

Thompson et al. (1968) discussed greentree reservoirs created in the elm-ash-maple association found on muck wetlands in the Northeast and Midwest. These areas differ substantially from southern delta greentree sites. The potential for acorn mast production is limited in northern muck hardwoods because oaks are not abundant. In addition, since muck soils are saturated with water for most of the growing season, there is little benefit to hardwoods from increasing soil water storage. Most northern impoundments freeze by late fall and become useless to waterfowl thereafter. Because spring flooding tended to stress tree growth, drawdown was recommended by the third week in June.

The recommended water depth for greentree reservoirs is 12 to 18 in., to provide optimal feeding conditions for dabbling ducks (Rudolph and Hunter 1964; Brakhage 1965b; U.S. Forest Service 1969; Yoakum et al. 1980). However, L. H. Fredrickson (personal communication) believed that these water levels are not optimal for either wood ducks or mallards. Progressive flooding may

prolong the attractiveness of bottomland forests because ducks are attracted to the flooding edge. This method continues to provide new feeding areas as the water level increases. High ridges need not be completely flooded because they provide desirable loafing areas for waterfowl.

When regeneration of the woods in a greentree reservoir is desired, the area must not be flooded for at least 2 years to allow for the establishment of new trees. Many tree seedlings cannot survive when submerged by flooding (Merz and Brakhage 1964). In addition, the consumption of acorns by feeding ducks may greatly reduce the opportunity for stand regeneration by reseeding (Brakhage 1965b). The planting of large seedlings can be substituted for natural regeneration if yearly flooding is desired. (Planting techniques and further propagation methods are discussed in Chapter 40.)

An important objective of greentree reservoirs is the continued production of high quality oak for commercial timber. When properly managed, these forest reservoirs increase timber growth and prevent hardwood mortality during drought years (Broadfoot 1958, 1959, 1967).

Bottomland hardwood stands in greentree reservoirs generally require improvement if they are to have maximum value for both waterfowl and timber production. Cull trees and unwanted species, except those of value to cavity or snag-nesting birds, should be removed. Selective thinning of desirable species opens the canopy and allow the crowns to increase. This increase, in turn, improves mast production. Brakhage (1965b) reviewed the literature on improvement of mast crops. Pin oak acorn production on greentree reservoirs in Missouri was studied by McQuilkin and Musbach (1977). Their 14-year study determined the effects of flooding and tree size on acorn production, tree growth, and oak reproduction. They concluded that dormant-season flooding of a greentree impoundment does not decrease the production of sound pin oak acorns. To maximize acorn production, large trees should be retained in preference to smaller trees. Selective thinning should be done in the late summer or fall when the acorns are visible, so that the most productive trees can be left.

Open marsh areas in greentree reservoirs create habitat diversity and attract waterfowl. Annual crops, such as barnyardgrass or smartweed, provide a secondary food base that will offset a general mast crop failure. Open marshes can be created by mechanically removing all nonmast producing trees and understory species in low areas.

Waterfowl food habit studies on greentree reservoirs conducted by Hall (1962) and Allen (1980) revealed that acorns were the major food item. Krull (1969), who reported on macroinvertebrate populations in a spring-flooded greentree reservoir in New York, noted an abundance and diversity of invertebrates that are valuable as waterfowl food. Protein resources are

readily available in lowland hardwood wetlands in the form of macroinvertebrates normally found in leaf litter (Hubert and Krull 1973). Christisen and Korschgen (1955), who discussed acorn yields and wildlife use in Missouri, offered the following conclusions:

1. Abundant mast crops are not produced every year; yields are irregular and vary from year to year.

2. General and simultaneous acorn crop failures of all oak species are unlikely.

3. Individual trees vary greatly in the production of acorns.

4. A high proportion of acorns fail to mature.

5. A large proportion (over 50%) of mature acorns are damaged by insects.

6. Relatively few acorns are both sound and mature.

7. Preferences by wildlife for a particular species of acorn are not evident.

8. Wild animals do not consume all of the sound acorns in good years, and squirrels aid regeneration of the woods by leaving buried acorns to germinate.

Cowardin (1969) studied waterfowl use of flooded, dead timber impoundments and evaluated various habitat types in impoundments that had been flooded for 7 and 21 years. These areas furnished valuable waterfowl habitat and received heavy use at certain times of the year. Flooded, dead timber was attractive to waterfowl because it furnished abundant loafing sites. Aquatic plants and invertebrates were abundant in the flooded timber areas. Cut timber with emergent vegetation received the greatest overall use.

37.3. IMPACTS ON THE ENVIRONMENT

The primary purpose of greentree reservoirs is to increase the availability of mast crops to waterfowl. This purpose is usually complementary to timber management. The impounded waters protect fallen acorns from insect depredation and prevent depletion of the mast crop by deer, squirrels, and birds before the ducks arrive. Cypert and Webster (1948) recorded a 5% per day removal of acorns by wildlife other than ducks on the White River National Wildlife Refuge in Arkansas.

Greentree reservoirs are valuable duck hunting areas. Many duck clubs in the lower Mississippi flyway develop this type of habitat (Rudolph and Hunter

1964). Many timbered areas normally flood each year and may or may not be used by waterfowl, depending on the time of flooding (Hall 1962). Migrant duck populations can be attracted by manipulating the time and extent of flooding. The management of shooting areas in flooded oak bottomlands was discussed by McDermott and Minckler (1961) and Merz and Brakhage (1964). Brakhage (1965b) and Fredrickson et al. (1977) warned of the possibility of lead shot poisoning in greentree impoundments.

Thompson et al. (1968) found that spring-flooded greentree reservoirs provide duck nesting habitat, high invertebrate populations, valuable waterfowl day-use areas, and desirable habitat for some nongame birds.

Greentree reservoirs can accelerate timber growth and increase acorn production (U.S. Forest Service 1969). Soil moisture conditions are improved by winter flooding, which may improve mast production (Minckler and McDermott 1960), growth rates, and seedbed conditions for new sprouts.

The primary adverse effect of greentree impoundments is potential damage to tree growth due to improper seasonal flooding or drainage. The presence of water year-round or during most of the growing season reduces growth of most trees and kills others. Annual winter flooding of bottomland hardwoods has a harmful effect on stand regeneration (Brakhage 1965b). The impoundments of northern greentree reservoirs reduced the density of gray squirrels (Thompson et al. 1968). A major fish-kill was observed due to anaerobic conditions that occurred during fall impoundment. Common carp, sunfishes, and bullheads were the major species affected. The effects of temporary anaerobic conditions on soil invertebrates and vegetation were not determined. These conditions did not occur during spring flooding and can be prevented in fall by delaying flooding until after the first frost. Green plant material creates a high biochemical oxygen demand when flooded. Plant biomass is reduced by frost and delayed flooding prevents severe depletion of oxygen levels.

37.4. COSTS

Few cost estimates for development of greentree reservoirs are available. Costs vary greatly, depending on site characteristics, regional construction costs, and water sources. (Costs for specific impoundment and water control structures are discussed in Chapter 39.)

Allen and Halls (1976) found that the establishment of a greentree reservoir on private land in eastern Texas was economically feasible for a timber company. The initial construction cost of a 303-acre impoundment was $1336. Construction involved an earthen dam, water from an intermittent stream, seepage, and floodwater. All investments were recouped within 2 years from hunter fees. The project was estimated to have returned a net profit

over a 10-year period of $1.91 per year per acre of flooded bottomland.

37.5. EVALUATION FOR USE ON UMRS

No greentree reservoirs are known to have been constructed on UMRS. Extensive areas of bottomland hardwoods in UMRS basin are subject to seasonal flooding. Sufficient waterfowl feeding areas probably occur so that greentree reservoir developments are unnecessary. Mast crops are usually readily available to wood ducks in many areas without artificial flooding. Suitable greentree impoundment sites occur on UMRS, and could be used to enhance waterfowl feeding conditions if justified. Timber production is not a major concern on UMRS, but good forestry practices should improve both mast and timber crops.

CHAPTER 38. VEGETATION CONTROL

38.1. SITUATION TO BE MITIGATED OR ENHANCED

In many areas on large river systems, vegetation has reached climax stages or other successional stages that are not beneficial to wildlife. Flood control developments have prevented normal flooding from influencing plant growth. Impoundments have created shallow marshes that quickly become choked with rank marsh vegetation of little value to wildlife. The lack of natural fires has allowed upland openings to close in, eliminating valuable edge habitat. Dense, lush growth of low-growing plants may accumulate until new shoots can no longer penetrate the mat of old foliage. Tall vegetation may overwhelm and shade out low ground cover or aquatic plants. Other plants with low value as wildlife forage and cover may develop dense impenetrable stands. An aggressive invading plant species may outcompete vegetation that is more valuable to wildlife.

Vegetation control techniques that improve wildlife habitat can be used to offset some of the impacts on river systems that have resulted from the suppression of natural forces. Improvements include the creation of openings in vegetation, removal of rank vegetation, encouragement of new sprouting, and freeing new plantings from competition. Vegetation control is needed to maintain the desired vegetational succession to improve and maintain wildlife populations. Climax woodlands and weed-choked marshes are of only limited value to wildlife, but some overgrown stages must be maintained because they provide shelter and escape cover. The removal of undesirable growth provides openings, creates additional "edge," and increases desirable plant species. Aggressive plants must be controlled to avoid domination of more desirable species. Woody plants or any tall overstory may have to be removed or thinned to allow a new vegetative community to develop. Because many wetland areas have been lost through drainage and development, the remaining ones have become more valuable and need to be effectively managed to best meet wildlife requirements.

38.2. DESCRIPTION OF TECHNIQUES

In this chapter we discuss techniques used to control or remove marsh and upland vegetation so that habitat values for wildlife will be increased. (Aquatic plant control as a fishery enhancement technique is discussed in Chapter 32.) The controls used to benefit recreational and commercial interests sometimes directly conflict with wildlife values. The basic categories of vegetation management include chemical, mechanical, and biological controls, water level fluctuation, and burning. The methods of vegetation control may be used in various combinations to improve the effectiveness of control.

38.2.1. Chemical Control

The use of chemicals for vegetation control in wildlife management is an outgrowth of the development of herbicides for agricultural purposes. Many herbicides have been developed specifically to control vegetation that is considered a nuisance by other interests, but these plant species are often valuable to wildlife. Nevertheless, herbicides can also be used effectively to improve wildlife habitat. The use of herbicides in marsh and upland habitat management has increased rapidly, and their use in marsh management is now common because chemical control is usually economical and efficient. Chemical uses in aquatic areas are substantially more restricted than land-based applications.

Our discussion is limited to herbicides that are currently registered for wildlife management uses by the U.S. Environmental Protection Agency (EPA). Several herbicides that have been recommended for vegetation control, including TCA, 2,4,5-T, and Silvex, have recently been banned or severely restricted or excluded. Our listings do not necessarily include all possible approved and available herbicides. The herbicides discussed here have been used in wildlife management; many commonly used agricultural herbicides may serve similar purposes.

Herbicides reviewed here have been found to be effective on three plant types or habitat classifications: emergent-moist soil vegetation; aquatic grasses; and shoreline, ditchbank, and upland vegetation. (Specific chemical control methods for submergents, algae, free-floating plants, and floating-leaved plants, generally for fishery or recreational enhancement, are discussed in Chapter 32.) Many submergents, such as the pondweeds, are valuable waterfowl food plants and are usually encouraged by wildlife managers. Some of the herbicides mentioned in the present chapter are also effective on the undesirable aquatic plants that require control for fishery management.

The discussion of specific herbicides and their potential application is divided into two parts. The first part includes a listing of the specific herbicides, product names, general information, and the type of vegetation controlled. The second part is a list of some of the most common plants that may require chemical control to enhance wildlife habitat. The herbicide list is divided into three categories based on registration restrictions regarding the use of herbicides near aquatic areas:

1. Herbicides approved for aquatic use, including food fish.

2. Herbicides approved for aquatic use, but only in nonfood-fish waters and with possible further restrictions.

3. Herbicides approved for nonaquatic use only.

Specific herbicide information discussed here was obtained from several sources. The Weed Science Society of America (1979) provided a listing of all herbicides of current commercial interest in the United States. The listing is not a summary of the current federally registered herbicides but does provide valuable application information. A list of registered herbicides was provided by EPA (1974). This list was supplemented with information from the Aquatic Plant Control Herbicide Handbook (FWS 1979b). Other chemical vegetation control information has been published by Applied Biochemists, Inc. (1976), Evans (1978), Burkhalter et al. (1974), Klussman et al. (1978), Linde (1969), Lueschow (1972), Martin et al. (1957), Nelson and Dietz (1966), Rollings and Warden (1964), and U.S. Forest Service (1969).

Before any chemical product is used, the label and the most recent EPA compendium should be consulted. In addition, State regulations regarding herbicide use should be followed.

Herbicides Approved for Aquatic Used in Food Fish Areas

Presentation of specific information about 2,4-D, diquat, glyphosate, and simazine is given in Chapter 32.

Herbicide Approved for Aquatic Uses, but Limited to Nonfish Areas or Otherwise Restricted

1. Amitrole (3-amino-1,2,4-triazole)

   Product names: Amitrol-T, Amizol, Weedazol, Amino Triazole Weed Killer; Cytrol Amitrole-T; combinations include: Amizine (amitrole plus simazine), Fenamine (amitrole plus fenac plus atrazine), and Kleer-lot (amitrole plus linuron).

   General information: For use as general weed killer in noncrop areas only. Spray or drift should not be allowed to contaminate edible crops, or water that will be used for irrigation, drinking, or other domestic purposes. It should not be applied to water where fish are present. No residue in crops is permitted. Amitrole kills by internal disruption of the plant's physiological processes and must be absorbed by the plant leaves and stems because it breaks down readily in soil. It should be sprayed on the plants after inflorescences have formed. Amitrole is relatively nontoxic to animals. It persists in the soil for 2 to 4 weeks.

   Vegetation controlled: Broadleaf weeds, grasses, woody plants, and emergent aquatic weeds, particularly cattails and bulrushes.

2. Dalapon (2,2-dichloropropionic acid)

Product names: Dowpon, Dowpon M, Radapon, Basfapon B

General information: For use in noncropland agricultural weed control. Very soluble in water; washes from foliage easily; leaches into soil readily. Soil persistence, 6 to 10 weeks. Livestock should not be grazed on treated area.

Vegetation controlled: Most perennial and annual grasses, and emergent aquatic vegetation, particularly cattails and bulrushes.

3. Diuron 3-(3,4-dichlorophenyl)-1,1-dimethylurea)

Product name: Karmex, combinations--Krovar I and II (diuron and bromacil)

General information: For selective weed control in agricultural crops, as a general weed killer at high application rates, and for irrigation ditch weed control. Should be applied only during noncrop season and when ditches are not in use. Must not be used where the chemical can gain access to water containing fish because diuron accumulates in fish tissues.

Diuron is a crystalline compound, only slightly soluble in water and oils. It is relatively nontoxic to mammals. It is also a soil sterilant and should never be used near or in water having contact with domestic crops, trees, or valued plants.

Vegetation controlled: Broadleaf weeds and grasses

4. Picloram (4-amino-3,5,6-trichloropicolinic acid)

Product name: Tordon

General information: Brush killer; remains active in soil for more than one season; highly mobile in soil and can be transported laterally in subsurface water.

Vegetation controlled: Broadleaf weeds and woody plants; most grasses are resistant.

Specific comments: Linde (1969) noted that Tordon had no effect on sedge.

Herbicide Approved for Non-Aquatic Uses

1. Atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine)

Product name: Aatrex 80W, 90W, 4L; 4LC; combinations: Aatram 20G (atrazine and propachlor), Atratol 8P (atrazine and sodium chlorate), Atratol 80W (atrazine and prometon), Bicep 4.5L (atrazine and metolachlor).

General information: For use as a selective herbicide for agriculture or rangeland purposes. Also can be used as a nonselective herbicide for vegetation control on noncropland or fallow areas. The residual activity of atrazine in soil at selective rates for specific soil types is such that most rotational crops can be planted 1 year after applications, except in arid or semiarid climates.

Vegetation controlled: Broadleaf weeds and grasses

Specific comments: Linde (1969) reported that smartweed was resistant to the residual effects of atrazine but that other plant growth was inhibited.

2. Bromacil (5-bromo-6 methyl-3-(1-methylpropyl)uracil)

Product name: Hyvar-X, Hyvar XL, Ureabor, Borocil, Hibor; combinations: Krovar I (bromacil and diuron), Krovar H (bromacil and diuron)

General information: Used on noncropland areas for a wide range of weed control. Also can be used for selective control in some agricultural crops.

Vegetation controlled: Annual and perennial grasses, broadleaf weeds, and certain woody species.

As an aid in determining how specific plants can be controlled with herbicides, we next provide a list of "specific vegetation to be controlled and effective herbicides." Each plant name is followed by the names of the herbicides effective for control of that plant. Special application techniques are described for some plants. No specific application volumes, mixtures, or rates are provided because of the wide differences in site specific characteristics and product concentrations. Most product labels provide application information required for the control of specific plants. The plants are listed by common name; both common and scientific names are listed in Part XII. More extensive lists of plants that can be effectively controlled by herbicides were given by DeVaney (1967) and Burkhalter et al. (1974).

Specific Vegetation to be Controlled and Effective Herbicides

a. Emergent Plants

1. Arrowhead: 2,4-D

2. Bulrush: 2,4-D, amitrole, diuron, glyphosate

3. Burreed: dalapon, 2,4-D

4. Chafflower: 2,4-D

5. Cattail: amitrole, dalapon, diquat, glyphosate

   Application: Amitrole is effective if two applications are used 1 month apart. This herbicide is not to be applied over a water surface. Martin et al. (1957) reported that dalapon was more effective on relatively dry sites. The optimum stage for application is when the flowers of the staminate spike are drying. The use of a surfactant with dalapon was recommended. Nelson and Dietz (1966) noted that dalapon was an effective method of controlling cattails in deep water, but that results were poor in shallow, fluctuating waters. The best period for spraying appeared to be in fall, while the plants were still green, before any frost, and when there was no time for regrowth. Spraying of mature cattails was more effective than spraying of regrowth. In general, chemical treatment of cattails is often ineffective or the results are only temporary.

6. Hibiscus or rosemallow: 2,4-D

   Application: Control is most effective when 2,4-D is applied at the full flowering or early fruiting stage.

7. Justicia: 2,4-D

8. Marshpurslane: 2,4-D

9. Pickerelweed: 2,4-D

10. Rush: 2,4-D, glyphosate

11. Sedge: amitrole, dalapon, 2,4-D, glyphosate

12. Smartweed: 2,4-D, diquat

13. Spikerush: diquat

    Application: Should be injected into nonflowing water.

14. Water hyacinth: amitrole, 2,4-D, glyphosate, diquat

    Application: Martin et al. (1957) reported that herbicide treatment has proved so effective on water hyacinth that

mechanical methods formerly used have been largely abandoned. The plant can be killed rather readily by light or moderate dosages of 2,4-D formulations, except where floating mats are so dense that herbicide spray does not penetrate into the lower layers. Diquat may be used instead of 2,4-D when drift is a hazard. Reinfestation may occur years after chemical eradication because seeds may sink to the bottom and remain dormant for years.

15. Waterleaf: 2,4-D

16. Waterplantain: 2,4-D, glyphosate

b. Aquatic Grasses

1. Bristlegrass: bromacil, diuron, dalapon

2. Cutgrass: dalapon

3. Panicum: dalapon

4. Paspalum: bromacil, diuron, dalapon

5. Reed: amitrole, bromacil, dalapon, diuron, glyphosate

   Application: Reeds are vulnerable on terrestrial sites during the growing season or during pollen release, a 3-week period from midsummer to early fall. Control reportedly unsatisfactory on flooded sites.

6. Southern-wildrice: dalapon

c. Shoreline, Ditch, and Upland Plants (including woody species)

1. Buttonbush: 2,4-D

2. Cocklebur: 2,4-D

3. Willow: 2,4-D

4. Most broadleafed bottomland or upland vegetation, woody or herbaceous plants: 2,4-D

Rollings and Warden (1964) presented the following precautions that should be followed when one uses herbicides for wildlife or fishery management:

1. Use only in specific places where an established need exists,

where herbicides can do the job best, and where benefits outweigh potential hazards.

2. Select the safest herbicide that will achieve the desired goal.

3. Treat the smallest possible area needed to accomplish the objective.

4. Spray when any potential hazard to wildlife is lowest.

5. Do not apply at rates higher than those recommended.

6. Use water-based sprays in preference to oil solutions or water-oil emulsions.

7. Read and follow directions on the labels of the herbicide container.

Additional safety precautions for applications were given by Applied Biochemists, Inc. (1976):

1. Avoid contact with skin or clothing; avoid prolonged breathing of vapors.

2. Store herbicides in a locked, cool, dry area in the original container and prevent freezing or excessive heat.

3. Do not reuse empty containers. Dispose of containers and unused material according to safe, prescribed methods.

Linde (1969) noted that the two main types of herbicide sprays used in wildlife management are foliar (or leaf-absorbed) and soil-absorbed (absorbed from soil by plants). Foliar absorbed chemicals include amitrole, dalapon, 2,4-D, diquat, and glyphosate. Their efficiency is improved if the area is partly cleared before treatment. Control of woody growth is enhanced when old growth is removed and new sprouts are sprayed. This produces a maximum kill and reduces chemical costs. Vegetation should be sprayed during the most active stage of plant growth. Herbicides produce the best effects when conditions are optimum for plant growth, during warm, sunny, humid weather (Martin et al. 1957). Water soluble foliar spray should remain on the plants at least 6 h before a rain (Linde 1969).

Atrazine, bromacil, diuron, and simazine are soil-absorbed herbicides. Picloram is a combination soil-absorbed and foliar spray. When using the soil-absorbed chemicals it is desirable that one reduce ground cover by mowing or burning it before application so that as much herbicide as possible is sprayed directly on the ground surface. This increases the speed of kill and the general effectiveness of the chemical. Penetration into the soil is

speeded if treatments are followed by light to moderate rains involving little surface runoff and maximum soil penetration. These herbicides often act slowly; affects on the vegetation may not be noticable for as long as a month after treatment. The results are therefore usually long lasting, and reinvasion of treated areas is usually slow because of residual chemical effects (Linde 1969).

Basal sprays can be used to kill trees or prevent new sprouting from stumps. Linde (1969) noted that a basal spray consisting of 2,4-D in oil was effective. Such application may be made at any time of the year; the stumps or the lower 18 in. of the tree should be completely covered.

Various types of spray equipment can be used for herbicide applications. (Direct water application techniques, including chemical drip systems and water injection, are briefly discussed in Chapter 32.)

There are two general categories of sprayers--hand powered and power-operated. One of the simplest types of equipment is the backpack sprayer, which has a spray tank that is pressurized with a hand pump and an adjustable hand-held gun sprayer. Manual agitation may be necessary when one is using a suspension. Some backpack sprayers include a CO_2 gas pressure system and automatic agitation.

The following various types of power-operated spray equipment, all used for herbicide application, have pumps powered by gasoline engines or power takeoffs; have large supply tanks as part of the sprayer; and have a pressure regulator to control spraying pressures and flows.

1. Boom sprayers are fitted with horizontally mounted tubes with a series of spray nozzles placed at various intervals. These are generally used for agricultural crops.

2. Broadjet or "T" sprayers project a fan-shaped spray on either side of a single cluster of nozzles.

3. Gun sprayers are hand-held sprayers that include an operator-controlled gun with a trigger control valve. These are most efficient where a constant spray is not needed and the operator must have flexible control of spray direction to improve coverage.

4. Mist blowers send out a vapor spray. They are most effective on large areas because the spray usually drifts farther than in other applications.

5. Aerial spraying is done with crop-dusting planes or helicopters, usually by commercial operators. This is the most efficient

application method for large areas.

Users should calibrate their sprayers often because nozzle wear frequently occurs and may result in overapplication of the herbicide and added expense. Spray calibration was discussed by Linde (1969) and Martin et al. (1957).

Thorough flushing of spray equipment is usually sufficient to remove most water soluble chemicals. The herbicide label gives directions for cleaning equipment. When phenoxy herbicides (2,4-D) are used, the same spraying equipment should not be used to apply other herbicides on horticultural or agronomic crops because the residues are difficult to remove. An effective cleaning method for equipment used to spray phenoxy herbicides was described by Burkhalter et al. (1974).

Herbicide uses are based on the level of active ingredients or the acid equivalent of the product. The recommended rate may vary among manufacturers and should be considered when one is preparing herbicide solutions for application. Linde (1969) and Martin et al. (1957) discussed the calculation of application rates, for use when herbicide labels do not provide adequate information.

Several types of chemical formulations are available for herbicide applications. An outline of these types was presented by Burkhalter et al. (1974):

1. Solutions are formed from solid or liquid chemicals that readily dissolve in water. A surfactant (sticker-spreader or speader-activator) may be included in applications of water soluble sprays. The surfactant provides more effective wetting of the waxy outer plant surface and spreads the spray without beading or spotting on the plants.

2. An emulsion is a solution formed by a compound that does not dissolve in the solvent or carrier but is dispersed uniformly throughout it.

3. An oil-based solution is a herbicide dissolved in an oil, such as fuel oil, kerosene, or diesel oil. These solutions easily penetrate vegetation but are extremely volatile and drift readily.

4. A suspension is a mixture of water and chemical powder in which the powder is not dissolved in water but is mixed with it. Continuous agitation is necessary to keep the chemical in suspension.

38.2.2. Mechanical Control

The use of mechanical equipment is a common method of controlling undesirable vegetation, especially on upland sites. A factor limiting the use of such equipment is its inability to operate well on wet marshland areas. Many types of underwater aquatic plant harvesters and cutters that have been developed for submergent weed control are discussed in Chapter 32. Conventional heavy equipment techniques are presented here for upland vegetation removal, and equipment adaptations for mechanical vegetation control in wet marsh areas.

Six principal types of major upland vegetation control techniques were outlined by the U.S. Forest Service (1969):

1. Anchor chaining. Chaining consists of dragging a heavy chain through vegetation to break off or uproot plants. The general procedure is for two tractors, 60 to 100 ft apart and attached to opposite ends of the chain, to travel on a parallel course across the target area.

2. Cabling. Cabling is suited to areas where stands of desirable shrubs and herbaceous cover are to be saved, and where the competing target species are not young and willowy. Cabling is essentially the same process as chaining except that a 150- to 200-foot cable, 1.5 in. in diameter, is used in place of a chain.

3. Hula dozer. The hula dozer is a 100- to 125-horsepower crawler-type tractor with a "hula dozer" blade. The blade consists of hinged pusher bars and hydraulic tilting attachments that tip trees, while the corner of the blade lifts them from the ground.

4. Scalping. Scalping consists of scraping off the plants and top layer of soil from target areas. It is a simple and highly effective method of removing vegetation and removes most weed seeds in surface soils as well.

5. Conventional tillage implements. Where soil and vegetative conditions permit, plowing may be used to eliminate competitive vegetation. Disk-type plows, such as heavy offset disks or wheatland plows, are good for controlling nonsprouting species on soils with relatively few rocks. The brushland plow is best for rough, moderately rocky areas.

6. Manual treatment. Undesirable vegetation can be removed with chain saws and hand tools where heavy equipment is impractical or unavailable.

Timber management techniques may also be used as a vegetation control method to improve wildlife habitat. In areas where harvestable timber is available, commercial logging can be contracted through bids. Selective removal may be desirable to preserve den trees and important mast producers. Small clearcuts are also beneficial because they create openings in the canopy. Wood chipping machines are sometimes used in timber management to replace traditional cutting and hauling equipment (Yoakum et al. 1980). Management problems and wildlife habitat management techniques relating to silvicultural practices on UMRS were discussed by U.S. Army Corps of Engineers, Rock Island District (1981).

Extensive use of equipment in managing marsh vegetation is limited because the equipment cannot operate on muddy or boggy substrates. Specially designed marsh tractors are necessary in many places where conventional equipment is impractical. Marsh vegetation can sometimes be controlled mechanically by dewatering the area and using conventional tillage implements. Large tractors pulling plows, disks, and harrows are practical for controlling persistent marsh weeds. The cutting of vegetation with hay mowers or rotary choppers is feasible on marshes that are not too wet. Crushing with special rollers may be more effective than cutting in controlling marsh plants (Martin et al. 1957).

Nelson and Dietz (1966) described several methods of cattail control used in Utah. A specially adapted tractor, equipped with dual front wheels and special half-tracks on the rear, was able to traverse heavy cattail stands in water up to 12 in. deep. A rotary mower effectively cut cattails except in water more than 1 in. deep. The use of a side mower was not effective. In areas where cut stems could be flooded, the cattails were killed.

Nelson and Dietz (1966) also found crushing to be a rapid and economical method of restricting cattail growth. Although cattail stands were not killed, they were thinned, and areas were opened for waterfowl use and to permit growth of more desirable plants. Annual crushing could keep many areas free of cattails. Cultivation killed cattails satisfactorily, but it was slow and required ideal conditions. Furthermore, a marsh had to be out of production for a year to dry the soil before it could be cultivated.

Linde (1969) reported that the crushing and burning of cattails was ineffective in Wisconsin because heavy resprouting occurred later in the summer; however, he noted several reports that mowing on the ice successfully controlled cattails. This technique was effective only if the water level could later be raised to seal off the dead stubble. An analysis of the effect of mowing on emergent vegetation in Wyoming was presented by Serdiuk (1970). Three years of over-ice mowing reduced the density of stands of cattails and tule bulrushes but increased the density of alkali bulrush. Because substantial regrowth occurred in all situations, Serdiuk did not consider the method to be practical in comparison with herbicides or drawdowns.

Martin et al. (1957) and Uhler (1956) reported that two separate mowings followed by flooding successfully controlled cattails. The first cuttings were made before seed maturity and the second mowings were of regrowth 2 to 3 ft high.

Mechanical vegetation control methods such as those used for cattails may be successful for many other undesirable marsh plants. Martin et al. (1957) discussed the effects of mechanical control methods on several marsh plants, including cutgrass, hibiscus, and reeds.

One method of mechanical aquatic vegetation control involves the use of a "cookie cutter," a device described by M. Abbruzze (personal communication). The cookie cutter consists of a 26-ft aluminum boat powered by a 174-horsepower diesel engine and two 5-cylinder radial hydraulic motors to turn two cutting and propelling blades 48 in. in diameter. The machine is designed to remove vegetation to create open-water areas. It can also be used to cut new channels or to clear existing channels of mud or silt. The machine has been used successfully on all types of floating and submerged aquatic vegetation, as well as on brush up to 2 in. in diameter. Water depth for ideal operation is 18 in. or more. Cutting speed varies with the material being cut and the water depth; top speed is 6 mph.

Burkhalter et al. (1974) noted that "Special dragline buckets are available for removal of hyacinths and other aquatic plants. Draglines are used extensively in canals and drainage ditches where there is a dual problem of siltation and excessive aquatic vegetation."

38.2.3. Biological Control

Biological control methods for vegetation are mostly limited to the reduction of undesirable vegetation by wildlife or livestock. Muskrats may be effective in reducing cattails, bulrushes, or reed beds. The grazing and browsing of rodents, rabbits, deer, or livestock may severely damage upland sites and destroy the succession of vegetation. Overgrazing can result in severe habitat degradation.

The use of insects for vegetation control is still experimental. Although some weeds are plagued by specific parasites, methods for using these control agents for marsh management remain largely undeveloped. Chafflower is the only plant considered here on which insects are commonly used for vegetation control (Burkhalter et al. 1974; Bennett 1974).

Bossenmaier (1964) recommended moderate grazing of marsh edges that have solid stands of tall rank vegetation such as cattails, reeds, bulrushes,

cordgrass, or willows. Trampling and grazing by cattle often open these stands and improve the plant community. Regulated grazing can improve and maintain breeding and nesting habitat for waterfowl.

The effects of muskrats and concentrations of snow geese on coastal marsh vegetation was discussed by Lynch et al. (1947).

38.2.4. Water Level Fluctuation

Water level fluctuation can be used to eliminate undesirable marsh vegetation. Adequate water level control structures must be available if this method is to be used to control vegetation. (Drawdowns, which are advantageous for the control of some marsh weeds, are discussed in Chapter 39.) Flooding is most often combined with previous mechanical or chemical treatments for the control of emergent species. Martin et al. (1957) noted that many kinds of emergent marsh plants can be eliminated by drowning, either as seedlings or at more advanced stages.

Mature stands of reeds cannot be controlled, but their seedlings can be drowned by raising the water level. A 12-in. depth of water during the summer production of runners causes them to float to the surface instead of becoming anchored and thus prevents extension of an established stand. Mowed needle rushes were destroyed by an 8-in. rise in water level held for 3 weeks. Mowed cattails can be controlled most effectively when water covers the cut bases of tall plants. Most stumps of trees and brush lose their ability to sprout if they are covered by water for one growing season. Complete flooding for 12 to 15 days kills cockleburs (Martin et al. 1957).

A permanent rise in water level of 3 ft drowned mature hibiscus in several impoundments. Seedlings of hibiscus can be drowned without destroying seedlings of desirable species such as smartweeds and barnyardgrass. Flooding, following cutting or herbicide application, is frequently helpful in eliminating plants such as rushes, hibiscus, and buttonbush. Many other species that are somewhat tolerant of flooding can be drowned if the depth and duration of submersion are sufficient (Martin et al. 1957).

Harris and Marshall (1963) cited numerous authors who reported that cattails died out of marshes when they were continuously flooded to depths ranging from 1 to 4 ft. In their own investigation, Harris and Marshall found that the common cattail was greatly reduced after 3 years of summer reflooding in 12 to 15 in. of water and was completely eliminated during the fourth year. Hybrid cattails showed little susceptibility to water up to 24 in. deep in 4 years of reflooding. Nelson and Dietz (1966) reported that flooding after herbicidal treatment of cattails helped control regrowth. Linde et al. (1976) reported that deep flooding is of no benefit if the entire bog mat floats up

when water is added.

Two years of summer flooding with over 15 in. of water virtually eliminated softstem bulrushes and spikerush (Harris and Marshall 1963). Sedges and willows died out after 4 years of similar flooding. McDonald (1955) discussed the effects of extensive die-offs of emergent vegetation due to extremely high water. Immediate effects of the die-off were an increase in the amounts of submerged waterfowl food plants, the breakup of large blocks of reed marsh, an increase in the amount of edge between reed marsh and water (important in American coot and gallinule nesting), the formation of expanses of flotage or mud banks above the water level, and a reduction in the amount of muskrat habitat. Later effects included an increase in bulrushes of the reed marsh through establishment by seeding; an increase in glaucous cattail over narrowleaf cattail because of more rapid vegetative reproduction, and a deepening of portions of the marsh by the rising and drifting of masses from the bottom.

38.2.5. Burning

Controlled or prescribed burning is an economical method of vegetation removal that is widely used in wildlife management as a tool for habitat manipulation. Controlled burning may be used to reduce competing plant species during seedbed preparation, to stimulate regeneration of sprouts and seedlings, to create openings in dense vegetation, or to maintain vegetation that is essential wildlife habitat (U.S. Forest Service 1969; Yoakum et al. 1980).

Linde (1969) listed the principal reasons for the use of controlled burning in wetland management:

1. Removes annual "rough" or dead herbaceous cover and thus prevents the buildup of debris on a marsh floor.

2. Reduces the level of a marsh floor where hot fires burn down into the organic soils.

3. Thins out or eliminates woody vegetation in impoundments.

4. Cleans up dead trees and brush in impoundment basins before flooding.

5. Destroys sphagnum moss and brings about a succession of sedges and grasses.

6. Creates nesting areas for waterfowl and prairie grouse by bringing about a succession of grasses and other herbaceous cover.

7. Produces open areas that provide improved spring grazing for waterfowl.

Many of the above reasons are also applicable to upland vegetation management.

A careful study of the vegetative types, soil characteristics, and water levels should be made before one uses prescribed burning to manage habitat. The establishment of fire breaks around the area to be burned should be the first consideration. Established roads, marshes, or water areas can be used as fire control lines if available. Heavy mechanical equipment or hand labor is generally used to establish fire breaks. Large areas can be divided into smaller units; controlled burning is safer when confined to small areas.

Warm, bright days when the humidity is between 25 and 40% are considered best for burning. Burning should not begin until the dew is off the vegetation. Wind speed should be less than 10 mph and wind direction should be steady. Linde (1969) indicated that five to six workers are needed to control an average 300- to 600-acre burn.

Backfires (burning into the wind) are usually used on small burns where hot fires are needed. Headfires (burning with the wind) burn much faster than backfires and are usually used for large burns (Linde 1969).

Burns in late summer or early fall are considered best because all nesting of waterfowl and other birds is completed. Burning in winter or early spring can be successful, except in areas with a heavy snow cover; however, the burn produced at this time of year usually is not as clean as that in late summer or fall. Sparsely vegetated marshes or uplands cannot be effectively burned (Yancey 1964).

Yancey (1964) discussed three major types of marsh burns: cover burns, root burns, and peat burns.

1. Cover burns are fall or winter fires that remove dense, rank vegetation while water levels are at or above ground level. Such burns quickly open marsh areas, but marked changes in the vegetative types seldom occur.

2. Root burns are designed to burn a dry marsh floor, damaging plant roots and usually resulting in significant changes in the plant community.

3. Peat burns involve burning extremely dry marshes growing above a layer of peat. The purpose is to create a series of shallow ponds by burning soil levels down to the water table or to

mineral soil. This should only be done where it is possible to flood the marsh to extinguish the fire.

Hoffpauir (1961) concluded that, to reduce undesirable plant species in a marsh, the water level must be well below the soil level to insure root damage. If a marsh is burned when the soil is wet, the only result is an immediate addition of nutrients to the soil, thus promoting further growth of the undesirable plant species. No lasting benefits are realized.

Fires are classed as being of either low or high intensity, depending on the burning temperature. Low intensity fires are used primarily where protection of woody growths is desired in the burn area. High intensity fires are used to burn through areas of low flammability and to produce a relatively clean burn (Linde 1969).

Several conditions help to keep fire intensity low:

1. High humidity and high moisture content in the plant material.
2. A backfire moving into a strong wind that beats the flames to the ground.
3. A headfire in which a relatively strong wind causes the fire to move so fast that an incomplete burn results.
4. Only sparse vegetation of low stem density and flammability is present.
5. Low air temperatures.

Several factors promote high intensity fires:

1. Low to normal humidities and low moisture content in the plants.
2. Moderately high to high air temperatures.
3. Plant material with high flammability and high stem density.
4. A slow backfire moving into a light wind.
5. A headfire moved by only a light to moderate wind.

On the Delta Marsh of Manitoba, Canada, two types of fire have been used (Ward 1968). Spring fires remove vegetation but do not affect regrowth. Summer burning has a more lasting influence on regrowth. Recurring fires perform a vital role in the marsh ecology by removing dense stands of dead and

decaying vegetation. Spring fires maintain the climax status of reeds. In Nebraska winter burning was successfully used to open reed marshes for summer and fall use by waterfowl (Schlichtemeier 1967). Vogl (1964) noted that burning muskeg marshes in Wisconsin helped to develop a more desirable successional stage of sedge meadows. Fire also improved game habitat by removing old vegetative growth, stimulating new growth, and increasing fruit and seed production.

Kirsch and Kruse (1972) reported that fire can be an important wildlife management tool on prairie areas. Complete nonuse for 20 to 30 years, or annual grazing and haying do not provide the type of habitat desired.

Ruffed grouse and songbirds were attracted to burned sites during the first 30 days after a prescribed spring burn in New York (Euler and Thompson 1978). The high numbers and availability of insects in the burned areas may have increased the attraction.

The Tall Timbers Research Station of Tallahassee, Florida, has published the proceedings of their annual conferences on fire ecology since 1962. These proceedings contain papers on the use of fire for wildlife habitat management. Also included are current papers on the values, procedures, and techniques of planning and implementing prescribed burning (Yoakum et al. 1980). Rutkosky (1978) provided a bibliography with selected abstracts on marsh burning and the effects on mammal and waterfowl utilization.

38.3. IMPACTS ON THE ENVIRONMENT

The general purpose of vegetation control is to improve wildlife habitat. Each method has specific advantages and disadvantages, but overall, the removal of undesirable plants or changing the plant community to benefit wildlife is the major purpose.

38.3.1. Chemical Control

The use of herbicides for vegetation control has many practical applications for improving wildlife habitat. Herbicides can be used to create openings, to clear out or kill undesirable plant species, and to set back vegetation to a more valuable stage of growth. Eabry (1973) provided the following list of the beneficial effects of using herbicides for controlling unwanted vegetation:

1. Individual plants can be treated without affecting others.

2. The concentration of the herbicide can be adjusted to provide

the amount of control desired; low concentrations set back only parts of the plant; high concentrations kill the entire plant or sterilize the soil.

3. Herbicide application is not difficult and requires less manual labor than other control methods.

4. The frequency of treatment required for maintenance is reduced.

5. Maintenance costs are reduced.

Eabry (1973) listed the following adverse effects of using herbicides:

1. Applicators may be exposed to potential health hazards.

2. Adjacent vegetation may be affected by spray drift, spills, soil and water movement, root passage to untreated plants, and possible persistence of herbicidal effects in the soil.

3. Water may be contaminated.

38.3.2. Mechanical Control

Mechanical methods of vegetation control are usually the most costly, but are sometimes the only techniques available or applicable. Eabry (1973) divided mechanical methods into cultivation and cutting tools and listed the effects of each method. For cultivation, the benefits were that large areas can be treated, compacted soils can be aerated and loosened, and nutrients are recycled when vegetation is plowed under; the adverse aspects were the vegetation removal is temporary, weed seeds are released into the soil, deeply rooted plants are difficult to control and woody plants are not destroyed, shallow soils are exposed to frost action and erosion, and most equipment cannot operate over wet boggy substrates. For the use of cutting tools, the benefits were that individual plants can be selected, mowing can reduce large areas of small stems, the regrowth of sprouts creates browse, and competition for light is reduced; the adverse aspects were that treated plants are seldom killed, immediate regrowth occurs because the root system is not affected, and extensive labor is usually required.

38.3.3. Biological Control

Biological methods of vegetation control are limited. Use of vegetation by livestock or wildlife is often inefficient as a control method, partly because undesirable plants are seldom eaten extensively. The greatest adverse effect of this method is overgrazing. If overgrazed, the ecosystem may suffer permanent change due to soil erosion, habitat and food destruction, and

replacement by undesirable invading species.

Insects and disease might be effective if beneficial plants are not also affected. Once these control agents are established, they cannot be controlled. Adverse effects can include complete destruction of a plant species, even though small amounts may be beneficial for wildlife.

38.3.4. Water Level Fluctuation

Water level control methods can change vegetative types in specific areas. Fluctuating water levels may facilitate the growth of beneficial plants while drowning out undesirable vegetation. However, water levels that are too high or held too long can damage valuable vegetation.

38.3.5. Burning

Controlled surface fires that do not destroy the humus and top soil often produce marked benefits for certain animal species, especially white-tailed deer (Dills 1970). Burning enhances browse production by stimulating sprouting by understory plants and by providing more light for growth. Burns increase the food supply and cover for deer. Only a slight nutritional improvement in the plant species occurs after controlled burning. Information on increased nutritional value of some plants was provided by Linde (1969).

Soil temperatures and the nutrient content of soils and water increase as a result of ash deposition (Hoffpauir 1961). Cover burns accelerate food production by removing canopy vegetation, increase the availability of food, provide future fire protection, and allow access for trapping (Lynch 1941). Root burns kill off climax vegetation and allow a lower successional stage of vegetation to appear. Dry burns are destructive to almost all marsh animals ls (except birds), but most areas of rank, dense vegetation contain little wildlife (Lynch 1941). Fire, by itself, may be an ineffective control for marsh weeds because it may encourage undesirable species by removing the excessive shading that keeps their growth under control (Martin et al. 1957). Spring burning does not change established cattail associations, but effectively removes accumulated dead material and encourages new growth (Bednarik 1972).

Waterfowl nest destruction by fire in the spring causes serious loss of production. Removal of high marsh vegetation by burning reduces the ability of a marsh to catch drifting snow that may be needed in areas of low precipitation (Cartwright 1942; Ward 1968). Peat fires may expose the underlying clay pan (Hoffpauier 1968) and indirectly result in turbidity in ponds that prevents the establishment and growth of aquatic vegetation. Burning should be avoided in areas where erosion is a problem, unless a dense

and more protective plant cover is regenerated (Yancey 1964). Uncontrolled wildfires can result in unwanted destruction of vegetation and valuable habitat, as well as private property.

38.4. COSTS

Costs of herbicides may be obtained from local chemical supply dealers. Prices vary, depending on brand names, concentrations, and amounts required. The type of control desired and size of the project affect the cost per acre. The application of herbicides is the most economical and effective method of controlling most plant species. See Chapter 32 for cost details on the use of 2,4-D, diquat, and simazine for aquatic plant control.

Costs of using 2,4-D for woody plant control in Wisconsin varied with the type of woody growth treated. In 1968, costs per acre were $5.57 for aerial spraying, $3.00 for ground application with a boom sprayer, $2.15 for T-jet spraying, and $1.98 for a application with a mist blower (Linde 1969).

Mechanical control is generally the most expensive vegetation control method. The costs of equipment, operating expenses, and labor are usually high. Linde (1969) reported that the average cost of land breaking with plows was $10.81 per acre. In the late 1960's, the average cost of clearing woody vegetation was $96 per acre by hand and $31 per acre when heavy equipment was used. Upland clearing costs may be reduced if contractors are allowed to remove marketable timber. The U.S. Army Corps of Engineers, Rock Island District (1981) noted costs of various forestry practices along UMRS. Linde (1969) placed the costs (in 1962) of crushing cattails and subsequent burning at $6.13 per acre. Representative costs of cattail control in Utah in the mid-1960's ranged from $3.33 to $10 per acre (Table 25). The rental rate for a cookie cutter, which includes two operators and all necessary fuel and operating supplies is $150 per hour (M. Abbruzze, personal communication).

We found no costs for biological vegetation control in the literature. Wildlife use of vegetation has no direct costs, and livestock grazing should provide monetary benefits rather than costs because of the forage value. Fencing and transportation are the only costs relating to livestock use. No information is available on the cost of using insect or disease control methods.

The use of water level management for vegetation control involves the initial costs of water level control structures, expenses involved in maintenance, and costs of obtaining a water source. (The costs of these developments are discussed in Chapter 39.)

Table 25. Costs of various cattail control methods in Utah in the mid-1960's (from Nelson and Dietz 1966).

Control method	Acres treated per hour	Cost per hour	Cost per acre
Rotary cutting[a]	1.5	$ 5	$ 3.33
Side-cut mowing	.75	5	6.66
Crushing	3.0	5	1.66
Disking	.50	5	10.00
Tilling	.50	5	10.00
Dalapon (aerial spray)	20.00	115[b]	5.75

[a]Amounts given apply to costs per cutting; two cuttings per season were often required.
[b]Includes plane rental of $35 per hour and cost of 20 lb of dalapon per acre at $0.20 per pound. Costs shown are for a single cutting. In many situations, two cuttings per year are required.

Burning costs depend on many variables, but usually the larger the area burned, the cheaper the cost per acre (Linde 1969). Some areas may require extensive firebreaks and precautionary measures that results in increased costs. Burning costs in Wisconsin ranged from $0.05 to $4.58 per acre (Linde 1969). Costs of burning on the Mead Wildlife Area, Wisconsin, ranged from $0.05 to $1.06 per acre (Table 26).

38.5. EVALUATION FOR USE ON UMRS

Vegetation control can be used to improve wildlife habitat on many areas of UMRS. Dense marsh vegetation dominates many local areas, leaving little open water and few valuable food plants. Many upland sites are overgrown with a monotypic plant association of little value to wildlife. Dense brushy sites could be cleared to establish herbaceous cover for nesting habitat.

Chemical methods of vegetation control have valuable application on UMRS, especially in areas where other methods cannot be used and where economics is a consideration. In many situations, herbicides may be the only effective control method. In others, herbicides can be used in conjunction with other controls.

Mechanical control methods have high potential for use on UMRS, especially on upland sites where monotypic forest and brush stands could be improved by clearing or thinning. The control of marsh vegetation with heavy

Table 26. Controlled burning costs for areas of various sizes on the Mead Wildlife Area, Wisconsin, April 1961 and 1962[a] (from Linde 1969).

Area burned (acres)	Cost per acre
450	$0.36
920	0.05
815	0.14
235	0.41
100	0.30
155	0.35
110	0.16
650	0.28
35	0.48
250	0.51
275	0.49
700	0.21
50	1.06
75	0.62
500	0.59
360	0.32
Average 355	$0.40

[a]No expensive fire controls were needed on this area, but costs include firebreaks and fire protection help when needed. Burns were in spring, when the ground was still frozen.

equipment will be limited in most places except for the possible use of mowers over the ice and the use of cookie cutters. Mechanical methods, however, are usually the most costly of all control methods.

With regard to timber management on UMRS, the U.S. Army Corps of Engineers, Rock Island District (1981) noted the following management observations:

> Installation of the locks, dams, and levees on UMRS in the 1940's raised the groundwater level. As a result, a moister soil regime has developed that favors silver maple and other water-tolerant species. In contrast, only the areas directly below the locks and dams retain some resemblance to the communities present before the locks and dams were installed. Unless land elevation can be increased, little can be done to resolve the problem of increased soil moisture. Increased moisture has made it difficult to regenerate stands of natural oak, pecan hickory, and hickory. Good forestry practices should be developed and implemented to aid

regeneration. Methods that can be used include harvest cuts, planting, timber stand improvement, and thinning to aid species reestablishment. Such procedures will also help maintain and improve sources of food for wildlife that live in or use the bottomland forests.

Biological control has only limited applicability on UMRS. Livestock grazing does not occur and most areas are not available or suitable for such use. Muskrat populations do not become high enough to heavily affect vegetation. Other methods of biological control have not been developed.

Water level management could be effectively applied in areas of UMRS where adequate control structures exist, and can be used to increase the effectiveness of other techniques. Water levels that are held too high or too long may damage valuable vegetation.

Burning has significant potential for use in improving wildlife habitat on UMRS. Fire can be used to clear out dense, rank vegetation, to stimulate new growth, and to increase browse and valuable food plants. Many upland areas are on islands or have existing natural firebreaks that reduce preparation costs. Destruction of bird nests or desirable vegetation are potential negative effects of burning.

CHAPTER 39. WATER LEVEL CONTROL

39.1. SITUATION TO BE MITIGATED OR ENHANCED

Natural or man-induced water level fluctuations or the lack thereof have directly effect the vegetative communities and wildlife fauna of wetlands. Flood control and navigation are the major reasons for specific water level control on large river systems. Unfortunately, the water level control needed for these uses is often detrimental to wildlife habitat.

Marsh habitats and their use by wildlife can be drastically altered through manipulation of the water level. Population levels of wildlife species occupying wetlands reflect the quality and quantity of the habitat available (Chabreck 1976). Man-caused alterations that prevent water level fluctuations have caused habitat conditions to deteriorate and wildlife populations to decline in many areas. Stability is neither common nor beneficial to most wetland systems (Weller 1978).

Water level management has three requirements: (1) adequate water sources, (2) control structures to permit manipulation of water levels, and (3) a properly designed impoundment system to retain water levels. We discuss here the various water control structures and drawdown techniques that are commonly used for wetland creation or improvement. The discussion is divided into three major sections: dikes and levees, spillways and water level control structures, and drawdowns. Planning and construction of water control structures usually require the advice and technical assistance of engineers and soil scientists.

39.2. DESCRIPTION OF TECHNIQUES

39.2.1. Dikes and Levees

In this discussion, dikes and levees are considered to be earthen embankments constructed to impound water over flat areas to create or improve a wetland habitat. Dikes are limited here to structures commonly used for wetland development that involve low heads of water and fills no higher than about 10 ft. Larger embankments require extensive soil studies and professional engineering design. More detailed and complete information on the design of dikes and levees was given by Foreman (1979).

We do not discuss planning and construction guidelines for small reservoirs built for the primary purpose of retaining water for wildlife because the availability of water for wildlife is not a problem in large river systems. Information on such construction was given by the U.S. Forest Service

(1969), the U.S. Soil Conservation Service (1979), and Yoakum et al. (1980).

The Atlantic Waterfowl Council (1972) listed three types of levees used for water retention:

1. Simple embankments (Fig. 61) are made of homogenous fill material. They are generally constructed on wetland areas where on-the-site soils must be used. They involve the lowest construction costs and are often the only feasible type of embankment.

2. Core-type embankments (Fig. 61) are constructed of relatively impervious soils as a core and an outer cover layer of more pervious on-the-site soils. A core trench, 3 to 4 ft wide, is dug into solid organic soil with a dragline, backhoe, or trencher, or by blasting (Linde 1969). The trench is filled with clay or other impervious mineral soils to prevent seepage through the dike. Cores are required in any situation where on-the-site soils are so porous that stability of the embankment is questionable. Core-type dikes are seldom used on low-head fills unless impervious soils are readily available on site.

3. Diaphragm embankments (Fig. 61) have thin concrete, steel, or wood upright sections in the center of the dike to form a barrier to percolation by water.

Several site-selection criteria were listed by Foreman (1979):

1. Use soils that will provide the best foundation and embankment materials.

2. Use the most economical length that will impound the largest usable area.

3. Avoid areas with high channel velocities or that will provide long reaches of open water. When dikes are exposed to potential erosive factors, use protective riprap or other material (described in Chapter 4).

4. Use natural vegetation for protection against wave action as much as possible.

Various design criteria were recommended by the Atlantic Waterfowl Council (1972) for earthen embankments:

1. The spillway capacity must be adequate to pass the expected maximum flow.

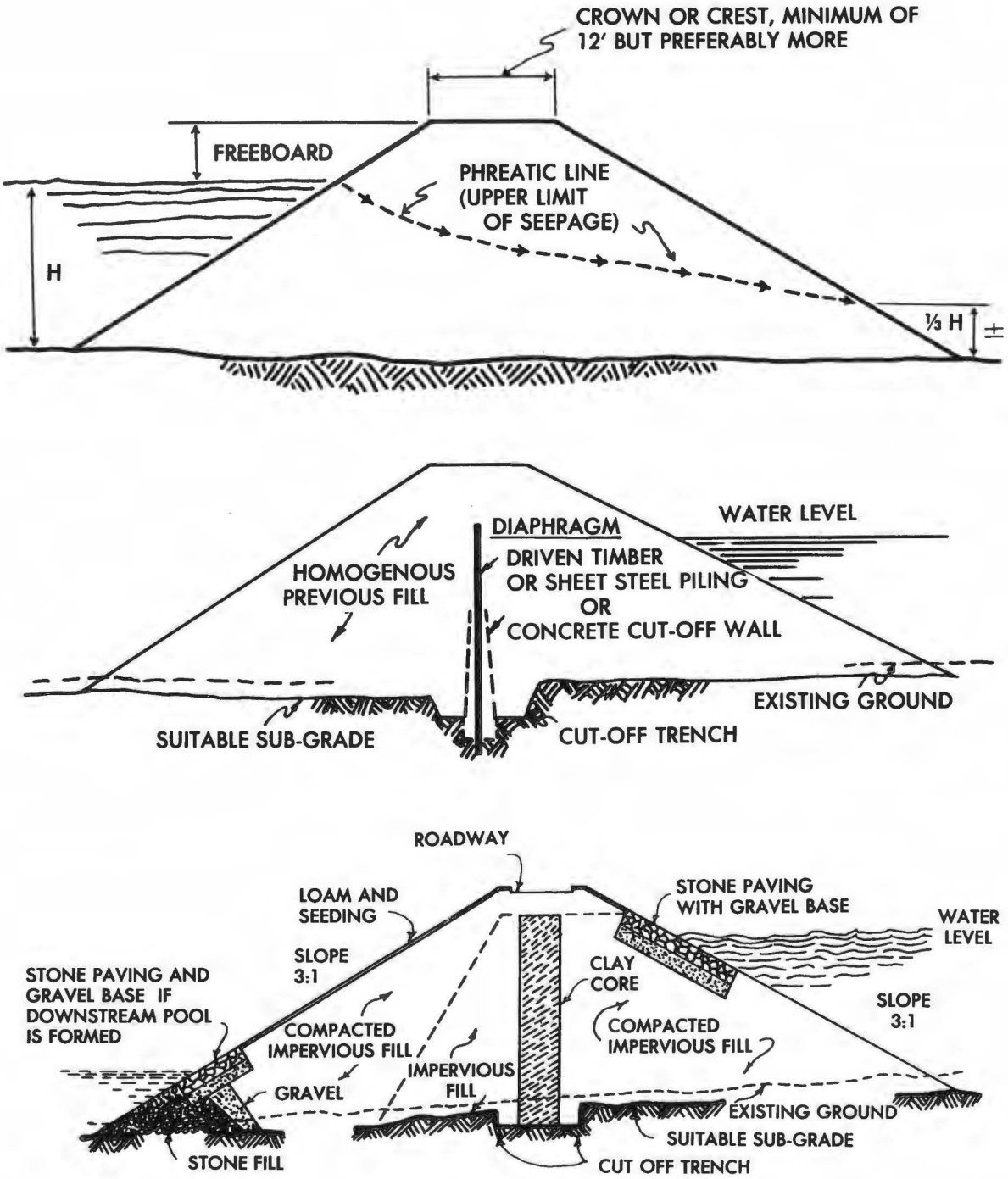


Fig. 61. Typical levees used for water retention: homogenous fill embankment (upper panel), clay core embankment (center panel), and diaphragm embankment (lower panel) (Yoakum et al. 1980).

2. Height of the dike must be related to contours of the area to be impounded (Linde 1969). High dikes are required to flood deep, narrow basins. The height should include enough freeboard to prevent overtopping by wave action at maximum high water levels. When low dikes are built for shallow, temporary impoundments, cost-benefit analyses should be made to determine if it is economically feasible to construct dikes high enough to prevent overtopping.

3. The foundation should be wide enough and stable enough to support the load imposed by the embankment. Most foundation soils are stable enough, but unstable or porous soils require precautionary measures such as soil removal and replacement, and rows of sheet piling.

4. The impervious qualities and compaction of levee material affect the seepage of water through the embankment. Loss of water is not dangerous if the supply retained in the impoundment is sufficient for operational needs and the seepage of water does not cause breaching of the levee.

Common methods of dike construction require the use of heavy equipment such as draglines, bulldozers, and scrapers. Before actual construction, the site must be cleared of large rocks, stumps, trees, and debris; otherwise seepage and washouts may occur in the area of these foreign materials (Linde 1969). In construction with draglines or bulldozers, on-the-site material next to the planned embankment is used. If scrapers are used, more suitable soil can be hauled in from outside the impoundment basin or removed from higher elevations within the project area. When fill is hauled in by truck, bulldozers can be used to shape and compact the dike. Levees constructed with draglines usually require drying before other heavy equipment is used. A sheepsfoot roller can be used for compaction, except on saturated soils. Dragline construction is often necessary in peat marshes because the soil is usually too wet for bulldozer work. Generally, dike fill is applied in layers 6 to 12 in. thick and compacted as construction proceeds (Linde 1969).

In another method of dike construction, dredged material is used (Fig. 60). The material, generally sand, is deposited with hydraulic pumps, draglines, clamshells, or trucks. The dikes are then reshaped with a dragline or bulldozer (if necessary) after they have settling and dried. Further information on dikes is given in Chapter 36 and more detailed information about the construction of dikes with dredged material was given by Hammer and Blackburn (1977) and the U.S. Army Engineer Waterways Experiment Station (1978).

Impervious mineral soils are superior to organic soils for dike construction (Linde 1969). Foreman (1979) provided information on the permeability and suitability of various soil types for dike construction.

Linde (1969) noted that soils high in clay produce a firm dike that is much less susceptible to most forms of damage, including muskrat tunneling. Soil may be brought in from high elevation areas if unavailable on-the-site. If only small volumes of mineral soil are available, that soil should be placed in the core, and the poorer soils on the sides, with the poorest soil type on the downstream side. Organic soils can be used to prepare the top surface for seeding and to prevent clay dikes from drying out and cracking (Linde 1969). Peat soils can be used for impoundment levees where no mineral fill is available or its cost is prohibitive, but such levees are inferior and usually have high maintenance costs due to muskrat damage.

During construction, dikes must be overbuilt in height to allow for settling. Foreman (1979) noted that the required settlement allowances depend on the soil materials used in the fill and foundation, the method of construction, and the moisture content of the soil. He recommended the following minimum settlement allowances: 5% if construction included compaction with heavy equipment; 10% for dumped and shaped fill; 20% for dragline construction; and 40% for highly organic soils. Dry, plastic soils that become unstable when wet and nonplastic soils that slump excessively require special treatment. Dikes on soft foundations require continuous maintenance to restore the settled fill to the required height (Foreman 1979).

Mineral soil dikes designed to control water depths of 6 ft or less should have a minimum top width of 6-8 ft for short sections blocking deep water (Foreman 1979). Foreman recommended a minimum top width of 8 ft for dikes composed of organic soil. A dike that serves as a roadway for maintenance vehicles should be at least 10 ft wide for single-lane travel and 20 ft wide for two-lane travel (Linde 1969). It is not necessary to surface the dike top for light traffic, but the area should be stabilized with grass to prevent erosion of the surface layers. If traffic is heavier, the amount of traffic and the type of vehicles using the road will determine the nature and amount of surfacing material required.

The Atlantic Waterfowl Council (1972) recommended a 3.5:1 or 4:1 slope (i.e., a slope with a drop of 3.5 or 4 ft for every 4 ft measured laterally) as the minimum because tractor mowing equipment usually cannot operate safely on steeper slopes. Slopes ranging from 1:1 to 4:1 have been used in Wisconsin (Linde 1969). The 1:1 slopes were used mostly on low dikes at small construction sites; they would not be adequate on high dikes. Linde noted that gently sloping dikes are the most desirable, but they cost more because they require more fill.

If borrow (borrow ditch, pit, or channel) is excavated parallel to the dike, the berm that separates the dike from the borrow ditch should be wide enough to effectively protect the toe of the dike (Foreman 1979). A greater base width and a wide berm between the borrow ditch and the dike help reduce muskrat damage where this is a problem (Linde 1969).

The size of the borrow ditch and its depth are governed by the quantity of material needed for the embankment, the type of earth moving equipment available, and the location of suitable soils (Atlantic Waterfowl Council 1972). Sides of the borrow pit should be sloped to reduce erosion. The borrow ditch can be located inside the area to be impounded by the dike if the head of water is to be low. The borrow ditch should be interrupted at intervals to slow the velocity of water moving along the toe of the dike (Foreman 1979). When high heads of water are to be held, it is best to locate the borrow ditch outside the dike. Foreman (1979) and the Atlantic Waterfowl Council (1972) provided detailed information about berms and borrow ditches.

39.2.2. Spillways and Water Level Control Structures

Spillways are included in major wetland developments to release surplus water or floodwater that cannot be contained in the impoundment basin without damaging the levee (Yoakum et al. 1980). A secondary purpose of spillways is to maintain the water level in the face of changing flows for proper management of the wetland impoundment. Desired management of the impoundment influences the spillway design required.

Impoundments are often designed with a principal spillway and an emergency spillway. The principal spillway is a permanent structure designed for normal flood protection and water level manipulation. The purpose of the reservoir and the spillway design dictate the discharge capacity. Only a small percentage of the peak flow is discharged if the impoundment is used for retarding flood flow. The principal spillway should be designed to discharge the runoff for the maximum storm for which the impoundment is designed at locations where an emergency spillway is not feasible (Renfro 1979). Emergency spillways (discussed later) provide a safe relief route when abnormally high flood volumes develop.

The spillway designs described here were compiled from various sources, including Atlantic Waterfowl Council (1972), Beauchamp (1979), Linde (1969), Renfro (1979), and Yoakum et al. (1980). The Engineering Field Manual for Conservation Practices (U.S. Soil Conservation Service 1979) provides one of the most detailed discussions of structures available for water level control.

The free overfall or straight drop spillway is a low-head weir structure suitable for large, shallow impoundments. Flow passes through the weir opening, drops to a nearly level apron or stilling basin, and then passes into the downstream channel (Beauchamp 1979). Reinforced concrete, rock masonry, concrete blocks, steel sheet piling, timber, and prefabricated metal are acceptable construction materials. The Atlantic Waterfowl Council (1972) found that reinforced concrete was more satisfactory (despite its higher cost) than log cribbing or sheet piling because maintenance costs were lower and longevity of the structure was greater. The design usually involves aprons

and cutoff walls to prevent side-cutting. Sheet piling is often used at sites where the foundation is poor and the ground is extremely wet, but the piling requires special equipment to drive it into place (Beauchamp 1979). Drop spillways can be modified with gates or stoplogs to allow water level manipulation (Fig. 62).

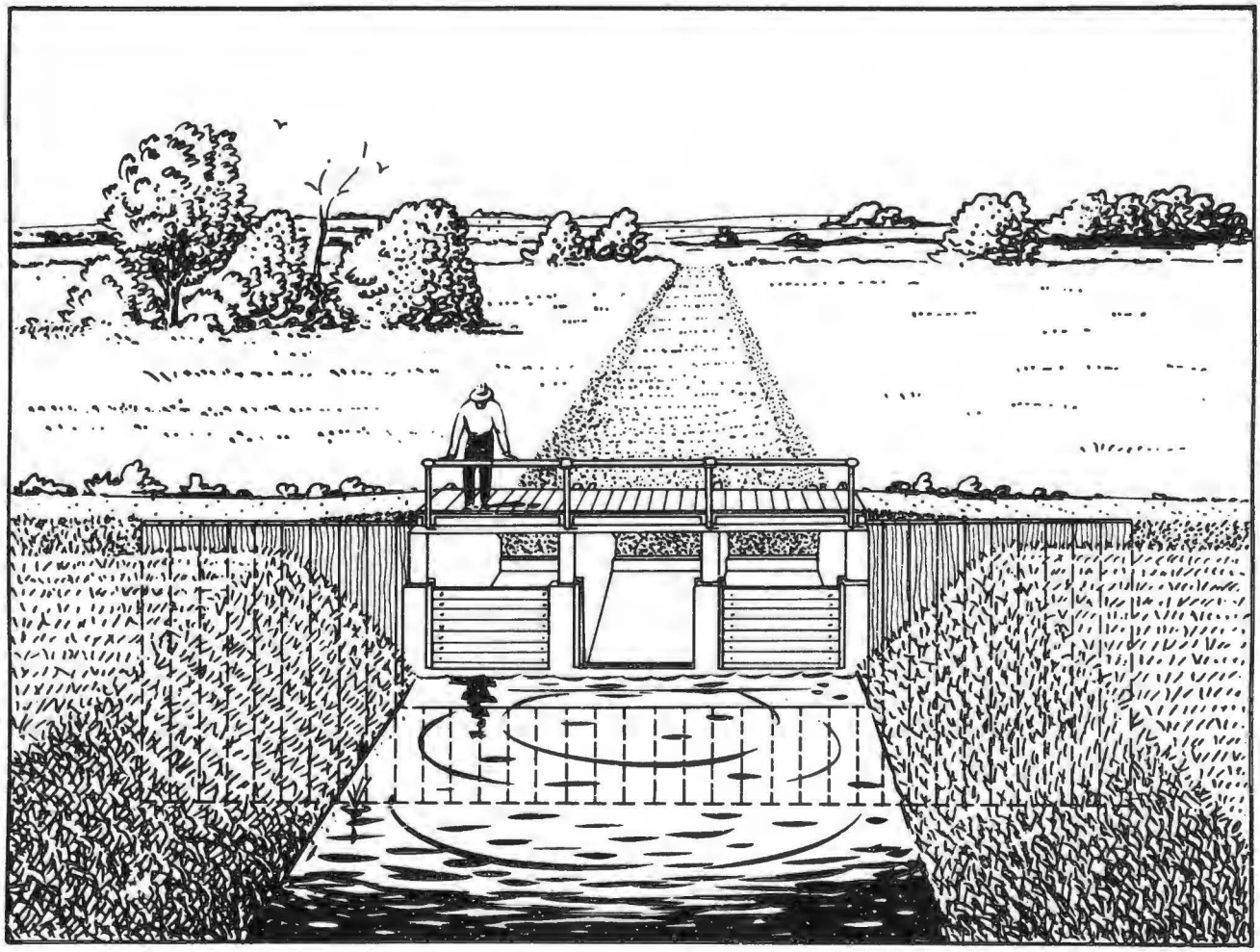


Fig. 62. Straight drop spillway water control structure in which stoplogs and sheet piling were used (Beauchamp 1979).

The ogee spillway delivers the flow over a curved crest and along a reinforced concrete weir that is S-shaped in profile (Fig. 63). This spillway attains near-maximum discharge efficiency and can be modified to include water level control features.

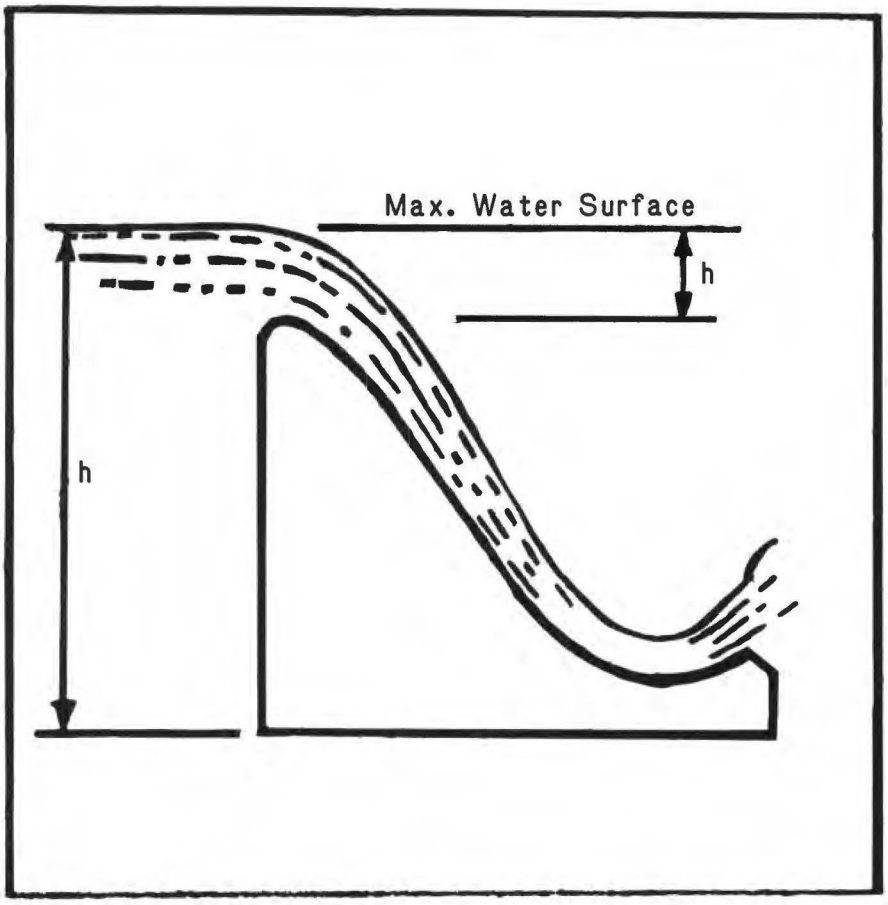


Fig. 63. Profile of an ogee spillway (Atlantic Waterfowl Council 1972).

Natural spillways deliver runoff over undisturbed ground or grassed runways. This type of structure is seldom used as a principal spillway because the runoff capacity, soil type, and vegetative cover are rarely all suitable. Natural spillways provide flexibility in water level control.

Log cribs are limited to sites where permanent structures are too costly. Generally, log spillway construction consists of toe piling driven on the upstream face of a bed log to create a spillway having a maximum incline of 30° (Atlantic Waterfowl Council 1972). Logs used should be stripped of bark unless they will be completely submerged. They should be of uniform taper and naturally resistant or treated. Log cribs can be modified to include stoplog sections but the maintenance costs are high.

Stoplog structures are planks placed horizontally in grooved recesses in supporting piers. They add flexibility to ungated systems, allow flexible water level control, and are often incorporated into other spillway designs. Stoplog dams are considered undesirable as the sole control device for large impoundments because stoplogs are difficult to remove under heavy water pressure and do not allow precise water control (Linde 1969).

Three designs of gate spillways are available--radial, roller, and sliding. Gate structures are often used on large impoundments with concrete base structures. They usually require engineering design and construction. The gate structure spans horizontally in guide grooves between supporting piers. Radial gates are large steel gates mounted on control arms, the outer ends of which are pivoted in their mounting on the structure. Sliding gates are heavy steel gates and are raised or lowered by an overhead hoist device. Roller gates are sliding gates equipped with rollers that bear between the gate surface and its track. This design avoids the heavy lifting pressures of ordinary sliding gates. Gate spillways provide water level control with almost unlimited flexibility. Although they involve higher costs than most other spillways, they are the best type for impoundments that require frequent drawdowns (Atlantic Waterfowl Council 1972; Linde 1969).

An overflow pipe or culvert is a horizontal tube placed with the lower edge at the height of the desired impoundment water level, so that any water higher than that level flows out through the tube (Fig. 64). The inlet opening should be placed vertically or inclined upstream (Atlantic Waterfowl Council 1972). The pipe should be set with a uniform grade profile and be large enough to accommodate the expected overflow. This design has no flexibility in water level control unless a gate valve is used. The volume of water passing through it does not increase when head is increased.

A capped or gated tube is a single, low tube capped or plugged on the impoundment side. The structure is best for use in shallow impoundments because heavy pressure in deep water makes the plug difficult to remove. Gated tubes allow easy draining of an impoundment and operate best with overflow tubes (Fig. 64).

Drop inlet spillways involve a vertical tube positioned at the desired water level. Any influx of water that causes the full level of the impoundment to be exceeded flows into the tube and is discharged through a horizontal pipe or culvert through the dike. This design allows no water level manipulation. A modified form consists of a vertical tube or riser made from half a culvert, open along its length, and fitted with channels for stoplogs (Linde 1969). The riser is attached to a horizontal culvert through the dike (Fig. 65). This arrangement allows water level manipulation and complete drainage by adjusting the stoplog height, but permits the discharge of top water only.

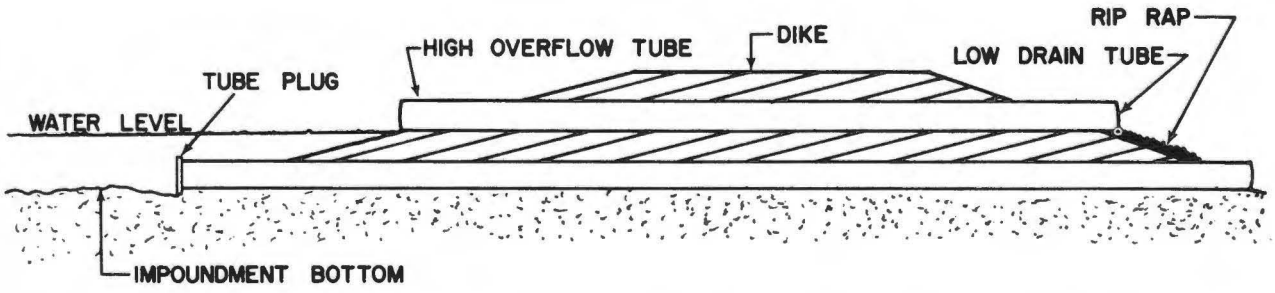


Fig. 64. Combination of an overflow tube and gated tube in a dike for water level control (Linde 1969).

A tin whistle (Fig. 66) is a vertical riser tube located in the dike, connected with horizontal intake and discharge tubes (Linde 1969). Stoplogs separate the intake (impoundment side) and discharge openings at the bottom, forcing the water to rise and spill over the stoplogs. Water levels can be regulated and the water can be completely drained if the tube is set low enough. This design provides discharge of bottom water. Such discharge can improve water quality of the impoundment by releasing deep, possibly oxygen-deficient water, and at the same time discharge nutrients to the area below the dam (Linde 1969).

An emergency spillway is an earth or a vegetated-earth channel, usually designed to discharge flows that exceed the capacity of the principal spillway (Renfro 1979). The emergency spillway must discharge the peak overflow at a safe point well away from the dam, at a nonerosive velocity. Emergency earth spillways should have the capacity to discharge the peak flow from the watershed resulting from the most severe flood expected to occur during a 25-year period (Renfro 1979). Earthen spillways are usually excavated, but may exist as well-vegetated natural draws, saddles, or drainageways. Renfro detailed the design, layout, and construction of emergency spillways. Emergency spillways are not required if the impoundment is completely surrounded by a dike and has no runoff discharging into it.

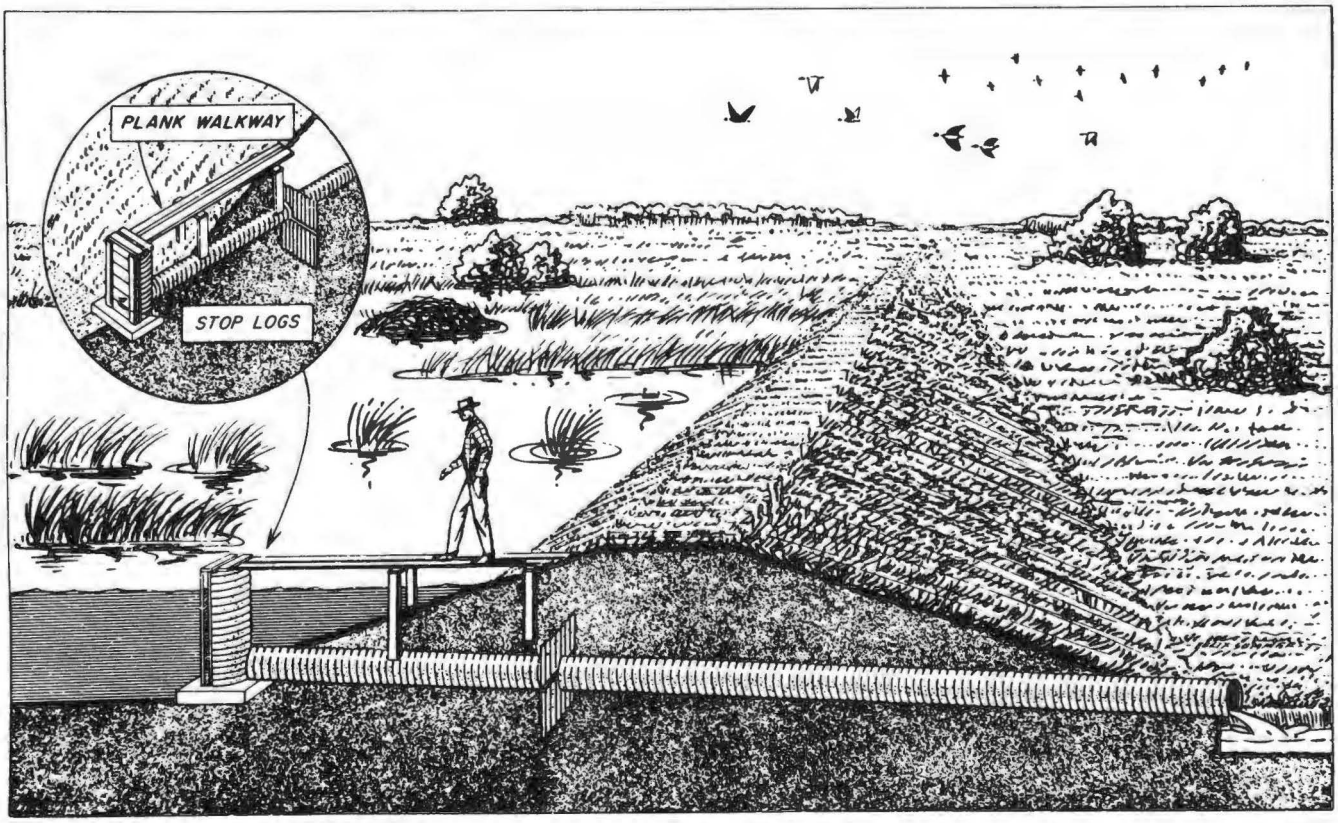


Fig. 65. Modified drop inlet spillway in which a half-section of pipe riser with stoplogs was used (Beauchamp 1979).

Linde (1969) discussed the variety of materials used for construction of spillways of different designs. Most tubes are built with corrugated, asphalt-coated steel culverts. Aluminum culverts have been used, but they are more expensive than steel and may bend during installation. The advantages of aluminum are its light weight, ease of handling, and nonrusting quality (although it may be dissolved by corrosive chemicals in the water). Wooden risers constructed with creosoted or pressure-treated lumber are generally

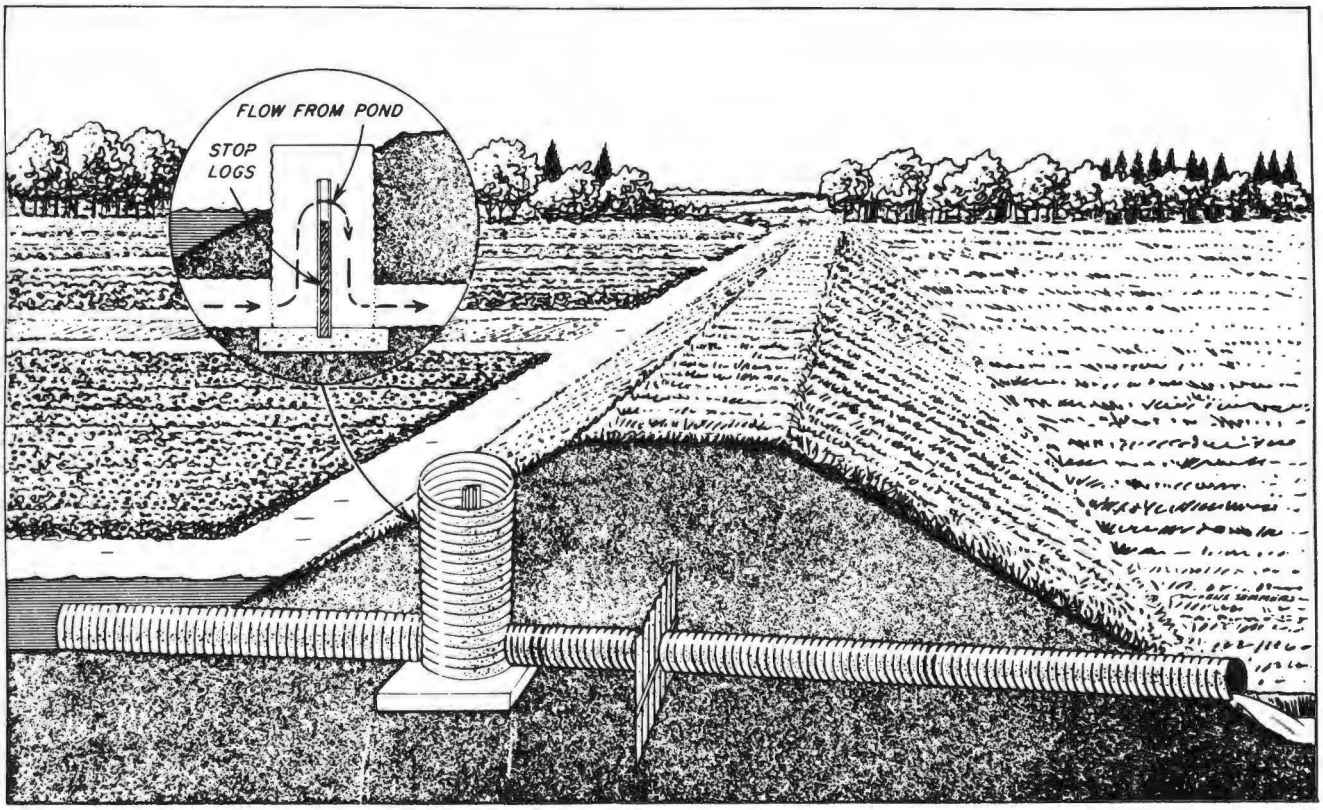


Fig. 66. Tin whistle spillway with a vertical riser tube that is connected to a horizontal intake and discharge tube. Stoplogs in the vertical tube force water from the impoundment to rise and spill over the stoplogs (Beauchamp 1979).

long-lasting, rigid, and inexpensive. Metal culverts are usually inserted into the wooden riser boxes. Concrete boxes are much more expensive and risers constructed with creosoted or pressure-treated lumber are generally difficult to install in spillways.

Pressure-treated lumber provides the most economical stoplogs because it

withstands the severe stresses from water pressure; however, untreated lumber can also be used (Linde 1969). The size or thickness of the stoplogs needed varies with their length and the head of water to which they will be subjected. Specific features of stoplogs were discussed by Linde (1969).

Anti-seep collars must be used to prevent washouts from side leakage around pipes. These collars are flat metal plates or fins that are clamped or welded to the tube to act as a vertical barrier to any horizontal flow of water within the levee (Linde 1969). When concrete pipe is used, the collars can be concrete slabs poured around the pipe.

Inasmuch as stream diversions and rainfall are unreliable sources of water, pumping is a viable option often used to flood an impoundment. High contour areas within an impoundment may require the construction of subimpoundments to flood the higher ground and still maintain desired water levels in the lower main pool. If the water is supplied from lower ground, pumping is the only method that can be used to fill the subimpoundments.

In selecting a pump, consideration should be given to required capacity, total lift, diameter of the well, location of the well, and the type of power available (Griswold 1979). Pump engineers should be consulted before pumps are installed. Linde (1969) discussed four types of pumps that are suitable for the high capacity pumping needed in wetland management:

1. Propeller pumps are best for high capacity pumping, where heads seldom exceed 10 ft. These pumps have low operating costs, and flows can be reversed to allow for drainage (Atlantic Waterfowl Council 1972).

2. Centrifugal pumps are high head, high pressure types commonly used where lifts exceed 12 ft. This design is best for continuous operation and low suction at specific speeds. Centrifugal pumps deliver more water through smaller pipes than do pumps of other designs, but operating costs are high where large volumes of water are moved (Atlantic Waterfowl Council 1972).

3. The mixed-flow pump is a hybrid of propeller and centrifugal pumps that operates efficiently against high heads.

4. Turbine pumps are used in wells where high pumping heads are involved. They are designed to operate at constant, specific speeds for use in wells 30 to 100 ft deep (Atlantic Waterfowl Council 1972).

The use of portable pumps in which outboard motors are used as power units was discussed by Linde (1969). These high capacity pumps are practical

for flooding or draining small impoundments and have the advantage of portability.

The volume of water and range in lift required govern the maximum size of the power unit (Atlantic Waterfowl Council 1972). Electric motors and internal combustion engines are the primary power units for pumps. Electricity is the most satisfactory source of power for irrigation pumping when it is available at reasonable rates. Advantages of electric power are the low cost of electric motors, their reliability, high efficiency, and low cost of upkeep (Griswold 1979). A disadvantage is the fixed location of electrically powered pumps.

Plugs are usually recommended for marshes where diking is not a feasible management tool, because of unsuitable physical conditions of the area (i.e., size, location, water, or terrain) or for economic reasons (Yoakum et al. 1980). Their purpose is to increase the water area of a marsh or prevent severe water level fluctuations. The Atlantic Waterfowl Council (1972) described three types of plugs:

1. Nonspilling earth plugs are similar to dams or dikes, except that the construction is done to block a small creek or flowage to increase the water level in the upstream floodplain.

2. Nonspilling wooden plugs are similar to earthen plugs except that a creosoted lumber structure is used to impound the drainage. Whether earthen or wooden plugs are used, measures must be taken to prevent undercutting or erosion around the ends.

3. Spilling gut plugs are wooden structures that are inundated by high tides but retain water after the tides recede.

Maintenance costs for water control structures will rise if initial construction costs are cut by increasing dike slopes, by installing only the minimum spillways required, or by providing only minimum erosion protection. Maintenance can be reduced by proper construction that includes the use of high quality materials and recommended slopes and erosion protection, and provides a dike wide enough to support traffic of maintenance vehicles. If settlement is excessive because composition was insufficient or unstable soils were used, maintenance refilling of the embankment will be required. Dikes should be mowed periodically (but only after the waterfowl nesting season) to suppress undesirable weeds and woody growths. Maintenance work on dike structures should be done during drawdown periods. Floating debris must frequently be cleared from spillway structures. A floating log boom can be effective for protecting large structures from debris. Frequent inspection and regular minor maintenance will prevent most major problems. The Atlantic Waterfowl Council (1972) provided a tentative maintenance schedule for levees.

Muskrat damage to dikes is common in impoundments, usually from burrowing and den construction and from plugging overflow structures. Beavers cause similar problems. Dens and burrows cave in, cause sloughing and leakage in the dike, and necessitate filling with sand, rock, peat, or gravel (Linde 1969). Linde noted that barriers made of sheet piling, chicken wire, or asbestos cement sheets, and placed in the center of the embankment, eliminate most further damage. However, the addition of such barriers may be more costly than the repeated filling of holes. Rock riprap placed from a point below the normal low water level to a point above the high water level can help prevent muskrat damage. Muskrat burrows can be sealed by compaction or blasting. Carbide pellets inserted into tunnels and sealed off produce acetylene gas that effectively controls muskrat activity. Trapping is not often effective because muskrats from other areas move in as the problem animals are removed. Problem beavers can usually be controlled by trapping. Unless muskrats are used as a fur crop or for the control of emergent vegetation, efforts should be made to eliminate them from the impoundment area (Atlantic Waterfowl Council 1972). Mineral fill dikes are least susceptible to muskrat damage, and peat dikes are the most susceptible (Linde 1969).

39.2.3. Drawdowns

Planned drawdowns of normal water levels can be efficient and productive measures in marsh management, provided that an adequate control structure and a reliable source of replenishment water are available (Linde 1969). Water levels in fresh-water impoundments are manipulated for the following reasons (Schmidt 1951):

1. To permit the natural propagation and growth of certain types of vegetation.
2. To retard plant succession.
3. To eradicate undesirable types of vegetation.
4. To reduce the effects of turbidity and high acid content in certain waters.
5. To control mosquitoes.

Planned drawdowns are effective in maintaining the productivity of a waterfowl marsh (Kadlec 1962). Many of the most productive waterfowl areas are subject to natural "drawdowns" as a result of droughts. Van der Valk and Davis (1980) concluded that periodic natural drawdowns allow some emergent species to coexist in a community because of their diverse response to disturbances. Periodic drawdowns are necessary if the productivity of an impoundment is to be maintained (Linde 1969). Givens and Atkeson (1957) stated that marsh units drained during part or all of the growing season produced more food than did permanent pools.

The effects of a drawdown fall into three categories (Kadlec 1962): First, the drawdown produces a temporary abundance of food in the form of

seeds of wetland plants; second, it provides suitable conditions for the establishment of emergent cover; and third, it results in improved soil conditions and improved aquatic plant food production after reflooding.

Stable water levels usually inhibit the establishment of desirable herbaceous emergent plants. Newly flooded impoundments have adequate cover for wildlife only as long as flooded trees and shrubs persist. A decline in waterfowl productivity must be expected if the woody cover is not replaced by herbaceous emergent plants (Kadlec 1962).

Critcher (1958) provided guidelines for physical characteristics of desirable drawdown sites:

1. The pond or drawdown area should be at least 5 acres in area, because smaller sites are relatively little used by waterfowl.

2. The location should be near areas used by waterfowl.

3. The site should have good soil, an adequate water supply, sufficient water control structures, and a shallow flooding basin. The flooding depth should be no greater than 18 in. for use by dabbling ducks (Linde 1969).

Many workers have noted that continuous annual drawdowns result in a succession of emergent aquatic plant species that take over shallow marshes, close open-water areas, and reduce productivity. Low and Bellrose (1944) reported that, as plant succession continues, fewer waterfowl food species are available. A 15-year study of annual drawdowns followed by reflooding each September was carried out on Lake Erie marshes by Bednarik (1972). The trends in plant succession in all the study units was the displacement of good, waterfowl food-producing plants (semi-aquatic species) with undesirable annuals and perennials, such as poplar and willow trees. For sole production of large stands of waterfowl food, the best sequence was found to consist of 3 years of drawdown in May followed by 2 years of flooding with 24 to 30 in. of water. Flooding is designed to eliminate undesirable perennials and to encourage less competitive, more valuable annuals to develop when drawdowns resume. In two units, Bednarik noted that extensive stands of cattails returned as a result of flooding designed to eradicate encroachments of woody plants. One unit flooded with 24 in. of water for 1 year became covered with a solid stand of cattails. The low areas of another unit were dominated by cattails after 1 year of flooding to a depth of 18 in. and woody growth was not eradicated. Green et al. (1964) noted that properly managed drawdowns in alternate years, followed by the maintenance of water depths of about 3 ft in the following year, may prevent encroachments of undesirable plants.

Schmidt (1951) also found that drawdown benefits generally end after the third successive year. Harris (1957) indicated that 1-year drawdowns were more beneficial than 2-year drawdowns for the establishment of emergent vegetation, providing that the water was removed by mid-June. After drawdowns of 3 to 5 years, the marsh substrate became thoroughly dried and the plant succession changed from annual weeds to solid willow stands. Uhler (1956) noted that biennial drawdowns were preferable to annual drawdowns because annual drawdowns permitted excessive development of undesirable plants. A detailed discussion of drawdowns and water level fluctuations related to the production of waterfowl food plants was provided by Green et al. (1964). The impact of water level fluctuations on Great Lakes coastal wetlands was discussed by Jaworski et al. (1979). Cooke (1980) listed 63 nuisance aquatic plants that respond to drawdowns.

Meeks (1969) studied the effect of timing of drawdowns on wetland plant successions in an Ohio marsh. Water was withdrawn at different times on four units over a 7-year period; one drawdown was in mid-March, one in mid-April, one in mid-May, and one in mid-June. After 7 years, the unit drawn down in May had the plant associations most favorable for wildlife. Plant succession followed the same general trend in all units, progressing from semi-aquatic species to predominantly annual weeds. Similar results were noted by other authors. Linde (1969) reported that early drawdowns tend to give emergent seedlings a longer period of growth that undoubtedly increases their numbers and survival rate. A drawdown in late June favors annual plants and survival of emergents is poorer. The effectiveness of early drawdowns is reduced because undesirable plant species become established before conditions are suitable for the germination of excellent waterfowl food plants such as the smartweeds (Hopkins 1962). Schmidt (1951) suggested that late drawdowns (June or July) favor the production of annuals and early drawdowns the production of perennials. Bednarik (1972) found that on Magee Marsh, Ohio, the earlier the drawdown, the more rapidly undesirable weeds replaced other species. He noted that May was the best month in which to begin drawdowns that would result in growth of high quality duck food.

Drawdowns must be early enough to dry out the soil so that heavy equipment can be operated in areas where cultivation is necessary. Drawdowns can be later if aerial seeding of mud flats is planned.

When an impoundment is being managed by the application a drawdown technique, annual plants supply most of the waterfowl food. Therefore, perennials left in the newly created pond will reduce waterfowl food production (Schmidt 1951). If an impoundment is being managed for muskrat production, however, the eradication of existing perennials is not necessary and might be undesirable.

Submerged organic material decomposes slowly. When water is removed, the rate of decomposition greatly increases. Released nutrients contribute to

increased plant vigor and productivity. This decomposition also retards filling of the impoundment with accumulated submerged vegetation (Green et al. 1964).

Soil fertility is increased if adequate moisture is retained during the period when surface water is lacking. Generally this means reducing the water only to the level at which the soil surface is exposed. In sandy soils, drainage that is too frequent or is excessive may be harmful (Kadlec 1962).

In areas of low soil fertility, the amount of food produced by a drawdown may be negligible, and such wetlands may be best adapted to brood production (Linde 1969). Unless a marsh is in need of complete rejuvenation or water control structures must be repaired, partial drawdowns are preferable to complete drawdowns for the following reasons (Linde 1969):

1. Partial drawdowns maintain summer waterfowl brood water.

2. A complete drawdown reduces or eliminates invertebrate populations.

3. On steeply contoured impoundment basins, complete drawdowns drastically reduce groundwater levels in upper elevations and prevent a heavy growth of mud flat plants. If plants develop in the lower elevations, later reflooding leaves them too deep for use by dabbling ducks, and shallow reflooding reduces the water area.

4. Complete drawdown each year on shallow marshes results in vegetative growth that closes open-water areas.

5. Complete drawdowns are usually detrimental to muskrat populations.

Overwinter drawdowns can be useful for managing aquatic plants if the nuisance species are susceptible; Nichols (1975) reported that a single overwinter drawdown in Mondeaux Flowage, Wisconsin, successfully controlled many submergent plants. Subsequent drawdowns were not recommended because species that tolerate drawdowns may replace those that do not. Beard (1973) detailed the effects of an overwinter drawdown in Murphy Flowage, Wisconsin. A winter drawdown on Lake Ocklawaha, Florida, provided excellent control for several submergent aquatic plant species, but other equally undesirable species increased substantially (Hestand and Carter 1974).

Stabilized water levels during the growing season sometimes are preferable in impoundments suitable for the continued production of submerged food plants (Green et al. 1964). Submergent plants usually react favorably to stable water levels (Kadlec 1962; Yoakum et al. 1980). Keith (1961) observed

that slowly dropping water levels during July and early August exposed extensive beds of pondweeds, which responded with heavy seeding. A rise in water level on a Utah marsh from 17 in. to 20 in. increased the weight of fennelleaf pondweed in shallow areas but decreased the weight at deeper sites (Robel 1962). Robel (1961) had previously noted that the best growth was in water deeper than 12 in. Lowering water levels at the time of seeding to stimulate seed production might be a technique that could be profitably used in impoundments where there is already a good crop of pondweeds (Linde 1969). Linde also noted that a drawdown that results in the drainage of organic bottom soils seems to be accompanied by increased growths of submergent vegetation when the area is reflooded.

Water drawdowns are a valuable tool for marsh management, but must be used with care. Bottom topography, soil characteristics, existing plant communities, current waterfowl use, productivity, and seasonal water supplies are important factors that affect the decision to use drawdown as a habitat manipulation technique (Yoakum et al. 1980).

39.3. IMPACTS ON THE ENVIRONMENT

The construction of water control and impoundment structures facilitates the manipulation of water levels for management of wetland habitat in a manner most beneficial to the target species. The addition of water to an upland site can transform nonwetland areas into productive marshes. Control of water levels is essential for the intensive and economical management of impoundments for wildlife, particularly waterfowl (Green et al. 1964). Depending on the timing, duration, frequency, and depth of water, wetland habitats can be beneficially or adversely affected. Changes in stabilization of wetland habitats sought by wildlife managers through water level control may benefit some species at the expense of others. The methods used for water level manipulation and the management goals achieved are not always compatible with fishery management (see, e.g., Chapter 27).

Some benefits of water level manipulation for waterfowl were listed by Linde (1969):

1. Waterfowl breeding habitat is increased when water levels are increased to improve the interspersion of cover and water.

2. Increasing water levels changes the vegetative composition of wetlands, flooding out undesirable species and allowing the establishment of more beneficial aquatic plants.

3. Food production can be increased by drawdown, followed by either natural germination or artificial seeding.

4. Removal of water may establish terrestrial food patches.

5. Desirable food or cover plants that were lost due to wave or ice action or to continuous deep-water flooding can be reestablished.

6. Muskrat damage to dikes can be controlled by winter drawdowns to reduce muskrat populations.

7. Populations of common carp can be controlled by drawdowns (see Chapter 33).

8. Water chemistry and quality may be improved (see Chapter 30).

Other benefits of drawdowns include consolidation of loose sediment, possible control of turbidity generated by waves and boat wakes; provision of an opportunity to improve, construct, or maintain water control structures; decomposition of organic material; release of nutrients; and increased plant growth and vigor.

A major adverse effect of water level control structures is the potential failure of dikes or spillways due to improper design or construction. Breaching of dikes or levees causes uncontrolled and destructive releases of water. Leaky dikes may not impound water at the level required for proper management. Sudden water releases from dike failure may adversely affect the vegetation, and replacement water may not be available for refilling the impounded area after the dike is repaired. Unprotected water control structures may fail due to erosion and undercutting. Spillways that cannot adequately handle normal or excessive flows may fail during high water or contribute to dike failure.

A number of potentially adverse effects of water level manipulation, particularly of drawdowns, include the establishment of undesirable vegetation, the destruction of valuable wetland plants, and the reduction of muskrat or beaver populations (Beard 1973); the loss of soil nutrients from leaching after a complete drawdown, and reduced invertebrate populations that adversely affect waterfowl production (Kadlec 1962); and a decline in attractive and available food plants for waterfowl, lowered levels in wells producing potable water, and lack of open water or of access to it for recreation (Cooke 1980). (The effects of water level manipulation on fish populations is discussed in Chapter 28.)

Impoundments in which the water level has been held stable for long periods often produce progressively fewer aquatic plants as time passes. Water areas are often reduced in value for waterfowl if the level is stable, or if water levels change at the wrong time of year (Green et al. 1964).

The effects of water level changes on waterfowl production were discussed

by Anderson and Glover (1967), Bednarik (1972), Linde (1969), and Wolf (1955). Wolf reported that fluctuating water levels of reservoirs in Utah and Idaho adversely affected waterfowl production, largely by submerging nests and eggs. He concluded that fluctuating water levels discouraged some waterfowl from nesting and that nest destruction would be reduced if the rate of rise was kept below the point of maximum tolerance, while still maintaining the desired water storage capacity.

Anderson and Glover (1967) suggested that waterfowl production is high when water is abundant before spring migration, and that low production can be anticipated if water is not available until after the spring migration. In a 2-year study in the San Luis Valley of Colorado, they showed that an experimental area upon which water was applied early in the spring produced nearly three times as many ducklings per acre as the control site. Although there were some changes in vegetation on the experimental area that improved the nesting habitat, the authors believed that the increased production resulted from early water availability rather than from vegetational changes. The data indicated that waterfowl production and use were increased on managed areas by the application of water before the spring migration.

During a 15-year study of water level manipulations on Magee Marsh, Lake Erie, Ohio, Bednarik (1972) recorded the effects of marsh drawdowns on plant succession, waterfowl production, and waterfowl harvest. Annual changes of marsh vegetation and water levels affected the quality and location of nesting sites and nesting success. High water levels resulted in nest destruction by flooding and in the concentration of nests on dikes and high ground, where they were subject to high rates of predation. Large numbers of breeding pairs were attracted during years when the water level was low, but nesting territories were abandoned or drastically shifted after a complete marsh drawdown. Bednarik recommended that water levels in diked marsh units be manipulated in the spring to expose the higher elevations of the marsh and create natural nesting islands. The islands and shallow water areas would still produce food plants, and thus would not interfere with food production. Bednarik also noted that waterfowl nesting was not adversely affected if water levels declined after nesting was well under way.

Linde (1969) observed that if a complete summer drawdown occurs in a subimpoundment that is adjacent to other water areas that remain flooded, the effects on breeding waterfowl will probably be negligible for that general area. However, if the impounded area that is drawn down is the only water available in that vicinity, it may have a negative effect on local waterfowl production. If only one impoundment is in the area, a partial drawdown will maintain some summer water for duck broods.

In most studies of the effects of water level changes on muskrats it has been found that fluctuating water levels and drawdowns adversely affect muskrat populations. Friend et al. (1964) measured the effects of winter water level changes on muskrats in Montezuma National Wildlife Refuge. In

areas where the water level had been lowered by drainage, the water was frozen solid to the bottom. Food beds were frozen and muskrats suffered severe weight losses. Winter weight losses were less in an area where normal water levels were maintained. Reflooding of the drained areas resulted in most of the lost weight being regained. Evidence of disease and parasitic infection was heaviest in muskrats from the areas of low water.

Donohoe (1966), who investigated muskrat reproduction in areas of controlled and uncontrolled water levels, suggested that diked units increase population densities through a reduction of mortality, but that the impoundments have little influence on reproductive physiology. Bellrose and Brown (1941) showed that muskrat populations in the Illinois River Valley were affected more by changing water levels than by types of marsh vegetation. They reported that the density of muskrat houses was higher in lakes with stable water levels than in those with fluctuating levels. Furthermore, stable and semi-stable water levels directly favored the species of plants that supported the highest populations of muskrats. Wilson (1960) noted that a tidal marsh in North Carolina that consistently flooded with 1 to 6 in. of water normally supported from 3 to 7 times as many muskrats as a marsh subjected to water level fluctuations.

Bellrose and Low (1943), who discussed the influence of high and low water levels on the survival of muskrats in the Illinois River Valley, wrote that a rise of 5 to 7 ft in the water level during an October 1941 flood drastically reduced muskrat populations by destroying lodges, and increasing mortality from exposure, predation, and intraspecific strife. Low water is considered more serious during winter, when muskrats may be forced to leave their lodges in search of food; however, low water in summer appears to adversely affect fall muskrat reproduction. Linde (1969) showed that, although summer drawdowns are not beneficial for muskrats, little mortality results if reflooding occurs in the fall before freeze-up. Complete drawdowns are not compatible with good muskrat management. However, if muskrats become too plentiful, drawdowns can be used as a form of control. A drawdown on Horicon Marsh, Wisconsin, almost eliminated muskrats, but reflooding and new vegetative growth resulted in a population explosion 3 years later (Linde 1969). Linde (1969) further noted that fall or early-winter drawdowns can cause complete freeze-outs and eliminate a muskrat population. If water levels must be drawn down in winter, the drawdown should begin as late in winter as possible. Muskrats can often survive low water levels if there is sufficient ice cover because the ice layer and the air beneath it act as insulators and prevent freezing of the deeper bottom muds, thus keeping a food supply available to muskrats.

39.4. COSTS

Costs are extremely variable for dikes and spillways; they are influenced

by construction methods, materials, design, soils, operating conditions, and other factors. Average costs of dike construction on Wisconsin wildlife areas (Table 27) may serve as general guidelines, together with cost information on "tin whistle" spillways (Table 28).

Table 27. Average dimensions and costs of dikes on Wisconsin wildlife areas (modified from Linde 1969).

Region of Wisconsin	Average dimensions (feet)			Cost per foot of dike		Equipment used
	Height	Width				
		Top	Base	Average	Range	
East central	4.5	11.8	27.4	$0.43	$0.20- 0.82	De[a]
Northeast	5.8	12.1	43.3	2.85	0.20-10.50	Bd[a]
Mead Wildlife Area[b]	4.5	12.1	30.0	0.16	0.11- 0.24	De
Northwest	7.8	12.9	57.7	5.23	1.47- 8.79	Bd

[a]De = drag-line; Bd = bulldozer. Average cost of leveling drag-line constructed dikes with bulldozers was $0.06 per foot.
[b]The Mead Wildlife Area is considered separately from others in the Northeast region.

Table 28. Size and costs of "tin whistle" spillway structures used on Wisconsin wildlife areas (from Linde 1969).

Diameter of horizontal tube (inches)[b]	Size of riser (inches)		Cost of steel structures	
	Range	Size most used	Average	Range
20	36	-	$900	-
24	36-48	36	402	$295-595
30	40-54	40	634	400-1,000
36	36-72	48	618[c]	500-889[c]

[a]See text (Chapter 39, Fig. 66) for description.
[b]Other structures used were 13 in. in diameter with risers of 20 X 20 in., and 48 in. in diameter with risers of 48, 60, and 72 in.; no cost data were provided for these structures.
[c]Average cost of aluminum structure of the same dimensions, $747; range, $619-$1000.

On a large impoundment, stream diversion structures initally cost more than pumping installations, but over a period of years the maintenance and operational costs of pumping cause the pumping systems to gradually lose their economic advantage (Linde 1969).

39.5. EVALUATION FOR USE ON UMRS

The control of water levels on UMRS with the existing lock and dam system can be used to benefit wildlife resources, although multi-use needs do not allow the flexibility required for some wildlife management practices. In general, moist soil plants have been negatively affected by the lock and dam system, but emergent and submergent plants have flourished.

The UMRBC Environmental Work Team (1981a) developed the following recommendations and enhancement techniques for UMRS pool level fluctuations on the basis of findings by a panel of experts:

Wetland Plants

1. Hold water levels stable during the critical growing season from late spring to early summer.

2. Maintain water at sufficient levels in winter to protect the rooted portions of perennial plants from freezing.

3. Maintain flow and stability of water in backwater areas.

4. Optimize production of seed-producing, moist-soil plants along UMR below Cassville, Wisconsin, by exposing the largest possible area of mud flats between July 15 and August 1. Earlier drawdowns are not desirable because the germination period of willows and cottonwoods may not have been concluded before July 15, and the invasion of shallow areas by these woody plants will be detrimental to food production. Moist-soil management to produce foods for waterfowl is less practical in the regions of UMR above Cassville.

5. Construct small levees on areas adjacent to UMR as part of a moist-soil program. Optimum water level manipulation will provide an abundance of natural foods for wildlife. The recommendation is most applicable for areas downstream from Cassville.

6. Promote soil conservation methods on upland areas to reduce sedimentation and water turbidity.

7. Measure sedimentation rates in open water and backwater areas on the Mississippi and Illinois rivers.

Waterfowl

1. Maintain stable water levels during the waterfowl nesting season. (See item 4 in the preceding list of recommendations on wetland plants.)

Muskrats

1. Fine-tune day-to-day pool level management by the U.S. Army Corps of Engineers with considerations for fish and wildlife.

2. Promote relatively stable water levels throughout the year for the benefit of aquatic plants and the animals that eat them.

3. Develop a water level management plan for each pool to improve the species composition and abundance of aquatic plants. This plan would include a study of the gage stations.

4. Rehabilitate degraded areas such as the Weaver Bottoms in Pool 5 of UMR.

CHAPTER 40. REVEGETATION

40.1. SITUATION TO BE MITIGATED OR ENHANCED

Vegetation is an essential element of wildlife habitat because it provides both food and cover. Plants can be established to create habitat on new substrates, disturbed or altered sites, or on undesirable existing habitat. Natural events or man-caused factors such as pollution, drainage, commercial operations, or inundation often change or destroy the vegetative community associated with large river systems. Although natural plant invasion may occur, it is often slow and may include undesirable plant species. The establishment of plants through artificial propagation can greatly improve the habitat and benefit wildlife populations.

Vegetation control is often required to renovate areas of undesirable habitat. After the removal or setback of the existing vegetation, revegetation with desirable plant species may give them an advantage over competitive invaders. Newly established substrates, such as dredged material deposits used to create islands or marshes, require planting not only for enhancement of wildlife habitat but also for substrate stabilization and erosion control. Farming methods can be used to produce supplemental food supplies for wildlife and to mitigate the loss of forage formerly produced in natural habitats.

We discuss revegetation techniques here from a wildlife habitat enhancement perspective. Establishment of vegetation to stabilize and protect shorelines from erosive forces is discussed in Chapter 11. Many references in that chapter, especially those relating to vegetation establishment techniques, may also be applied to the improvement of wildlife habitat.

40.2. DESCRIPTION OF TECHNIQUES

A primary consideration before one initiates a project to revegetate wildlife habitat is the habitat requirements of the target wildlife species. The objective may be to attain a certain population level or quality of habitat, or both. Current trends in management are diverging from individual species toward a diversity of species, but management for individual species is suitable for such target species as game animals, endangered species, raptors, or colonial waterbirds (Hunt et al. 1978). Management for individual species may not be as successful as it might be because information on the requirements of the species concerned may be inadequate. The vegetation may be planned to provide wildlife forage, or cover for reproduction, overwintering, or migration. A list of references on the habitat and life requirements for individual species or groups of similar species was provided by Hunt et al. (1978).

40.2.1. Selection of Plant Species

When revegetation projects are planned, advance consideration must be given to plant types that will create the desired habitat for the target wildlife species. The selection of the plant species appropriate to the region, to the site, and to the wildlife habitat development goals is the first step toward vegetation establishment. Success of the project may hinge on the species being planted, types of propagules used, and the use of the plant material by wildlife. Plant species to be used should be selected during the planning phase, even though alternate species may prove to be more acceptable after the site is established, and may then be substituted (Hunt et al. 1978).

Selection of a species or mixed group of species for planting at a particular site should be based on the following considerations:

1. Wildlife value. The value of the plant or plants for wildlife in general or, more precisely, for the target wildlife species is of primary importance in species selection. An extensive evaluation of marsh and aquatic plants for their value for waterfowl, other birds, and muskrats was made by Kadlec and Wentz (1974). The U.S. Army Engineer Waterways Experiment Station (1978) has developed general wildlife values for many marsh plants. A similar list was presented for upland plant species by Hunt et al. (1978). All three sources include lists of references. Martin and Uhler (1939) listed the plant foods used by ducks in the United States and Canada. (A list of common bottomland trees grouped according to their waterfowl food value--mast production--is given in our Chapter 37.)

2. Plant location. As a rule, native plant species have definite advantages for use in wildlife habitat development (Ocean Data Systems, Inc. 1978): (1) the wildlife of the area normally depends on these plants; (2) the plants are adapted to the climate and to physical and chemical properties of the local sediments; (3) native plant species are usually less susceptible to disease and insect damage than cultivated plant species; and (4) native species are less likely to spread out of control.

3. Plant species characteristics. Various characteristics must be considered in selecting plant species (Hunt et al. 1978): (1) basic growth requirements; (2) tolerance to extremes of temperature, light, moisture, pH, salinity, contaminants, and nutrients; (3) growth form (viney, upright, spreading, etc.); (4) rate of growth and life span; (5) form and flexibility of reproduction; (6) production of wildlife food and cover (quality, amount, form, time, and duration); (7) competitive ability, including inhibition of other species; (8) ability to

modify site conditions (e.g., decrease wind erosion or add nitrogen to the soil); (9) hardiness; (10) resistance to insects and disease; and (11) need for maintenance, management, or control.

4. Maintenance and management requirements. After establishment, intensive or frequent maintenance of plants, such as pruning or hand-weeding, is costly and inefficient. Selection of species requiring such care should be avoided. Plans must be limited to providing a low level of maintenance, which might include seasonal mowing or periodic fertilization. Management or control of a species that can become established to the detriment of others should be considered, and that species must either not be planted or some control measures must be guaranteed (Hunt et al. 1978). Species that provide food or cover in one region may be a liability elsewhere (Erickson 1964). The usefulness of a plant may be altered by its abundance or the form in which it occurs.

5. Soil characteristics. Plant species must be able to survive, grow, and reproduce in the soil existing at the site. Soil texture, moisture-holding capacity, fertility, pH, salinity, and contaminants must all be checked to determine possible limitations on plant growth (U.S. Army Engineer Waterways Experiment Station 1978). Soil conditions that favor many of the upland plant species used in habitat development were listed by Hunt et al. (1978).

6. Water quality. All marsh and aquatic plants have definite tolerance limits for physical and chemical characteristics of water, including salinity, contaminants, alkalinity, acidity, mineral concentrations, and turbidity. A detailed listing of the physical and chemical conditions under which most common marsh and aquatic plants occur was provided by Kadlec and Wentz (1974). They also listed aquatic and marsh plants as related to their tolerance of turbidity and pollution.

7. Water level fluctuation and depths. Two aspects of water levels are important to plants: the degree of fluctuation and the water depth. The categories of wetland plants (submergents, emergents, and floating-leaved), are usually closely associated with water depth. The close association of plant species with water depth is due to several factors (Kadlec and Wentz 1974), which include variations in light penetration, in their competitive ability with increasing water depth, and in the conditions under which seedlings become established. The tolerance levels of many marsh and aquatic plants to marsh moisture conditions were also noted by U.S. Army Engineer Waterways Experiment Station (1978). (The effects of water level fluctuations on wetland plants are discussed in Chapter 39.)

8. Current, waves, and ice action. The physical action of these factors on aquatic and marsh plants significantly affects their distribution. A stable substrate is vital to successful plant establishment (U.S. Army Engineer Waterways Experiment Station 1978). Strong waves and currents wash away fine materials, leaving coarse-grained sediments that are frequently unstable and provide poor anchoring for plants (Kadlec and Wentz 1974). Moving ice has the potential to destroy existing vegetation, particularly of emergent species. Many plant species, especially floating-leaved plants, require calm and sheltered water.

9. Climate and microclimate. Climatic factors of precipitation, temperature ranges, wind patterns, and frost-free days control the distribution patterns of vegetation. Microclimate features such as slope and topography control more localized patterns. The location of a site restricts selection to plants tolerant of the prevailing climate. Only species with universal ranges, such as many agricultural crops or varieties that can be obtained from local sources, should be planted (Hunt et al. 1978).

10. Availability. Selection of a plant species must often be based on availability. Numerous species that would be acceptable may not be obtainable because of limitations in time, money or manpower. This is especially true if the plant species is not commercially available, if it must be harvested by hand labor, or if its seeds cannot be used as propagules (U.S. Army Engineer Waterways Experiment Station 1978).

11. Ease of propagation. Unless an easily handled form of propagule can be found for a species, that species will be of little use in a vegetation establishment and management program.

12. Costs. Plant species that cost more to obtain and plant than the project budget allows are of little value. Costs are generally lower if a commercial source of propagules is available. Costs increase in proportion to the amount of hand labor that is required.

13. Topography, configuration, size, and location of the proposed site. The topography of a site determines the flooding potential of uplands and the water depths that will occur in marsh and aquatic habitats. Size and location will affect the value of a revegetation project as wildlife habitat. Large areas provide more habitat, but small sites offering critical habitat may be equally important. Location is important as related to potential wildlife use, human disturbance, and predator populations. The configuration of the area will determine the amount of edge habitat and influence the effects of currents and waves.

Several investigators have published lists of plant species that can be used in habitat development projects. In addition to the lists of aquatic, marsh, or upland plants that may be used to select plants for wildlife habitat projects, two more specific lists were provided: (1) a list of 28 freshwater marsh plant species recommended for planting on dredged material marsh sites, prepared by U.S. Army Engineer Waterways Experiment Station (1978), included plant description, range, habitat type, associated species, method of establishment, wildlife value, and general comments; and (2) a synopsis of 100 plant species of value for terrestrial wildlife habitat-development on dredged material, published by Ocean Data Systems, Inc. (1978), include information on range, description, life history, habitat, soil requirements, establishment and maintenance, disease and insect problems, and wildlife value for each species.

Wentz et al. (1974) gave additional references on specific wetland plant species and their management.

40.2.2. Site Preparation

The characteristics of the substrate should be assessed for nutrient levels, soil texture, salinity, pH, etc. before the site is prepared. These characteristics will indicate what soil cultivation and other treatments, such as liming and fertilizer are needed. The first step of site preparation is the removal of any undesirable vegetation (see Chapter 38). After vegetation is removed, the surface of the site may require grading or shaping to modify the topography, improve water circulation, or mix the soil types to create uniformity. Exposed mineral soil may have to be placed on organic litter substrates to help ensure the germination and growth of some plant species (Yoakum et al. 1980). Seedbed preparation may involve plowing or disking to break up the soil, turning under of organic material, aerating the soil, and equalizing the moisture content (Hunt et al. 1978). The type of equipment needed for seedbed preparation varies with the plant species and site conditions. Heavy equipment and farm machinery are most often used for soil preparation, but special low-ground pressure vehicles (tracked, wheeled, or unconventional ground-crawling equipment) may be needed on wet substrates. The use of low-ground pressure vehicles for substrate modification was discussed by Willoughby (1978). For all soil types, mechanical tillage by conventional agricultural techniques, when possible, will improve the substrate as a bed for direct seeding of plants (Kadlec and Wentz 1974). A highline arrangement that includes a dragline bucket, winch, and deadman (at the opposite side of the disposal area) may be used to modify submerged aquatic substrates when the operation of other equipment is not feasible (U.S. Army Engineer Waterways Experiment Station 1978). This arrangement allows the bucket to be pulled back and forth over the area being graded.

Soft, unstable substrates often make it difficult to establish plants, but sometimes a soft soil becomes consolidated if it can be dried (Kadlec

1962; Linde 1969). Soft substrates may be contributing to turbidity problems because they are subject to erosion by waves and currents (Kadlec and Wentz 1974).

The chemical analysis of the soil will help determine any special treatments that may be needed. Three principal soil features may prevent normal plant growth:

1. Salinity. Soils with high salt content require salt-tolerant plant species; alternatively, planting can be delayed until sufficient leaching or reclamation has occurred to lower the salt content to nontoxic levels (Hunt et al. 1978).

2. Acidity (low pH). Soil acidity may be corrected by the addition of lime. Agricultural limestone (calcium carbonate) may require several months to increase soil pH, but it has a longer residual effect than do quick-acting forms of limestone. The amount of lime needed to increase soil pH depends on the initial soil pH and other factors (Hunt et al. 1978). Liming is not always successful and the amount needed sometimes exceeds practical limits (Kadlec and Wentz 1974).

3. Nutrient level. The addition of elements other than those that are essential creates unnecessary expense and can result in reduced plant growth. Fertilizer, correctly applied, aids in plant establishment and can give the desired plant species an advantage over competitors (Hunt et al. 1978).

In a study of the relation of fertilizers to wildlife forage, Yoakum et al. (1980) noted that plants growing on soils of low fertility or on soils having an improper nutrient balance responded more to fertilizer applications than did plants growing on fertile soils or on soils having proper nutrient balance. Plant species selected also define nutrient demands, since the requirements of plants vary greatly (e.g., grasses have a high demand for nitrogen, and legumes a high demand for phosphorus and potassium). Although the response of some marsh plants to fertilization has been studied to some degree, the mineral requirements of most marsh and aquatic plants are unknown. Currents, tides, or fluctuating water levels may flush added fertilizers out of wetlands (Kadlec and Wentz 1974). Chemical regulation of soil to insure the production of crops attractive to waterfowl was discussed by Cook (1964).

Split applications of fertilizer, or slow-release fertilizers, improve nutrient availability to plants. Initial fertilization should occur just before seeding or planting because nitrogen and other elements are quickly lost from the soil (Hunt et al. 1978). Additonal applications may be applied after the plants are well established.

40.2.3. Planting of Stock or Propagules

Planting stock or propagules from natural sites or nurseries may consist of entire plants, cuttings, vegetative structures, or seeds. Seven forms of propagules for the establishment of vegetation were listed and defined by U.S. Army Engineer Waterways Experiment Station (1978):

1. Seeds. These common reproductive structures are found on plants singly, in clusters, in pods, and on multistemmed or single-stemmed seed heads.

2. Rootstocks. Rootstocks consist of the root system of a plant, including the small portion of stem normally below ground. The propagule may be divided into sections or clumps for planting; new growth generates from the old root systems.

3. Rhizomes. This propagule refers to underground stems that usually grow horizontally. Rhizomes are divided into sections; at least one viable growth point (meristematic tissue) must be on each section to ensure new growth.

4. Tubers. Tubers are large fleshy underground stems often associated with rhizomes. They should be dug near the end of the growing season to obtain the new crop for planting.

5. Cuttings. Cuttings involve sections of the top shoots of a plant that include nodes. For woody marsh species such as willows, cuttings should be 1 to 2 ft long from the end of a branch or a twig of 1-year-old growth. Cuttings of herbaceous marsh species can be taken from any section of the top shoots (with nodes); when they are planted shallowly, new growth occurs.

6. Seedlings. Seedlings are young plants with weakly developed root systems. They may be obtained by digging the plant from a natural stand or by germinating seeds in a greenhouse and growing them to the seedling stage.

7. Transplants (sprigs). Transplants are by far the most common and most successful type of propagule for marsh establishment projects. A transplant involves an entire plant dug and removed from a natural site and transplanted to the new site. The term sprig generally refers to small transplants, often very young, that are obtained in the same way. It is best to keep soil with transplants when they are dug to reduce the shock of root loss and disturbance. Plants dug during the dormant (winter) season usually suffer less from the stress and shock of being moved than do those transplanted in the late spring and summer. The transplant should be the largest size that is practical.

When the species selection has been completed, detailed consideration must be given to the type and availability of plant propagules, the amount of plant material needed to fully use the site, and the costs. Criteria for selection of propagule types are similar to those used for the selection of plant species. These criteria were listed by Hunt et al. (1978) and U.S. Army Engineer Waterways Experiment Station (1978):

1. Availability and costs. When more than one propagule type is acceptable and available for a species, a balance should be reached between availability, cost, probability of success, and ease of handling. Some types of propagules may be available only at certain times of the year.

2. Ease of collection and handling. The form of propagule selected should be easy to locate, obtain, and handle. Many species are available from commercial or government seed sources. Vegetative propagules generally require more labor for collection and handling than do seeds.

3. Ease of storage. Because of their small bulk, seeds can be stored with little difficulty but storage techniques influence germination success and vary with species. Storage of vegetative propagules is more difficult.

4. Ease of planting. Seeds can be broadcast or planted in rows by machine or by hand. Some vegetative propagules can be planted by machine but usually they must be hand-planted.

5. Disease. Plants at the sources of supply are sometimes infected with fungal or viral diseases that limit the selection of propagules. Vegetative propagules or seeds should never be taken from infected stands. Disease lowers the viability of plants and reduces the chances for successful propagation.

6. Need for rapid establishment. The selection of a propagule may depend on the urgency of the need for vegetative cover. On highly visible sites or sites subject to erosion, it may be necessary to establish a plant cover as quickly as possible. The most rapid and effective way to establish vegetation is to use transplants.

Other factors to consider when choosing a propagule type include the size of the area to be planted, the degree of water level fluctuation, and anticipated physical stresses on the site, such as siltation, erosion, and current or wave action (Kadlec and Wentz 1974). Advantages and disadvantages of propagules differ by source and type (Table 29). A list of 87 common North American aquatic and marsh plants and their methods of propagation was published by Kadlec and Wentz (1974). An extensive list of marsh plants and their recommended propagule types for revegetation was prepared by the U.S. Army Engineer Waterways Experiment Station (1978). Hunt et al. (1978)

recommended propagule types for an extensive list of upland plant species used in revegetation projects.

Table 29. Comparison of advantages and disadvantages of propagules obtained from different sources (nursery or natural stand) or of different types (seeds, tubers, rootstocks, cuttings, sprigs, seedlings, or transplants) (modified from Hunt et al. 1978).

	Advantages	Disadvantages
Comparison on basis of source		
1. Nursery	Uniform quality; little or no disturbance of natural stands; reduces labor	May increase costs in certain situations; requires planning and ordering in advance; may not be adapted to local conditions
2. Natural stand	Decreases costs; adapted to local conditions	Disrupts natural stands; can be difficult to locate sufficient supply; increases labor; seeds may not be available due to heavy predation; viability and percent germination of seeds are often low; noncommercial species may have unknown requirements
Comparison on basis of types		
1. Seeds	Reduce labor and costs; suitable for large sites; can be stored for several months or longer	Not suitable for fine-textured materials; wide range of viability, reliability, and success; storage requirements known for relatively few species; restricts harvest time; restricts planting time; cultivation generally required; requires advanced planning to harvest and store supply
2. Tubers	Can be harvested mechanically if small; planting effort smaller (can be broadcast)	Large tubers difficult to extract from soil; susceptible to washout
3. Rootstocks (rhizomes)	Maximizes use of plant material	Susceptible to washout; cultivation generally required; success limited

Table 29. (cont.)

Type (cont.)	Advantages	Disadvantages
4. Cuttings	Reduces labor and costs; rapid collection; maximizes use of plant materials	Susceptible to washout; must be planted promptly or potted and stored; some disruption of natural stand; lower survival than rooted propagules
5. Sprigs	Less costly than transplants	Must be planted promptly or potted and stored
6. Seedlings	Can be planted over longer periods; can be stored in greenhouse or nursery; permits flexibility in coordinating project engineering and planting	Requires planning and preparing in advance; increased costs
7. Transplants	Rapid establishment; increases probability of success, especially on salt marsh sites; stabilizes soil rapidly	Highest cost and labor requirements; may be difficult to dig, transport, and plant

Sources of propagules for upland plant species were listed for each state by Hunt et al. (1978). A list of suppliers of aquatic and marsh plants is given in Table 30.

Table 30. Some suppliers of aquatic and marsh plants in 1973 (from Kadlec and Wentz 1974).

Diamond Rice Company
Kelliher, Minnesota 56650

Three Springs Fisheries
124 Hougar Road
Lilypons, Maryland 21717

Everglades Aquatic Nurseries, Inc.
P.O. Box 587
Tampa, Florida 33601

William Tricker Inc.
74 Allendale Avenue
Saddle River, New Jersey 10758

Table 30. (cont.).

Game Food Nurseries P.O. Box 2371 Oshkosh, Wisconsin 54901	William Tricker Inc. 7125 Tanglewood Drive Independence, Ohio 44131
R. A. Gasser Route 2, Box 75 Stuart, Florida 33494	Van Ness Water Gardens 2460 North Euclide Avenue Upland, California 91786
Slocum Water Gardens 1101 Cypress Gardens Rd. Winter Haven, Florida 33880	Wildlife Nurseries P.O. Box 399 Oshkosh, Wisconsin 54901

If commercial sources of propagules are not available, wild propagules must be collected and stored. The collection, storage, and handling of the seeds of upland and wetland plants were discussed in detail by Hunt et al. (1978), Kadlec and Wentz (1974), U.S. Army Engineer Waterways Experiment Station (1978), and U.S. Forest Service (1969). Unlike upland and agronomic plants, few marsh species are available from commercial sources as transplants and other vegetative propagules. Guidelines for the collection, storage, and handling of vegetative propagules for upland and wetland plants were provided by Hunt et al. (1978), Kadlec and Wentz (1974), and U.S. Army Engineer Waterways Experiment Station (1978).

Vegetation establishment is usually accomplished by natural plant invasion, by planting selected species, or by a combination of natural invasion and planting (Hunt et al. 1978).

The ability of propagules to reach a site is the most important factor determining the potential for natural colonization. This ability increases as distance from the source decreases and as the size of the site and ease with which the propagule can be transported increase. Propagules may be transported by wind or water, by attachment to animal fur, feathers, or feet, by being ingested and excreted by an animal, or by attachment to humans. Secondary factors affecting natural colonization include the physical and biological features of the site itself. Natural establishment of marsh and aquatic plant species was discussed by Kadlec and Wentz (1974).

Natural plant establishment has the following advantages (Hunt et al. 1978):

1. Development efforts and costs are limited to increasing the

likelihood of plant invasion through site selection, project design, or protective measures.

2. Invading plant species that are successful are those best suited to the site conditions and that can be expected to outcompete other species.

3. Little maintenance is required.

Disadvantages of natural plant establishment include potential invasion and establishment of undesirable plant species, and the usually slow rate of colonization (Hunt et al. 1978).

Standard practices used in horticulture are usually adequate for plant propagation on upland sites (Hunt et al. 1978). Few of the sophisticated agricultural planting techniques are applicable for wetland revegetation attempts (Kadlec and Wentz 1974). In general, annuals must be propagated by seed, and perennials may be propagated by seed or by vegetative methods.

Direct seeding has the advantage of being inexpensive but it may be an unreliable method of propagation (Hunt et al. 1978). Several procedures commonly used for direct seeding include deep-furrow drills; Hansen browse seeders; cutout disks; seed dribblers; rotaseeders; and broadcast (aerial, ground, or hand) seeders (U.S. Forest Service 1969; Yoakum et al. 1980). It is often necessary to induce germination in some seeds by chemical or mechanical destruction of the seed coat (scarification). Methods of inducing germination in seeds were discussed by Kadlec and Wentz (1974) and Ocean Data Systems, Inc. (1978).

Field planting methods used on upland sites are determined by accessibility of the site for farm equipment and by prevailing soil conditions (Ocean Data Systems, Inc. 1978). Sites that are inaccessible or unsuitable for mechanical planting must be planted manually with simple hand tools. Marsh and aquatic sites must usually be planted by hand unless the site can be drained. Methods for planting seeds and vegetative propagules of upland plants were provided by Hunt et al. (1978) and Ocean Data Systems, Inc. (1978). Planting methods for aquatic and marsh plants were discussed by Kadlec and Wentz (1974) and U.S. Army Engineer Waterways Experiment Station (1978). Various revegetation techniques used for coastal marsh improvement were discussed by Lewis and Bunce (1980); many of the techniques described by them can be applied to freshwater plant species.

Artificial introductions are of greatest value on small areas where the site can be managed and controlled intensively. Planting of large marshes, river bottoms, or extensive impoundments is often very costly. When a planting program is begun, small plantings should first be made to determine

the adaptability of selected species for the site (Yoakum et al. 1980).

Spacing of plants is highly site specific and is affected by the quality of the substrate, the type of propagule used, length of the growing season, and the desired rate of growth of the plant cover. If the site is extremely unstable, subject to heavy wildlife pressure or severe physical stresses, or if aesthetics are an immediate concern, dense plantings may be desirable. Vegetative propagule types should be spaced more closely than transplants. General spacing of plants was described by the U.S. Army Engineer Waterways Experiment Station (1978).

Patterns of vegetation are important considerations in habitat development. In general, a site planted with a variety of species over a range from deepwater to upland areas is preferred. Exceptions are sites where physical stresses are particularly harsh, where stabilization is critical (as on dike slopes), where only one species can tolerate the conditions, or where quick cover by a vigorous single species is needed (U.S. Army Engineer Waterways Experiment Station 1978). Variations in elevation, and thus in water depth, require the planting of wetland sites with species that are adapted to both deep and shallow water. Diversity of plant species in an area provides more habitat for wildlife, encourages wildlife species that prefer mixed habitat types, insures revegetation if selected plantings fail, and makes desirable plants available for a long-range succession. An important factor related to the established plant community is the provision of food and cover for wildlife. The desired ratio of cover types to density of vegetation is important in establishing the necessary habitat. Typical freshwater marsh plant associations and patterns are shown in Fig. 67.

The timing of planting is important, regardless of the type of propagule used, as it strongly influences plant success. Optimal seeding times vary with climatic regions, and local horticultural authorities should be consulted before planting is done. Hunt et al. (1978) provided species-specific details on the timing of planting for many upland species used for wildlife habitat development and listed numerous sources. Planting times for aquatic and marsh plants have not been well defined. Erickson (1964) recommended fall planting for marsh plants because water levels are usually lowest, over-winter storage is unnecessary, identification is easier, and the rest period at low temperatures may favor spring germination and growth.

Newly planted substrates must often be in a protected low-energy area or be shielded by a protective structure, such as a permanent or temporary dike. Plants themselves can be used as a protective shield if large, erosion-resistant transplants are placed on the outer fringes of the marsh. More susceptible, but less expensive, propagules such as rootstocks and tubers should be planted in the interior and high marsh areas of the site (U.S. Army Engineer Waterways Experiment Station 1978). Wildlife depredation on newly

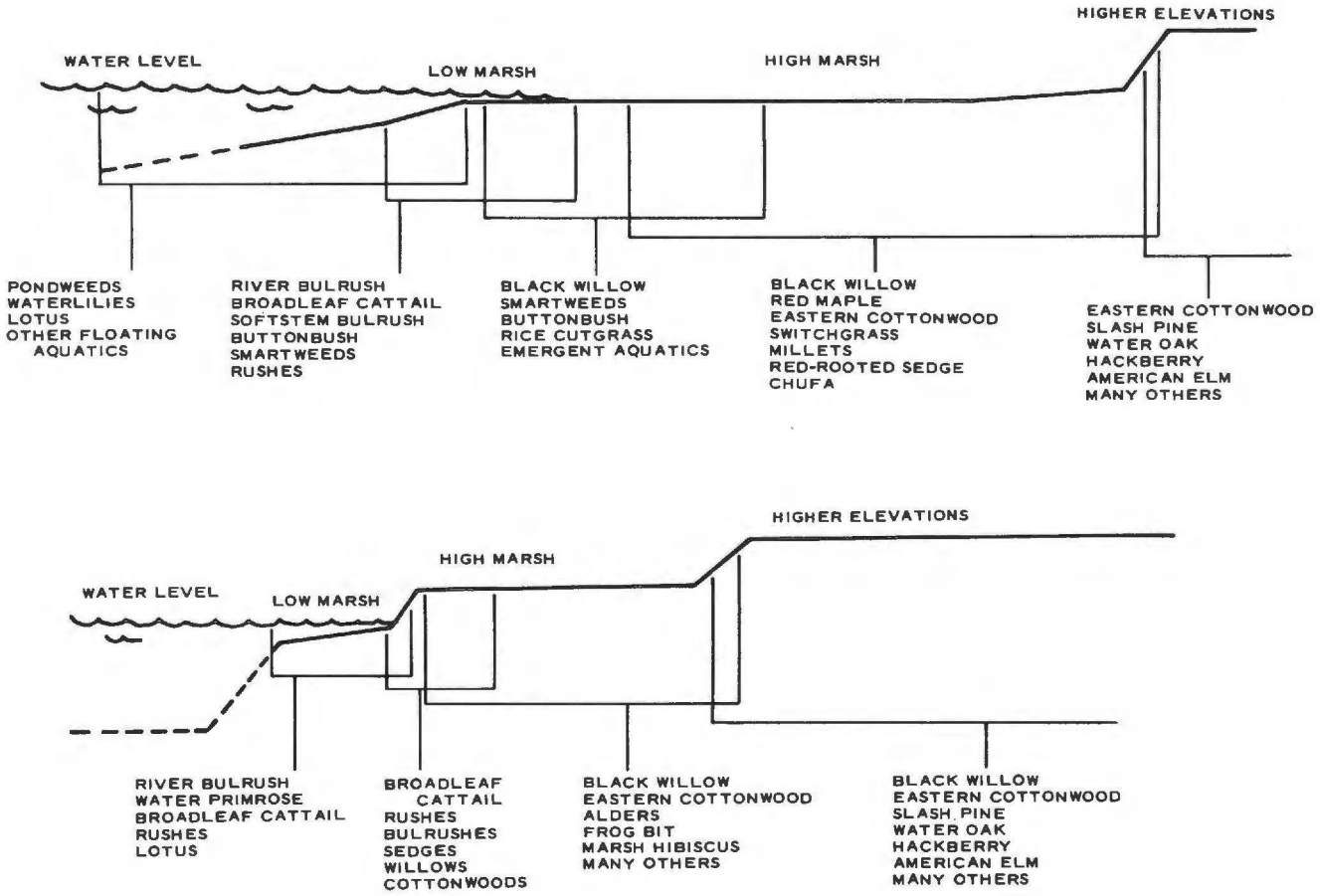


Fig. 67. Sketches of typical freshwater marshes near lakes or ponds (upper panel) and rivers (lower panel) in eastern and interior United States, showing plant associations that usually occur in these marshes (U.S. Army Engineer Waterways Experiment Station 1978).

established marshes must be controlled in extreme cases to ensure successful revegetation.

After revegetation of a particular site, maintenance becomes a major consideration. Nonmaintenance allows natural succession to proceed and involves no additional costs unless undesirable effects develop. The site should be monitored to determine whether maintenance measures are needed such

as fertilizer application, plant replacement, additional planting, or control of invading plants, plant diseases, or wildlife depredation.

Wetland farming is used in some situations: water levels are lowered in the spring or early summer and the bottom is planted with waterfowl food crops (Linde 1969). The soil is mechanically tilled and planted or the exposed mudflats are seeded. Water must be available for fall reflooding so that the crops produced will be available to waterfowl.

Linde (1969) discussed the techniques and potential success of growing several wetland plants for waterfowl food. Early flooding may result in premature consumption of the food crop by large concentrations of waterfowl. Seeding and flooding at intervals can be used to spread out production of the food supply by maturing crops at successive stages. Givens et al. (1964) discussed the growing of food crops for ducks and geese.

Spoilbanks and impoundment dikes should be revegetated as soon as practical after construction to keep erosion and siltation to a minimum. In some areas, spoilbanks revegetate naturally, but artificial propagation is usually necessary. Linde (1969) discussed the seeding of certain plants for cover and protection on dikes, spoilbanks, and emergency spillways.

Duebbert et al. (1981) described techniques used for the establishment of seeded grasslands within the prairie pothole region of the North Central United States. The primary purpose of this grassland establishment was to benefit nesting waterfowl and other prairie wildlife. Fowler and Whelan (1980) noted that experimentally established forage in a reservoir inundation zone is an important food source for white-tailed deer.

40.3. IMPACTS ON THE ENVIRONMENT

This discussion concerns the use of revegetation to enhance wildlife habitat. Additional revegetation benefits include shoreline, marsh, or aquatic substrate stabilization; erosion protection; enhancement of invertebrate and fish habitat; improved water quality; and improved aesthetics. The advantages of revegetation projects to wildlife depend on the amount and quality of existing habitat and the changes in habitat conditions that can be induced at the site. The species composition can be changed by adding more valuable species, increasing diversity, creating new habitat, and providing forage or shelter that is lacking. When bare substrate areas are revegetated, completely new habitat conditions are created. However, bare substrate is sometimes the most desirable, and revegetation of the site would adversely affect breeding birds, such as certain colonial nesting waterbirds.

Hunt et al. (1978) listed the advantages and disadvantages of planting selected species:

Advantages

1. The most suitable vegetation to fulfill the project objective will be present.

2. Substrate stabilization will occur rapidly, with top growth catching sediments on the surface and root growth spreading and stabilizing the substrate.

3. Plant species can be selected for their ability to correct a specific soil deficiency (e.g., legumes can be planted to increase nitrogen content).

4. Aesthetic appearance of the site can be improved.

Disadvantages

1. Extensive prior planning and effort are required to locate, obtain, and plant the propagules.

2. Considerable lead time is needed to allow for seed harvest or dormancy, or for growing transplants.

3. Arrangements and facilities must be available to handle, store, and treat the propagules.

4. The soil may require extensive modification to prepare a seedbed.

The advantages and disadvantages of natural plant establishment are discussed in the preceding section.

The production of farm crops can be used to manipulate wildlife migration patterns and timing and to help alleviate depredation on agricultural crops. Changes in migration may be detrimental if the concentration of wildlife, especially waterfowl, creates the potential for disease epizootics.

Improper species selection may result in the establishment of a desirable plant species in such great abundance that it becomes a liability. Introduced plants may also outcompete native plants and become a nuisance to local agricultural crops.

40.4. *COSTS*

Revegetation costs of a habitat development project vary greatly, depending on regional differences, plants selected, collection and planting techniques, skill of personnel, and other factors. Selected substrate modification costs (in 1978 dollars) were provided by Hunt et al. (1978) and U.S. Army Engineer Waterways Experiment Station (1978):

1. Bulldozer or motor grader: $30 to $75 per hour of operating time, depending on the size of equipment.

2. Tractor and disk: $4 to $14 per acre for each trip over the site. Proper seedbed preparation requires multiple disking.

Costs (per pound) of fertilizers were given by Hunt et al. (1978): nitrogen, $0.20; phosphate ($P_2O_5$), $0.15; and potash ($K_2O$), $0.09. U.S. Army Engineer Waterways Experiment Station (1978) listed the cost of all-purpose 13-13-13 (NPK) fertilizer as $5.10 per 100 lb.

Costs were $6 to $8 per ton for applying agricultural limestone (Hunt et al. 1978) and $9 to $14 per ton for applying lime (U.S. Army Engineer Waterways Experiment Station 1978).

U.S. Army Engineer Waterways Experiment Station (1978) noted that labor required, in man-hours per acre, ranged from 40 to 80 for transplants and sprigs; 40 to 60 for rhizomes, tubers, and rootstocks; and 4 to 16 for seeds. Estimated man-hours for collecting, handling, and planting vegetation, based on actual operating time and excluding transportation, and equipment rental, covered a wide range (Table 31). Man-hours and costs for digging transplants, planting, and seed collection were also provided by U.S. Army Engineer Waterways Experiment Station (1978).

Marsh transplants could be obtained in 1978 from some commercial firms at costs ranging from $0.14 to $0.75 per plant; seeds of some species may be available (U.S. Army Engineer Waterways Experiment Station 1978). A list of commercial and government sources for propagules of upland plants was provided by Hunt et al. (1978). Many of these sources may also supply propagules for marsh plants.

Costs for mechanical and semimechanical planting and fertilizing of 1 to 5 acres with peat-potted stock are $6000 and $9000 per acre, respectively (Garbisch 1978).

Cost estimates for wetland farming operations are given in Table 32.

Table 31. Estimated labor required for various steps in vegetation establishment (modified from Hunt et al. 1978).

Item and action	Labor required (man-hours)	Remarks
Seeds (50,000 per unit)		
Collecting	6-8	Rate variable[a]
Storing	2 initially, 0 daily	No maintenance required
Planting	1-2	Mechanical planting
	3	Broadcast by hand
	>8	Planted in rows by hand
Other propagules (1000 per unit)		
Digging	12-16	Rate variable[a]
Storing and handling	16-24 initially, 2-4 daily	Maintenance required
Planting	2	Mechanical operation
	8	Hand labor
Maintenance		
Fertilizing (per 2.5 acres)	1.5-2	Mechanical operation
Liming (per 2.5 acres)	1.5-2	Mechanical operation
Cultivating (per 2.5 acres)	1.5-2	Mechanical operation
Mowing (per 2.5 acres)	1.5-2	Mechanical operation
Staking and pruning (per 1000 plants)	4-8	Hand labor

[a]Rate depends on species and training of personnel and (when applicable) the form of the propagule.

Table 32. Costs (not including seed) for wetland farming operations in Wisconsin (modified from Linde 1969).

Operation and area	No. of acres	Cost per acre
Aerial seeding of mud flats		
Northeast	6	$ 2.97
East central	12-16	3.75
Horicon Marsh National Wildlife Refuge[a]	---	1.65
Average		$ 2.79
Plow, disk, and plant		
East central	10	$11.83
East central	17.3	12.42
East central	5	14.32
East central	8.8	13.45
Average		$13.01
Disk and plant		
East central	16	$11.02
East central	18.1	4.19
East central	16.5	7.72
Average		$ 7.64

[a]The Horicon Marsh Refuge is in east-central Wisconsin

40.5. EVALUATION FOR USE ON UMRS

Revegetation has good potential for use on UMRS. In many locations, valuable aquatic plants and marsh vegetation have been severely reduced in area and numbers or largely destroyed; some have disappeared. If the causes of loss or reduction can be identified and corrected, affected areas would benefit from revegetation. Natural reestablishment is often slow and unreliable; planting helps expand and speed the revegetation of barren sites.

Many sources of aquatic food for waterfowl are lost when backwaters fill with sediments. To replace this loss and to provide a dependable food supply for waterfowl, wetland farming can be done in suitable locations. The existing levee and drainage districts can be used to establish marsh vegetation and to increase wetland habitat. In addition, areas that formerly

contained large beds of aquatic plants (e.g., Pool 8 of UMR, which once had many American wildcelery beds) could be improved by revegetation.

Waterfowl nesting habitat on islands in UMRS could be improved by the establishment of suitable cover. Flood-secure upland habitat is significantly lacking in the river corridor and is available mainly on bluffs, some 300 ft above the water surface (Fernholz 1981). A revegetation study of a dredged material island in Pool 8 of UMR, conducted by the University of Wisconsin-La Crosse, River Studies Center (1975), showed that the establishment of vegetation on dredged material disposal sites was feasible, but that low surface moisture content limited planting success.

In situations where vegetation control is possible on UMRS, there may be useful applications for revegetation. After timber clearing operations, especially in monotypic stands, the planting of more desirable forest species would be beneficial. Many of the more valuable timber- and mast-producing tree species have been logged on much of the UMR basin, leaving no seed source for regeneration. In addition, the higher groundwater levels caused by the lock and dam construction resulted in moister soil. As a result, many desirable plant species have been confined to drier sites. Irregular and unreliable mast production, the removal of seeds by floods, and heavy growths of ground layer vegetation also contribute to a scarcity of valuable species on otherwise desirable sites (U.S. Army Corps of Engineers, Rock Island District 1981). Tree species valuable for wildlife and timber require artificial regeneration to establish or increase their numbers in the overstory. Mast production and browse conditions for many wildlife species could be improved by management of the plant communities.

PART IX. SUMMARY

Mitigation and enhancement techniques identified and described in this handbook can be used by resource managers on UMRS and other large river systems to reduce the impacts of various perturbations: present and future navigation; operation and maintenance of a navigational channel; industrial and urban development; and natural processes, such as sedimentation. We have attempted to indicate which techniques are most useful, least expensive, easiest to implement, and least likely to cause environmental damage. The techniques are discussed under four primary headings: (1) Bank Stabilization Techniques, (2) Dredging and Disposal of Dredged Material, (3) Fishery Management Techniques, and (4) Wildlife Management Techniques.

BANK STABILIZATION TECHNIQUES

Bank stabilization is commonly used to channelize river flow for navigation. Protection of the bank from erosion inhibits lateral migration of the channel bed, and the energy of the river is dissipated by scouring the bed and deepening the channel. Bank protection can be applied to banks that have failed, that are about to fail, or that could fail if not protected. Erosion may result from the forces induced by wave and current action or by slope failure. Currents, wind- and boat-generated waves, and the hydraulic forces within the bank affect the shoreline in varying combinations. The relative contribution of any one factor to bank recessions is highly site-specific and can vary significantly with channel width, bank materials, presence of vegetation, depth of water or stage of river flow, duration and frequency of vessel traffic, and other factors. Determination of the relative importance of the factors contributing to bank recession is desirable because the protective measure chosen may fail if consideration is not given to the force causing the greatest damage.

Riprap revetments. The use of riprap is an effective technique for protection against the erosive forces of river currents, wind- and boat-generated waves, and local scouring. As such, riprap can be used almost anywhere for many purposes--e.g., for upper and lower bank protection; at river bends; in backwater and discharge areas; as toe protection for other bank stabilization structures (jetties, breakwaters, dams, dikes, other revetments, levees); around hydraulic structures such as piers, culverts, and bridges; at island heads; at point bars; along a narrow channel exposed to extensive or intensive boat traffic; or near any discharge area where velocities are high and scouring may occur. Riprap, in combination with other alternatives of bank stabilization, can be used to effectively mitigate the detrimental impacts of erosion on a system-wide basis, as well as at site-specific areas such as barge fleeting areas and terminals.

Riprap can have several beneficial effects:

1. Providing substrate for benthos and periphyton.
2. Providing cover and reducing current velocities.
3. Providing a stable channel bottom for colonization by mussels.
4. Providing gravel bed substrates for mussels and spawning beds for fish.
5. Reducing erosion, which could secondarily affect other habitats.

Riprap may also have disadvantages:

1. It does not provide habitat for wildlife and can eliminate existing habitat.
2. Too much riprap results in loss of habitat diversity.
3. It may not be compatible with other land uses.

An ad hoc review panel of UMRCC deemed it appropriate to limit the extent of riprap that should be applied in various subsections of UMRS. Total shoreline riprap includes that put in place before inundation by the navigation dams. If use of riprap exceeds (or has exceeded) the limits recommended by the panel, the loss of habitat diversity must be compensated. Panel recommendations relate to selected portions (rivers) of UMRS as follows:

1. Head of navigation to lock and dam (LD) 10 of UMR--allow up to 50% total shoreline riprap on the main channel border on a pool-by-pool basis.

2. From LD 10 to LD 27 of UMR--allow up to 30% total shoreline riprap on the main channel border on a pool-by-pool basis.

3. From LD 27 to Cairo of UMR--90% of the shoreline is riprapped; accept no additional riprap except in emergency situations. Some removal of riprap in low energy areas is desirable. Other bank stabilization techniques should be used.

4. Kaskaskia River--shoreline is 100% riprapped on the lower 30 miles. Riprapping of the remaining 6 miles of navigable stream should be limited to 10% of the total length of the shoreline.

5. Illinois River--no riprapping exists and none is anticipated due to the low energy regime of the river.

6. St. Croix River--accept riprapping of an additional 5% of the total shoreline length.

7. Black River--accept no additional riprapping.

8. Minnesota River--accept riprapping of up to 50% of the total shoreline.

Other revetments and bulkheads. Revetments and bulkheads are continuous structures that parallel the shoreline and directly protect the bank from erosive processes. Revetments are sloped structures that are built to protect existing land or newly created embankments against erosion by wave action, currents, and weather. Bulkheads, on the other hand, are normally vertical and are primarily designed to prevent sliding of the land behind the structure.

Cellular concrete grids, articulated concrete mattresses, Enviroblox, and gabions are excellent replacements for riprap where natural stone is in short supply, and where it is difficult to place riprap. These units can provide protection that is as good as, if not better than, riprap, and they are no less attractive. They generally are easy to install, reasonably inexpensive, and have no adverse effects on the environment. Articulated concrete mattresses and Enviroblox can be hung vertically, whereas riprap and other techniques require a slope. This feature makes them useful for steep slopes, ramps, and access areas for fishermen. Cellular concrete grid revetments are unstable in severe wave climates, but are an economic and visually attractive alternative to riprap in more moderate wave climates. The appearance of cellular concrete grids, Enviroblox, and gabions, like that of riprap, can be enhanced by promoting the establishment of vegetation. Gabions and Enviroblox have many interstitial spaces that promote colonization by aquatic flora and fauna and provide cover for fish. Gabions provide more weight and interlocking between armor units than are provided by loose riprap or sand bags. Gabions are durable, flexible, porous, require less stone than riprap, and do not need stones of a given minimum size, as loose riprap does. However, the construction of gabion revetments is relatively labor intensive. High sediment loads and ice floes may shorten the expected life-span of gabions, although gabions have sometimes withstood severe floods and ice floes without damage.

Used-tire revetments are inexpensive and effective for reducing erosive forces. They are easy to manipulate and assemble in various configurations, but are not visually attractive unless covered by vegetation. Used-tire revetments can provide both fish and wildlife habitat. Revetments constructed of sand- or concrete-filled synthetic bags are not as attractive as other revetments that promote vegetation, and are not as permanent as cellular concrete grids or polypods. However, they have potential for intermediate protection on most eroding slopes on UMRS. The fact that sand on the construction site can be used to fill the bags is a real advantage. In addition, bag revetments are an inexpensive alternative to riprap.

There is some application for the use of broken concrete on UMRS if the projecting steel reinforcing rods are cut off (for safety reasons). Polypods, due to their great weight and size, are useful in high energy areas such as those in the Middle Mississippi River around wing dams and bridge piers.

Bulkheads are effective in steep or vertical slope situations where riprap cannot be used, but bulkheads generally have more adverse impacts on the environment than do revetments. Aluminum bulkheads are preferable to those made of wood, steel, asbestos, or concrete because the alumimum structures require little or no maintenance, are more durable than the others, and are easy to construct. Although timber crib bulkheads filled with rock can provide aquatic habitat, they cannot withstand high energy regimes and are subject to rotting if not chemically treated.

River training structures. River training structures, for the purpose of this discussion, are usually perpendicular to the shoreline, and guide or train river flow to protect banks from the scouring processes of river flows. When these structures are installed primarily to maintain shorelines or beaches, they are called groins. Impermeable river training structures (stone wing dams, stone-filled timber pile dikes, earth- and stone-filled wood cribs, sand bags, and gabions) are efficient in providing bank protection because they deflect the flow away from the bank. Whereas the impermeable structures act as a buffer between the bank and erosive forces, permeable structures (unfilled-timber pile dikes, fences, jacks, tree retards, tire- or brush-filled wood cribs) slow the current to noneroding velocities, encourage sediment deposition, and allow time for the establishment of vegetation.

Because permeable dikes require fairly high sediment loads to operate effectively, they may not be applicable to the upper reaches of UMR, where there is relatively little of suspended sediment. Permeable structures may be practical for bank stabilization in the Middle Mississippi River, where sediment loads are higher. They can stabilize banks without loss of habitat and increase habitat diversity. Impermeable structures such as submerged stone wing dams have some fishery enhancement value because they provide cover and boundary roughness in the main channel of the river. However, accretion can occur, even in low sediment areas, thereby necessitating the modification of these structures to reduce this process. From the standpoint of economics and possible changes in river stages, it is not recommended that impermeable structures be constructed merely to enhance the fisheries of the main channel border of UMR. The building of emergent wing dams (such as those on the Middle Mississippi River) can be detrimental because they result in decreased island areas, lowered and reduced riverbeds, reduced flow areas, elimination of side channels, and exchange of agricultural lands for fish and wildlife habitat.

Timber pile dikes provide aquatic habitat similar in quality to that provided by stone dikes. Timber pile dikes require more maintenance, however, and are less effective as a training structure, which limits their application. Timber pile dikes, tree retards, and timber cribs could be used to enhance fishery habitat in certain areas.

Sand-filled synthetic bags and gabions have been used successfully as

groins in the Great Lakes for bank protection; certain areas of UMRS could benefit from the use of these structures.

Fixed and floating breakwater structures. Breakwaters are constructed or located offshore parallel to the shoreline. Their primary function is to reduce wave action on the shore by wave deflection and energy absorption. Breakwaters are unique mitigation structures because they are designed to dissipate wave energy before it reaches the shore. Fixed breakwaters, as compared with floating breakwaters, provide better wave attenuation, require less frequent maintenance, and have a longer life-span. However, fixed breakwaters may obstruct littoral drift and contribute to wave resonance within a harbor; are very susceptible to scouring (particularly toe erosion); require more extensive construction activities; may decrease water circulation; inhibit fish movement and migration; and are much more costly than floating breakwaters. Structures made of vertical wood piles, wood cribs, low rubble mounds, or sheet piling are useful in shallow areas not subjected to severe wave action. They do not cause some of the adverse environmental impacts of other structures and are less expensive than some of the other fixed breakwaters. Any wood used should be treated with chemical preservatives and should not be cut or drilled after that treatment.

Principal advantages of floating breakwaters include their greater potential for multiple use (i.e., as fish attractors or spawning structures, or substrates for colonization by flora and fauna); their only minor interference with water circulation, shore processes, and fish migration; their automatic adjustment to fluctuations in water level; their transportability and reusability; and their low cost relative to that of fixed breakwaters. Floating breakwaters can be used in conjunction with riprap, gabions, and other revetments or structures in areas exposed to intensive wave action. In general, floating breakwaters--and particularly floating tire breakwaters--are likely to be used in major pools that have relatively long fetches, considerable small-boat traffic, or housing developments. Potential uses include (1) protection of marinas and harbors, (2) creation of artificial spawning reefs, (3) protection of beach areas, (4) protection or creation of nursery coves, (5) provision of midwater spawning platforms, (6) protection of barge fleeting areas, and (7) protection of areas below locks and dams.

Vegetation. Vegetation can attenuate wave action, reduce current velocities, buffer the bank against the impact of floating ice and debris, protect against surface erosion due to piping and minor variations in river stage, add structural support (i.e., roots) to the bank, and act as a sediment trap. Vegetation is the least expensive, most visually attractive, and least complex method of combatting bank erosion. It is applicable in all areas of UMRS for stabilization of dredged materials, levees, and natural banks. The major disadvantage of vegetation is that its usefulness as the sole method of bank protection is limited in areas where current velocities are high and banks are high and steep. In such areas, vegetation must be used in

conjunction with other structural bank stabilization techniques. Protective vegetative cover also expands wildlife habitat, enhances recreational opportunities, and improves water quality. In addition, vegetation is the only self-renewable method of bank protection.

Chemical soil stabilizers. Chemical soil stabilizers are used for temporary erosion control until vegetation is established. They are also used as tackifiers for organic mulches for revegetation, as stabilizers for clay canal banks, and as binders for gravel for a riprap substitute. These materials are fairly inexpensive and easy to apply in most situations. The more sturdy chemical soil stabilizers may be used by themselves to protect banks in certain limited situations, such as small areas subject to only medium or light erosive forces.

Erosion-control mattings. Erosion-control mattings help establish and maintain vegetation on river banks; the more sturdy mattings may also replace riprap in controlling surface erosion on banks subjected to medium erosive forces. These materials are particularly useful when a bank has been eroded, denuded, or newly formed. Erosion-control mattings are more effective than chemical soil stabilizers in controlling soil erosion, but the matting products are considered too expensive to use on a large-scale basis to help establish vegetation. Small applications would be reasonable and feasible.

Filter fabrics and grouting. Filter fabrics may have some application in reinforcing underwater surfaces subject to erosive forces caused by the churning action of passing vessels. Filter fabrics have replaced grouting in the lining of many revetments and seawalls. The use of grouting for additional protection of riprap revetments is limited, and provision for adequate drainage to reduce hydrostatic pressure is critical.

Island creation. The creation of artificial islands is probably the only method available to reduce fetch in the pools and backwater areas of UMRS. In large, open water areas created by the lock and dam system, the wind and wave action resuspends bottom materials and causes shoreline erosion, resulting in turbidity and sediment accumulation. Islands created to reduce fetch could result in greater stability of the area, decreased turbidity, decreased shoreline erosion, higher production of invertebrates and vegetation, and beneficial use of dredged material for wildlife and recreation.

Berm creation and beach enrichment. Berms and enriched beaches can be built to protect beaches or backshores by dissipating wave energy before it reaches the river bank. The beaches can also enhance recreational potential. Construction of berms and beaches constitutes a beneficial use of dredged material. Careful consideration is needed in maintaining beaches because they may affect downdrift shorelines--particularly beaches on enriched barrier islands adjacent to the main channels of UMRS. Side channel openings fill in

quickly from eroding beaches, and thus may cut off sources of fresh water to the backwater areas.

Water level control. Fluctuations in water levels can cause river banks, bluffs, and shorelines to become unstable and erode. The banks along UMRS are stratified, consisting of layers of noncohesive materials that are subject to erosion. Failures of this type of bank may be induced by either the presence or absence of water. Changes in the river stage as a result of either the storage and release of water for hydroelectric and navigation purposes, even though relatively small, can cause water flow within the banks. Any gain in erosion control by water level manipulation may not be enough to offset disadvantages caused to navigation and hydroelectric operations. In some situations, only a 7 to 9% reduction in erosion would result from regulation of water level fluctuations. Further study is needed to determine if the regulation of water levels in UMRS would result in significant erosion abatement.

Regulation of boat traffic. Mitigation of the erosive forces and other adverse environmental conditions generated by boat traffic may require regulatory measures that restrict speed or horsepower, decrease the draft of vessels, restrict the volume or frequency of boat traffic, restrict seasonal navigation, require improved maneuvering devices and techniques, or maintain off-limit zones between boats and river banks.

The regulation of boat traffic on UMRS has some merit, but detailed analyses need to be developed before the direct impact of boat traffic on the environmental resources of UMRS or other large river systems can be soundly evaluated. When scientists have qualified and quantified the impacts of navigation, they can determine what improvements can be gained by regulating boat traffic.

DREDGING AND DISPOSAL OF DREDGED MATERIAL

The principal purpose of dredging is the creation and maintenance of waterways for commerce, recreation, and defense. Rapid siltation from urban, industrial, and agricultural sources often forces continual dredging to maintain navigable channels. The proper disposal of the dredged material has been a historical problem on UMRS; extensive studies have been made to try to discover solutions.

Two basic types of dredges are used on navigable waters--hydraulic and mechanical. Hydraulic dredges pump the dredged material to a discharge point and the mechanically dredged material is usually removed by barge. Dredging disturbs bottom sediments, causes resuspension of fine sediments and associated pollutants throughout local currents, and reduces light penetration

needed for plant growth. The disadvantage of mechanical dredges is the excessive turbidity they develop. The advantage of mechanical dredging over hydraulic dredging is that less water is incorporated into the material. Hydraulic dredges are advantageous because the spoils can be disposed of through a pipeline while the dredging operation continues; however, if the slurry is not contained, the water returning to the river will retain suspended sediment.

Traditional disposal of dredged material has involved terrestrial and aquatic methods. Terrestrial disposal is made in containment structures in shallow water areas that become land masses, on adjacent riparian zones, or on temporary upland sites from which the material is later removed. Riparian disposal can be destructive to the plant community, and shallow-water containment areas fill in valuable wetlands. Aquatic disposal sites includes areas adjacent to navigation channels or the main channel (thalweg) itself. Thalweg disposal may be the most promising method for disposal of dredged material.

Methods of productive use of dredged material in upland areas have been developed because of the need for alternate disposal sites. Dredged material has been used productively in making sanitary landfills, in agriculture, in surface mine reclamation, in construction (as a construction material), and in the development of upland habitat. Island and marsh creation can be productive results of the disposal of dredged materials.

The GREAT I and GREAT II reports provided information and recommendations for dredging and disposal of dredged material in UMRS. The most extensive and detailed product of GREAT I and GREAT II was a site-specific dredged material placement plan. In addition, GREAT recommended that the U.S. Army Corps of Engineers purchase efficient dredging equipment to best accomplish all objectives of the GREAT Channel Maintenance Plan.

FISHERY MANAGEMENT TECHNIQUES

The process of altering river systems for navigation, hydropower, irrigation, and recreation has imposed both physical barriers (e.g., dams) and physiological barriers (e.g., various pollutants) to the well-being of desirable and indigenous fish populations. The mitigation and enhancement techniques described in this guide are designed to offset, ameliorate, or overcome such barriers. Some techniques facilitate reproduction, early-life survival, and migration of fishes; others are designed to increase living space and enhance or ensure good water quality; and still others are designed to protect fish from direct destruction.

In general, the variety of techniques reflects the complexity of fish

management problems in large river systems. Problems will only intensify as human demands on river systems increase.

Fish attractors. Structure is an important feature in aquatic ecosystems. Structure can be defined as any irregularities of substrate or relief, either artificial or natural, living or nonliving, that are concave or convex on the lake bottom or floating on the surface. Sedimentation, water level fluctuations, and decay of flooded timber can cause the loss of valuable structure. The installation of fish attractors is one way of mitigating such losses. Fish attractors are installed for two principal reasons--to create habitat features that promote fish production and survival, and to encourage desirable fish to congregate near installations, thereby facilitating their harvest by anglers.

Materials that have been used in freshwater attractors are varied; they include scrap tires, brush, trees, vitrified clay pipes, cement blocks, rubble, bricks, stake beds, clumps of plastic strips, automobile bodies, and old boats.

Fish attractors promote increased angler harvest as a result of the response of the fish to increased food and shelter. When a fish attractor is installed, a localized ecological complex develops that promotes increased production at each trophic level and can ultimately lead to increased angler harvest. The structures provide stable substrate for the development of a periphyton community. The structures stabilize local conditions and sometimes promote the development of aquatic macrophytes. Colonization by macroinvertebrates increases the food base, which can improve growth and production for the fish populations that use the structures.

A number of adverse effects can result when fish attractors are installed improperly or without proper planning. The structures may promote fish community imbalance and overharvest by anglers. They may also be a hazard to navigation and can be aesthetically displeasing. Although the areas of UMRS in which fish attractors can be installed may be limited, their value may be great. If properly constructed and securely anchored to the substrate, fish attractors made of small groups of scrap tires may be the least expensive, most durable, and most easily installed replacement structures for stump fields. Concrete block, brush, and vitrified clay pipe structures may also be of value, especially to some of the catfishes.

Spawning structures. The primary purposes of spawning structures are to provide a stable substrate that will reduce egg mortality due to siltation and predation, and perhaps provide a more secure spawning habitat for adult fishes (e.g., black bass and catfish) that provide parental care for eggs and fry.

Spawning structures can be used to mitigate the destruction of pristine spawning shoals incurred by construction projects or catastrophic climatological and geological events, and to mitigate the degradation of spawning shoals caused by gradual siltation, which often results from poor land use practices and dredging activities. Structures used to facilitate catfish spawning can be used to offset depleted catfish spawning habitat due to the gradual loss of the original stumps, logs, and timbers that occur in most impoundments.

Spawning structures can be constructed from a variety of materials. The shape, size, and type of material used is species-dependent. Rock and gravel are used most often; however, various cavity-forming materials (e.g., clay and iron pipe) can be used for the catfishes. Well-designed spawning reefs not only enhance fish reproduction, but also provide other benefits to the aquatic environment. The reefs may promote increased primary production by providing a stable substrate for benthic algal communities and further the production of high-quality benthic fish-food organisms.

If reefs are improperly located or constructed from inappropriate materials, they can have a negative effect on fish communities, but usually such planning errors merely render the structure ineffective. Undesirable, nontarget species may also benefit from spawning structures. Target species may be drawn away from quality, historical spawning sites only to spawn on a less effective "new" site where reproductive failure is more likely.

Spawning structures can be used in almost any body of water capable of sustaining natural fish populations; UMRS is no exception. The potential target species--walleyes, black basses, and catfishes--are all important sport fishes in UMRS; however, spawning habitat for these species does not appear to be limiting. Perhaps the procedures would be useful in discrete backwater lakes and sloughs where the effects of deteriorating spawning habitats are known and the benefits of spawning habitat improvement techniques can be quickly realized.

Nursery ponds, coves, and marshes. Whenever fish stock recruitment rates are insufficient, and augmentation by fry stocking fails, the use of isolated nursery waters may be desirable. Nursery waters are used primarily to protect young fish from predation and interspecific competition and are usually developed adjacent to or within a reservoir or lake. However, outlying ponds that meet certain requirements may also be used. In all nursery pond, cove, and marsh applications, the objective is an increased recruitment rate. This is achieved by providing a more secure and productive environment for fish in vulnerable early life stages.

A nursery pond is developed as a separate body of water that has a discharge system leading directly to the body of water being managed. Nursery

coves are located within the managed lake or reservoir and are constructed by screening off the entrance or mouth of the cove. Nursery marshes can be built as separate bodies of water adjacent to a lake, or the marshes may already be present, so that only water control facilities need to be constructed.

The nursery habitat development techniques are methods of habitat enhancement directed at increasing fish stock recruitment rates and, as a rule, have little potential for negative environmental effects; however, unaccountable losses of northern pike brood fish and excessive predation of fingerlings as they were released have been reported.

If recruitment problems arise among desirable sport fish populations in UMRS, both managed spawning marsh and the nursery cove techniques may be applicable. If recruitment problems develop among northern pike populations in UMRS and a decision is made to try to increase recruitment, an abundance of potential managed marsh locations should be available for development. Nursery cove management can be applied to small sloughs that meet appropriate requirements. The placement of water control structures in selected ponds and sloughs to maintain stable water levels during spawning may be applicable. Also, levee and drainage districts in the Middle Mississippi River may be made into useful habitat for spawning and nursery areas by flooding.

Fish screens and barriers. Fish screens and barriers can be used to mitigate the effects of water-related construction projects. Fish screening devices either prevent or guide the movement of fish and, except for barrier dams, are designed to mitigate fish losses incurred through entrainment of fish and fish eggs in industrial, irrigational, hydroelectric, and domestic water diversions. A number of different designs have resulted from attempts to improve screening efficiencies and reduce losses by impingement.

Barrier dams direct fish migrating upstream to a fishway or holding pond and may prevent the upstream movement of undesirable species. Other uses include preventing emigration of desirable species from an impoundment, restricting the availability of spawning habitat to undesirable species, and preventing the intermingling of fish populations.

Few adverse effects result from the installation of fish screening devices. From a biological perspective, fish losses incurred because of a screening device would have also occurred in the absence of the device. Losses can be significantly reduced only by incorporating the best technology available. From an engineering perspective, fish screens cause a loss of hydraulic head; appropriate design (i.e., size of intake and type of device) can reduce this loss. In addition, fish bypasses may result in a loss of water, an important consideration in irrigation diversions.

Some adverse effects of certain barrier devices have been identified. Electric fences pose a potential hazard to humans and animals, particularly in areas of high visitor use. When barrier dams are used to block upstream passage of fish, a small impoundment is formed that may cause habitat to be lost because flow is reduced and siltation is increased; unfavorable water temperatures may be promoted when barrier dams are installed on small coldwater streams.

Usefulness of fish screens in UMRS is probably limited to mitigating entrainment of fish at municipal, industrial, and cooling water intakes. If proposed hydroelectric facilities were developed, fish would need to be protected at the turbine penstocks. The applicability of fish barriers is also limited. If a problem involving fish barriers exists on UMRS, it relates to facilitating rather than to restricting fish movement. One potential application of barriers would be to direct fish to fishways, if such structures are ever constructed.

Fish passage. Periods of migration are often critical in the life histories of stream fishes. Spawning migrations of resident populations often proceed from river pools or lakes into faster flowing reaches or more stable headwater brooks. If such migratory movements are impeded or blocked for extended periods of time, fish populations may be severely diminished or lost entirely. Dams can impede or obstruct fish migration, and some have caused the decimation or loss of valuable fishery resources. Improper installation of highway culverts can also obstruct fish passage. The cumulative effects of several poorly installed culverts within a stream drainage can be substantial.

Fishways have four principal components that must be properly designed for each installation: the entrance approach, the entrance, the fishway proper, and the exit into the upstream water. The types of fishways available include the weir, orifice, vertical-slot or Hell's gate, and Denil. Other fish passage structures include fish locks, fish lifts, and properly designed culverts. Each structure has unique design characteristics that make it more applicable than the others in certain situations.

Fish passage facilities have only one beneficial effect--they allow fish to negotiate total or partial barriers to their movement. A few adverse effects, however, may develop. Depending on the size of the structure, fishways may require a substantial volume of water to function effectively. If the fishway is installed at a hydroelectric or irrigation storage facility, the water loss to the fishway may adversely affect the operations of the facility. Fishways may also allow undesirable fish species to pass into a watershed where they did not live previously. Furthermore, fishways may provide access of undesirable fish to quality spawning and nursery habitat that would permit them to proliferate beyond previous population levels. When culverts are baffled to facilitate fish passage, the structures must be made

larger to permit the same rate of discharge; costs increase accordingly. Moreover, culverts with baffles tend to accumulate debris and require extra maintenance.

It is likely that the installation of fishways at the dams on UMRS would facilitate fish passage. However, fishway design may be difficult because the fishery is far more complex than those in the rivers of the Pacific seaboard. Variability in swimming ability and time of use of the species present would probably be two of the most important considerations. The navigational dams act as partial and temporary migrational obstructions on UMRS, and significantly obstruct the movements of fish.

Water control structures. Water control structures can be used to mitigate the various impacts of dam construction and operation on riverine habitat and fisheries. The structures help control water quality within the impoundment and tailwaters, dissipate the destructive force of high energy releases, stabilize extreme variability of release flows, and help maintain the water quality in backwaters and side channels.

Skimming weirs, multi-level penstocks, and deep-water withdrawal can be helpful in maintaining desirable water quality in both reservoirs and tailwaters by controlling the nature of reservoir mixing and water exchange and reservoir releases. Flip buckets, stilling basins, and baffle-type energy dissipators control the destructive forces of high energy reservoir discharges. Flip buckets and high-turbulence stilling basins can also reduce nitrogen supersaturation problems. Reregulation dams relieve the environmental flux caused by hydroelectric generating facilities. These dams are especially valuable when they can stabilize the combined flows of several offstream hydroelectric facilities. Complete and partial closing dams, gated culverts, and vortex tube sand traps mitigate the effects of altered river hydraulics on backwaters and side channels. The structures can be used to facilitate freshwater flows and reduce the harmful influx of sediments.

These structures generally benefit aquatic environments; they are sometimes a part of normal construction and water management plans. Some of the structures, particularly multi-level penstocks and reregulation dams, are very costly.

Multi-level penstocks are far more versatile than skimming weirs and deep water intakes. The structures are adaptable to changes in reservoir hydrology and stratification patterns. Deep-water intakes sometimes benefit a reservoir by flushing silt; however, the release of silt may adversely affect downstream spawning habitat, and harm fish populations by increasing stream turbidity.

Stilling basins can provide ancillary benefits to tailwater fisheries. In arid regions, where large offstream water diversions are often allocated, stilling basins may provide a survival pool for fish. They are particularly important when provisions for a maintenance flow are not incorporated in water management plans.

When culverts are installed to supply side channels with fresh water, impoundment storage capacity is lost. The culverts, however, are usually installed in closing dams on floodplain river navigation projects on which such water losses have almost no effect. Improperly placed closing dams can have an adverse effect on water quality in backwaters and side channels.

Vortex tube sand traps may require substantial maintenance. Moreover, the devices are largely untested except on strictly controlled canals. The vortex tube sand trap is useful for the investigation of bed loads in streams.

Only complete and partial closing dams, gated culverts, and vortex tube sand traps of the water control structures have applicability on UMRS. Other mitigative devices would not be useful on the dams of UMRS. Closing dams, gated culverts, and vortex tube sand traps can also be used as part of side channel modification measures.

Management of water levels and flows. Reservoir water levels are manipulated for several reasons. Such manipulations may improve fish production by creating quality environmental conditions for primary and secondary producers (i.e., fish food) and improving spawning and rearing success by providing stable spawning substrate, stable water levels during spawning, and quality rearing cover for young fish. Minimum pool allowances protect the carryover capacity of the system. Instream flow strategies are implemented to maintain flow requirements for fish passage, spawning, incubation, and rearing. Such strategies also help to protect water quality, increase production of benthic invertebrates, and maintain escape cover.

If rapid and severe fluctuations of reservoir pools can be prevented, potential damage to the fishery and reservoir habitat can be avoided. Rapid decreases in water levels, such as those experienced in hydroelectric storage facilities, can adversely affect benthic fauna, fish spawning success, and riparian vegetation. Excessive bank sloughing may also ensue.

Minimum pools are generally of a size considered essential to the survival of fish populations. Usually the holdover capacity of a reservoir is positively correlated with the size of the minimum pool. Moreover, longer water retention times facilitate plankton production, thus increasing the carrying capacity for fish.

The management of reservoir and stream water levels and flows for fisheries often conflicts with water management strategies for many of the primary functions of a reservoir. The effectiveness and efficiency of hydroelectric projects, navigational impoundments, and irrigational storage and diversion projects would be impaired by maximum management for fish production.

If long-term stabilization of stream flows for the benefit of the fisheries is achieved, deleterious changes may develop in the streambed of the river, as well as in the streambeds of the tributaries. If high flows are abolished in the main stream when the tributaries are in spate, flows will increase in the tributaries near the mouths, and degradation of their channels will occur. Meanwhile, because the materials deposited in the main stream can no longer be swept away, aggradation will occur and bars and deltas will be formed. The abolishment of flood flows can also have serious deleterious impacts if a river flows through a marsh or estuary. The water necessary to maintain marsh vegetation will not be replenished.

The management of water levels and flows may have considerable applicability in the navigational pools of UMRS, particularly the management of pool water levels for fisheries. If fluctuations of water levels can be reduced during the spawning seasons of pikes and sunfishes, spawning success by those fishes should be increased. Water level management would be most applicable on pools with the greatest storage capacity (i.e., in vertical distance) above the 9-ft channel maintenance elevation. Alternating water level control from year to year and from pool to pool may optimize the effectiveness of the technique.

Minimum instream flows and minimum conservation pools are not an issue in UMRS because navigational water requirements have primacy. These requirements are such that a 9-ft navigational channel will be maintained, which in turn will provide adequate water for fishery needs. However, contingency plans for an event such as a severe drought should include provisions for minimum instream flow requirements of fish and wildlife.

Wing dam modification. Stone wing dams are valuable as sources of food and cover for various species of fish in riverine ecosystems. These structures form a stable substrate that provides important interstitial space, serves as a catchment for detritus, and provides a high surface-to-volume ratio for colonization by periphyton only if the dams are not covered with sediments. Sedimentation reduces niche diversity and the amount of rock substrate available for colonization by invertebrates, and reduces the area and depth of water areas created by wing dams.

Sedimentation behind impermeable wing dams may be inhibited by modifying the structures to promote scouring. Wing dam modifications used on the

Missouri River since 1974 included notching, eliminating the root, and lowering the height of the structure. Modifications have also been made on emergent wing dams in the Middle Mississippi River. Where notches or gaps are made, the accretion process is reduced and about a half acre of slack water is typically formed downstream from the structure.

The modification of wing dikes is intended primarily to be an immediate and inexpensive means of partly restoring main channel habitat for fish and periphyton by retarding or eliminating sediment accretion. The modification also functions as a method of reducing the development of agricultural land downstream from a wing dam such as has occurred on the Missouri River.

The adverse impacts of wing dike modification are generally associated with improperly placed notches, which increase sedimentation rather than decrease it. Bank erosion below notched and rootless dikes has also been cited as an adverse effect associated with wing dike modification. The creation of gaps in these structures essentially reduces the overall efficiency of the river. Overindulgence in wing dike modification may require increased dredging and many of the negative impacts (e.g., increased temporary turbidity, destruction of benthos) associated with dredging.

Wing dam modification may be very beneficial on UMRS, particularly on emergent structures that are imposing severe adverse effects. Additional study of the influence of modification of submerged wing dams is needed. In addition to notching, dredging sand from the stream above wing dams may prove beneficial to aquatic organisms.

Side channel modification. Side channel modifications mitigate the loss or deterioration of side channels and backwaters as a result of the stagnation and accelerated sedimentation that occur when flow regimes are altered. The principal cause of flow regime alteration is the construction of river training structures (e.g., locks and dams, closing dams and dikes, and wing dams) for navigational purposes.

When side channels and backwaters deteriorate, valuable fish and wildlife habitat is lost. Stagnation benefits rough fish populations for a time, but sometimes the entire fishery is eliminated. Accelerated siltation destroys submergent and emergent vegetation, which in turn reduces the suitability of the habitat for fish and wildlife.

Side channel modification or backwater rehabilitation, as practiced on UMR and the Lower Colorado River, is conducted to alter flows through backwater habitats. These flows can be altered by the installation of gated culverts and spillways, and by dredging openings. In addition, undesirable openings can be blocked with dredged materials or partly occluded with closing

dams. Installation of wave barriers and dredging to increase water depth has also been suggested at locations where appropriate.

Techniques used in side channel modification are by no means fully established. In each management measure contemplated, a site-specific set of circumstances is encountered that must be fully investigated before action is taken. After a complete ecological survey is made, a list of potential modifications can be developed, followed by an engineering assessment of their hydraulic effects. The plan can then be completed.

The hydraulic characteristics of side channels and backwaters are generally complex and not easily identified; therefore, predictions of the effects of side channel modifications may be inaccurate. If the hydraulic characteristics are not properly identified, side channel modifications can promote sediment influx or excessive scouring, necessitating further modifications.

Two ancillary benefits, in addition to improved fish and wildlife habitat, that may accrue from side channel modifications are increased accessibility to backwaters for recreationists and a reduction in maintenance dredging.

Side channel modification methods are widely applicable in UMRS. Deterioration of backwaters due to sediment aggradation is a major problem; side channel modification shows promise as a quality restorative technique. Indeed, a number of modifications have been developed. However, the technique should not be considered a panacea for all problems of backwaters and side channels because it cannot solve all backwater problems.

Aeration techniques. The application of aeration techniques increases dissolved oxygen concentrations that have become unacceptably low, usually because of the accumulation of biodegradable organic wastes (direct) or the presence of excessive plant biomasses (indirect). Organic pollutants originate from sources such as effluents of sewage treatment plants, agricultural runoff, septic system leachates, drainage from sanitary landfills, and concentrated wastes of domestic animals. Oxygen depletion reduces the quantity and quality of habitat for fish and fish food organisms. It causes physiological stress in fish and often leads to the development of imbalanced fish communities dominated by undesirable fish species such as common carp and bullheads. Furthermore, anoxic conditions cause taste and odor problems in domestic water supplies, and may cause the development of reduced forms of iron, manganese, and sulfides. In addition, anoxic conditions can intensify eutrophication rates by promoting the dissolution of phosphorus across the sediment water interface.

Aeration techniques can be divided into three major categories: destratification (whole lake aeration), hypolimnetic aeration, and supplemental instream aeration. A water body may be destratified by circulation with either an air-lift or a pump. This technique is used in fish management as a method of restoring habitat losses caused by anoxic conditions in the hypolimnion of eutrophic, stratified lakes and reservoirs and to prevent winterkills of fish populations. Hypolimnetic aeration or oxygenation is a method of adding dissolved air or oxygen to the hypolimnion of a lake without disturbing thermal stratification. The process differs substantially from aeration by destratification and is used when maintenance of cold oxygenated hypolimnetic water is desired (e.g., for a salmonid fishery or for drinking water). Supplemental instream aeration can be provided by the use of several devices and techniques. Mechanical and diffuser aerators have been used successfully in rivers, as have U-tubes located at dams; aeration of water during passage through hydroelectric turbines is also sometimes practicable.

Destratification and hypolimnetic aeration provide benefits to many aspects of water quality, in addition to increasing the quality and amount of fishery habitat. Both techniques effectively reduce concentrations of hydrogen sulfide, iron, and manganese and alleviate other conditions associated with anoxic conditions. The techniques also help to reduce internal phosphorus loading by oxygenating anoxic sediments, and in turn increase the rates of release of phosphorus from the sediment. Destratification can lead to a reduction of algal standing crops and to beneficial shifts in the composition of algal communities. Zooplankton communities may also benefit. Provided that the equipment used is properly designed, possible nitrogen supersaturation and resuspension of toxic contaminants are the only potential adverse effects that can result from hypolimnetic aeration.

Supplemental instream aeration and winterkill prevention may have the most immediate application on UMRS. Supplemental instream aeration may be a particularly important management alternative if significant increases in organic loading occur within the UMR basin. Winterkill prevention techniques, possibly incorporating remote wind-powered aerators, can probably be put to immediate use. It has been demonstrated that, even with advanced waste treatment, certain streams sometimes have low dissolved oxygen. Untreatable, nonpoint inputs may constitute the major sources of biochemical oxygen demand. Dissolved oxygen concentrations are already substandard in some places in UMRS, and these conditions may persist even after waste treatment is improved.

Destratification and hypolimnetic aeration may be of only limited value on UMRS. However, if hydroelectric facilities are developed at the navigational dams, or if modifications to the dams are made in conjunction with the development of a deeper navigational channel, the river system might be altered to the point that some degree of thermally induced density

stratification would occur. If oxygen depletion results, remedial destratification or hypolimnetic aeration systems may have to be used.

Control of nuisance aquatic plants. Excessively dense growths of aquatic vegetation can interfere with the commercial, recreational, and aesthetic uses of waterways. Such growths can also create human and domestic animal health hazards and adversely affect fish communities. Because excessive growth of aquatic vegetation can interfere with almost every human use of waterways, considerable effort has been directed toward developing control or management techniques. Biological, mechanical, and chemical controls, and habitat manipulation are management approaches that have been investigated and applied. A variety of approaches have been developed for use in the many types of ecological situations because of the limited applicability and variations in effectiveness of individual techniques.

The concept of biological control agents has recently been subject to intensive investigation. Attempts have been made to use herbivorous fish, mammals, waterfowl, insects, and crustaceans, and control by the spread of diseases caused by microorganisms or by the introduction of allelopathic plants are also being scrutinized. Too little is known of the potential consequences to permit the use of biological plant control on UMRS at this time.

Cutting and harvesting of aquatic plants is an effective means of reducing many of the objectionable aspects of excessive aquatic plant growth. The ecological impacts of harvesting are minor, and unlike biological and chemical control techniques, the harvesting operation is always controllable. Mechanical harvesting of submergent and floating-leaved aquatic vegetation has little value as a fish management practice on UMRS. Though it is often a desirable management alternative on small lakes and ponds, it is far too costly for application on large river systems, and may be physically impossible in some situations. It would, however, be very useful for providing better boat access and travel conditions in certain weed-choked areas.

A variety of habitat manipulation techniques directed at aquatic plant control have been developed. Overwinter drawdown, flooding, dredging, sand blanketing, use of light-occlusive dyes, and nutrient inactivation are techniques that have been applied with some degree of success. Overwinter drawdowns have been effective in Wisconsin and the southeastern United States, and flooding has been effective in controlling broadleaf cattails wherever it has been attempted. Either technique can be used on any lake with water level control facilities; pumping to manipulate water levels can be effective on small lakes and ponds. Dredging to depths below the photic zone can effectively limit the growth of rooted aquatic plants. The technique also removes nutrient laden sediments and may be used to reexpose less productive sand and gravel substrates that have been buried by excessive siltation.

Several habitat manipulation techniques appear to have only limited utility in controlling aquatic plants in large river systems. Nutrient inactivation, which limits growth only in nonrooted species (e.g., algae, duckweeds), is unsatisfactory for reservoirs with short water retention times. The long-term utility of sand blanketing is questionable and its application is confined to areas with only limited siltation problems. Shading with black, plastic sheeting and light-occlusive dyes would be applicable only to small bodies of water, such as ponds. Because navigation is the prime consideration in UMRS, overwinter drawdowns for submergent aquatic plant control are generally inapplicable.

Chemical herbicides are usually effective and economical. Consequences of using such compounds are not always understood and their applicability is often limited. Only registered products should be used. Impacts of herbicides are usually temporary, and some compounds can be used selectively if properly applied. If the resulting effects are not those sought by managers, no long-lasting ecological damage is likely to occur. Given an appropriate situation, chemical treatment may not only be more effective, but can also be far less expensive than mechanical control. Intensive investigations have demonstrated the safety of the herbicides that have been registered for aquatic use.

Manipulation of fish populations. The primary objective of fish population manipulation methods is to restore or maintain balanced fish populations. Balance as used here connotes a partial fulfillment of Optimum Sustainable Yield (OSY) objectives. If a fish population becomes unbalanced and no longer produces satisfactory yields to the fisherman, several optional management techniques can be initiated to influence the fish populations directly and restore balance. These options encompass techniques of controlled removal and addition of fish.

Stocking fish can, in certain situations, adversely affect endemic fish populations. Dilution of high quality, wild stock gene pools, as well as immediate stress from crowding has been observed in some waters. Moreover, the potential effects of stocking exotics are seldom fully realized ahead of time because the effects of introductions may not be manifested until several years after the fish are introduced. Stocked fish can reduce fishing pressure on native stocks and can be used to provide a fishery in waters where reproduction has failed. Such fish can also provide diversity for anglers by giving them an opportunity to pursue and catch species that otherwise would not be available. Stocking would probably not enhance the fishery of UMRS. If quality habitat can be protected or improved, game fish populations should respond positively. Considering the success of stocking striped bass or its hybrids in some landlocked reservoirs in the United States, these forms may warrant investigation as a possible exotic introduction.

Angler harvest regulations that restrict the catch of an overabundant

species can be relaxed or removed. If the angler harvest is properly regulated, no adverse effects on the fishery should ensue from angling. Problems occasionally arise because angling regulations sometimes apply to entire States or regions and do not consider the unique characteristics of individual bodies of water. Tailoring regulations for each body of water would, in many respects, be ideal. However, such regulations cannot be properly set without adequate population and environmental information. For States such as Wisconsin and Minnesota, which contain thousands of lakes, such a task would be nearly impossible because of fiscal constraints. The public outcry would be overwhelming because of the complex set of regulations that would be needed. Underfishing and overfishing can also adversely affect the populations being managed.

Mechanical removal, generally a form of netting, can be encouraged. Depending on the type of gear used, mechanical removal of fish may produce minor adverse impacts on nontarget populations. Gill nets often kill fish that are caught and are generally size-selective. Species selectivity depends on the time of fishing, net size, and placement of the nets. However, habitats used by different species of fish overlap and nontarget species are nearly always caught. In view of the success of some mechanical rough fish removal projects, direct damage to nontarget species is probably often insignificant. The benefits to sport fish populations resulting from the large-scale removal of dominant rough fish species should outweigh any direct damage to nontarget populations.

Reproductive failure of certain target species can be induced by properly timed water level drawdown. The primary adverse effects of drawdown techniques involve the loss of aesthetic values and of water that may be needed for offstream users. Drawdowns in spring and summer are the most aesthetically unpleasant because odors released by decaying vegetation and dead fish are offensive; furthermore, a drawdown may be impractical then because water impounded for irrigational purposes is at a premium. Losses of nontarget species, particularly invertebrates, may also occur. Beneficial effects of drawdowns, in addition to those intended, include compaction and aeration of sediments and certain desirable changes in plant communities.

Chemicals alone, or in combination with other methods, offer practical means for partly or completely controlling fish in streams. A toxicant in appropriate solution or suspension, properly applied to obtain thorough dispersion in a moving block of water, can reach all fish living in cascades, riffles, pools, at the sides, on the bottom, and in the upper layers of water in streams. None of the registered piscicides are totally fish-specific. However, the concentrations at which registered toxicants are applied are generally safe for nontarget organisms. If invertebrates are affected, their populations usually soon rebuild to pretreatment levels.

Integrated pest management should be pursued to use all tools available. The use of attractants (yet to be developed) might draw undesirable species into areas where a selective toxicant could be used effectively with little impact on the rest of the community. Mechanical harvesting and spot removal with toxicants are two fish population manipulation measures that have immediate applicability on UMRS. Rough fish (especially common carp) are prevalent on UMRS, and a commercial fishery directed toward those species is in operation. Efforts should be made to facilitate the effectiveness of the commercial fishermen, especially by helping the operators locate good fishing grounds and develop better techniques. If localized concentrations of rough fish are not exploited by commercial fishermen, spot removal with toxicants might be useful. However, the need for such removal should be justified on a case-by-case basis.

WILDLIFE MANAGEMENT TECHNIQUES

Wildlife and wildlife habitat associated with large river systems such as UMRS have been greatly affected by man-induced changes resulting from developments in navigation, industry, urban areas, agriculture, and recreation. These changes may have adverse, neutral, or beneficial impacts, but many of the current multiple uses of river systems have adverse effects on wildlife. Maintenance and manipulation of the wildlife habitat are needed to preserve wildlife resources. Management objectives include the maintenance of quality habitat as it exists in a natural ecosystem and provision for quality habitat where it has deteriorated or where a specific habitat component is lacking. The techniques identified here were chosen on the basis of their possible application to large river systems according to two criteria: (1) value in mitigating adverse impacts on wildlife; or (2) value in enhancing the existing wildlife resources. All techniques discussed deal directly with maintenance and manipulation of wildlife habitat.

Artificial nest structures. The loss of suitable avian and mammalian habitat has created a need for increased use of artificial nest structures. Such structures are used to improve or replace nesting habitat for each target species and to mitigate losses caused by timber harvest, snag removal, agricultural clearing, channelization, or inundation. The use of artificial structures should be a secondary technique applied after the existing habitat has been protected, but man-made structures are sometimes the key to the survival of a species. Artificial nest structures can compensate for a deficiency of natural sites in otherwise suitable habitat.

Artificial nest structures have potential for improving wildlife habitat and populations. Cavity-nesting birds (e.g., wood ducks) have greatly benefited from nest box programs. Artificial nesting platforms have also been successfully used by waterfowl, raptors, and colonial-nesting waterbirds.

Properly constructed, erected, and maintained man-made nest boxes platforms have greater longevity and stability than most natural sites and often provide a higher rate of nesting success. Artificial structures are most beneficial when natural sites are limited, but also can improve nesting habitat conditions in areas where natural sites are abundant.

Many types of artificial nest structures have direct beneficial application in UMRS. Waterfowl and colonial-nesting waterbirds may benefit most from the availability of artificial nest structures.

Island creation or development. Islands are considered important wildlife habitat areas because they are relatively predator-free and isolated. Their value has increased in many areas as a result of losses of mainland habitat. Man-made islands have become more important as natural islands are lost to erosion or development. Construction and development of islands, like the provision of artificial nest structures, is most likely to benefit waterfowl and colonial-nesting waterbirds.

Extensive information on dredged material islands has been presented in various reports by the U.S. Army Corps of Engineers Dredged Material Research Program. According to these reports, habitat on islands constructed of dredged material is considered to be critical for some colonial waterbird species but is relatively unimportant for others.

Waterfowl nesting islands are considered important habitat because high nesting densities and nesting success are associated with them. Heavy island use has been attributed to predator-free nest sites, high ratio of water-land edge to land mass, and the proximity of water, food, loafing sites, and nesting cover. Islands should be separated from the mainland by several hundred feet, surrounded by water at least 2 ft deep, and elevated several feet above the maximum high water level.

New islands can provide nesting sites similar to those on existing islands and at traditional mainland locations, and offer additional benefits, including protection from ground predators and generally reduced human interference. The construction of islands is primarily a beneficial use of dredged material. The potential negative effects of using dredged material for island creation include improper placement and the effects associated with disposal of dredged material in the water. Invasion of important nesting islands by predators may result in the complete destruction of nests.

The creation or development of islands in UMRS can create new wildlife habitat and improve existing habitat primarily to benefit nesting waterfowl. The presence of an island may also improve the associated habitat surrounding the island.

Marsh creation or development. Marsh creation or development is a technique designed to offset wetland losses or improve existing wetlands of low productivity. Marshes are recognized as extremely valuable natural systems because of their importance as fish and wildlife cover and in food production, nutrient cycling, erosion control, floodwater retention, groundwater recharge, and aesthetics. Low-quality wetlands that have filled in with vegetation or sediments and lack open water can be improved by creating potholes (small, shallow, open-water retention areas or basins usually constructed to increase waterfowl breeding territories) or constructing level ditches (ungraded ditches usually built with draglines in wetlands areas). The purpose of both potholes and ditches is to increase habitat diversity for furbearers and waterbirds, to provide food and cover for wildlife during dry periods, and to improve the dependability of the water supply.

Shallow-water impoundments involve the conversion of upland areas or wetlands to marsh environments. Marsh creation with dredged material is a method of creating or improving wetland habitat as an alternative to traditional techniques used for the disposal of dredged material.

Shallow wetlands provide habitat for waterbirds, furbearers, and upland wildlife. Large impoundments sometimes inundate valuable terrestrial habitat, but small impoundments more often enhance the surrounding uplands. The open water or adjacent spoilbanks created by level ditches are valuable to waterbirds, furbearers, and fish. Marsh creation with dredged material may improve wetland habitat, but the potential disadvantages include a lack of suitable locations, loss of other habitats, and the potential release of toxic contaminants.

Marsh creation and development techniques may have potential use on UMRS. Many backwaters have filled in with sediments, and wetlands now lack diversity due to vegetative growth that crowds out open water. Increased diversity could improve habitat for all wildlife, particularly for waterfowl, furbearers, and fish.

Greentree reservoirs and mast management. Greentree reservoirs are forested river bottomlands that are artificially flooded to attract certain species of migrating ducks. The production of mast from various oaks and other tree species as a wildlife food source is the most important objective. Mallards and wood ducks are the principal target species, but greentree reservoirs also benefit wild turkeys, squirrels, deer, quail, furbearers, and many species of nongame mammals, birds, reptiles, amphibians, and fish. Timber production is also considered an important management objective. Bottomland hardwoods can be safely flooded while the trees are dormant.

Complete drainage before the growing season is required because summer flooding may damage or kill desirable mast-producing tree species. Selective thinning may be necessary to maximize mast production.

Suitable greentree impoundment sites occur on UMRS, and could be used to enhance waterfowl feeding conditions if justified. The primary adverse effect of greentree impoundments is potential decrease of tree growth due to improper seasonal flooding or drainage.

Vegetation control. Vegetation control is needed to maintain the desired vegetational succession that improves and maintains wildlife populations. It is also needed to free new plantings or regrowths from competition so they can become established and develop. Rank, dense vegetative growth generally has little value to wildlife if it covers large areas. Climax woodlands and weed-choked marshes are of only limited value to wildlife. The removal of undesirable growth benefits wildlife by providing openings, creating more edge, and increasing desirable plant species. As habitat losses increase, the remaining areas become more valuable and need to be effectively managed to best meet wildlife requirements.

Five categories of vegetation control for wildlife management purposes include chemical, mechanical, and biological control measures, water level fluctuation, and burning. Herbicides have been effectively used in wildlife habitat management and their use provide the most economical and efficient method of control. Disadvantages include potential health hazards, possible contamination of water, and destruction of desirable vegetation. Mechanical methods are usually the most costly, but may be necessary to create specific habitat conditions; unfortunately, most mechanical equipment for vegetation removal cannot operate on wet soils. Biological methods of vegetation control (e.g., grazing by wildlife and livestock and parasitization by insects) are limited and may be associated with severe adverse effects. Water level fluctuation is an effective method of changing the vegetative composition, but this method requires water control structures. Water levels that are held too high or for too long can damage valuable vegetation. Burning is an economical technique of vegetation removal and may be used to stimulate new growth. The destruction of bird nests or desirable vegetation are potential negative effects of burning.

Vegetation control could be used extensively on UMRS to improve wildlife habitat. Chemical control, mechanical control, burning, and water level fluctuation can all be used effectively. Biological control has extremely limited application. Timber management techniques could be applied on UMRS to diversify the forest composition, improve mast production, and promote timber growth.

Water level control. Natural or man-induced water level fluctuations, or the lack thereof, have direct impacts on the vegetative communities and wildlife fauna of wetlands. Flood control and navigation are the major reasons for specific water level control on large river systems. Unfortunately, the water level control needed for these uses is often detrimental to wildlife habitat.

The management of water requires adequate water sources, control structures to permit manipulation of water levels, and a properly designed impoundment system to retain water levels. Dikes and levees are used to impound the water. Various spillway designs are incorporated in the levees to allow surplus water out of the impoundment and additional manipulation of water levels.

Planned drawdowns of normal water levels can be an efficient and productive technique in marsh management, provided that adequate control structures and a reliable source of water are available. Drawdowns may be used to permit natural propagation and growth of certain types of vegetation, to retard plant succession, to eradicate undesirable types of vegetation, to reduce the effects of turbidity, to increase decomposition of organic material, to allow the cultivation and planting of wetland soils, and to allow repairs or maintenance of water control structures. Possible adverse effects of drawdowns include establishment of undesirable vegetation, destruction of valuable wetland plants, reduced furbearer populations, loss of soil nutrients, reduced invertebrate populations, lowered levels in potable water wells, and unavailability of open water for recreation.

The control of water levels on UMRS with the existing lock and dam system can be used to benefit wildlife resources. In addition, small impoundments within the system could permit water control for specific areas. However, multiple-use practices and the lock and dam systems of UMRS do not allow the flexiblity required for the application of some management techniques.

Revegetation. The improvement of wildlife habitat through revegetation is an important enhancement technique for both wetland and terrestrial sites. Revegetation can reestablish valuable cover plants or increase forage production for wildlife. The loss of natural forage plants, especially aquatic species, often requires the planting of domestic crops to offset the loss of suitable feeding areas. Newly created islands or marshes often require planting to establish the most desirable vegetation for wildlife. Specific application may be made to improve aquatic sites devoid of waterfowl forage or upland sites containing monotypic bottomland forest species.

Each plant species has definite requirements that limit its distribution. Native species should be given first consideration because they are usually better adapted to the area and offer a better likelihood of survival.

Plantings create an advantage for species that may be slow invaders or that are normally outcompeted by less desirable species. The establishment of vegetation on dredged material has been the focus of extensive research and has yielded promising results for creating wildlife habitat.

Water level control has an important role in the growth and establishment of wetland plants. Soil moisture is an important factor when new vegetation is being established, particularly on coarse-grained, dredged material. Fertilizer applications may be necessary where soil fertility is low. In general, revegetation of existing wildlife habitat and of newly created islands and marshes may greatly improve wildlife habitat in UMRS and other large river systems.

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PART XI. GLOSSARY[1]

ACCRETION - May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a BEACH by deposition of waterborne or airborne material. Artificial accretion is a similar buildup of land resulting from an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

ACRE-FOOT - A unit for measuring the volume of water, equal to the quantity of water required to cover 1 acre to a depth of 1 foot. Equal to 43,560 cfs or 325,851 gallons. The term is commonly used in measuring volumes of water used or stored.

AEROBIC - Live or active only in the presence of free oxygen.

ALLELOPATHY - The baneful influence of one living plant upon another due to secretion of toxic substances.

ALLUVIAL CHANNEL - A channel whose bed is composed of noncohesive sediment that has been or can be transported by flowing water.

AMPLITUDE, WAVE - (1) The magnitude of the displacement of a wave from a mean value. An ocean wave has an amplitude equal to the vertical distance from stillwater level to wave crest. For a sinusoidal wave, amplitude is one-half the wave height. (2) The semirange of a constituent tide.

ANTHROPOGENIC - Induced or altered by the presence and activities of humans.

APRON - An adjunct to a dam or other structure, consisting of a surface protection against erosion.

ARMOR - Artificial surfacing placed on the banks of a stream to resist erosion or scour.

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[1]Compiled primarily from the following sources: Brown (1980), Cole (1956), Gray (1967), Keown et al. (1977), Mulvihill et al. (1980), Odum (1956), Simons et al. (1975, 1979), U.S. Army Coastal Engineering Research Center (1966, 1977), Upper Mississippi River Conservation Committee [n.d.], and Webster's Third New International Dictionary of the English Language (1961).

ARTICULATED CONCRETE MATTRESS - Rigid concrete slabs usually hinged together with corrosion-resistant wire fasteners; primarily for lower bank protection.

ASPHALT (BULK) - Mass uncompacted asphalt used to stabilize the bank against erosion; usually dumped from a truck (for upper bank protection) or a barge (for lower bank protection).

ATTENUATION - (1) A lessening of the amplitude of a wave with distance from the origin. (2) The decrease of water-particle motion with increasing depth. Particle motion resulting from surface oscillatory waves attenuates rapidly with depth, and practically disappears at a depth equal to a surface wavelength.

AUFWUCHS - Periphyton; all organisms that are attached to, or move upon, a submersed substrate, but which do not penetrate it.

BACKFILL - Material used to fill behind a small structure such as a seawall or bulkhead.

BACKSHORE - That zone of the shore or beach lying between the foreshore and the coastline, which is acted upon by waves only during severe storms, especially when combined with exceptionally high water.

BACKWATER - Water backed up or retarded in its course as compared with its normal or natural condition of flow. In stream gaging, a rise in stage produced by a temporary obstruction such as ice or weeds, or by the flooding of the stream below.

BANK - (1) The rising ground bordering a lake, river, or sea; of a river or channel, designated as right or left as it would appear when one faces downstream. (2) An elevation of the sea floor of large area, located on a Continental (or island) Shelf and over which the depth is relatively shallow but sufficient for safe surface navigation; a group of shoals. (3) In its secondary sense, a shallow area consisting of shifting forms of silt, sand, mud, and gravel, but then used only with a qualifying word such as "sandbank" or "gravelbank."

BANK PROTECTION - Placement of revetment or other armor to stabilize a streambank against erosion or use a river training structure designed to deflect the hydraulic erosive forces away from a streambank.

BANK-FULL STAGE - Stage at which a stream first overflows its natural bank.

BEACH - The zone of unconsolidated material that extends landward from the low-water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach--unless otherwise specified--is the mean low-water line.

BEACH EROSION - The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind.

BED (STREAMBED) - The bottom of a water course.

BED LOAD - The part of the total sediment load that moves by rolling or sliding along the bed. The term "bed load" may be used to designate either coarse material moving on or near the bed, or material collected in or computed from samples collected in a bed load sampler or trap. In other words, load that is not sampled by a suspension load sampler.

BENTHIC COMMUNITY - A group of plants or animals living in or on the streambed.

BENTHOS - Aquatic organisms growing on or associated principally with the bottom.

BERM - The nearly horizontal part of beach or backshore formed of material deposited by wave action.

BIOTA - Animal and plant life of a particular region.

BITUMINOUS PAVING - An impermeable rock-, mesh-, or metal-reinforced mattress of asphaltic or other bituminous material placed on a streambank to prevent erosion.

BREAKWATER - A structure protecting a shore area, harbor, anchorage, or basin from waves.

BRIDGE ABUTMENT - Structure supporting the bridge at the point where the land meets the water, as distinguished from a pier (which is wholly in the water).

BRIDGE PIER - Structure in the water that supports a bridge.

BROOD - A group of young birds, usually accompanied by a hen.

BULKHEAD - Structure or partition built to prevent sliding of the land behind it. It is normally vertical or consists or a series of vertical sections stepped back from the water. A bulkhead is ordinarily built parallel (or nearly parallel) to the shoreline.

BUOY - A floating object attached to the bottom of a waterway, used for marking moorage.

BYPASSING, SAND - Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may be natural or induced by man.

CAISSON - A watertight chamber used as a foundation.

CANAL - An open conduit for the conveyance of water; distinguished from a ditch or lateral by its larger size; usually excavated in natural ground.

CAPACITY - The ability of a stream current to transport, in terms of quantity.

CELERITY - Speed of motion or action.

CELLULAR BLOCK - Regularly cavitated concrete block placed directly on a streambank or filter to prevent erosion. The cavities facilitate the growth of either volunteer or planted vegetation.

CHANNEL - (1) Deepest portion of a river bed, in which the main current flows. (2) Natural or artificial, clearly distinguished waterway that periodically or continuously contains moving water, or that forms a connecting link between two bodies of water.

CHANNEL, BACKWATER - Side channels that do not carry appreciable flows, even at high stages.

CHANNEL, SIDE - The smaller channels (other than the main or thalweg channel) in a reach of river where islands divide the reach into two or more channels.

CHOP - The short-crested waves that spring up quickly in a moderate breeze, and break easily at the crest.

CHUTE - Natural or artificial steep-sloped reach of an open channel.

CHUTE AND POOLS - The flow phenomenon and bed configuration accompanying flows that occur where slopes are steep and bed-material discharges are large. The flow occurs at slopes steeper than those of antidunes and consists of a series of pools in which the flow is tranquil, connected by steep chutes where the flow is rapid. A hydraulic jump forms at the downstream end of each chute where it enters the pool. The bed configuration consists of triangule elements with a steep upstream slope, a flat, almost horizontal back, and a gentle downstream slope. The chutes and pools move slowly upstream as erosion progresses.

CLAY - Sediment finer than 0.004 mm, regardless of mineralogical composition.

CLIMAX - Final and most stable of series of communities in succession, remaining relatively unchanged as long as climatic and physiographic factors remain constant.

COLONIAL WATERBIRDS - Colonial nesting birds (e.g., terns, gulls) associated with large water areas.

COMMUNITY - Association of plants or animals, or both, in a given area or region in which various species are more or less dependent on each other.

CONCRETE BLOCK - Precast whole or broken concrete material placed on a streambank or filter to prevent erosion.

CONFLUENCE - Joining, or the place of junction, of two or more streams.

CONVERGENCE - (1) In refraction phenomena, the decreasing of the distance between orthogonals in the direction of wave travel. Denotes an area of increasing wave height and energy concentration. (2) In wind-setup phenomena, the increase in setup observed over that which would occur in an equivalent rectangular basin of uniform depth, caused by changes in planform or depth; also the decrease in basin width or depth causing such increase in setup.

CRIB - An open-frame structure filled with earth or stone ballast designed to absorb energy and to deflect hydraulic currents away from a streambank.

CRITICAL SHEAR STRESS - The minimum amount of shear stress exerted on a sediment particle that causes the particle to begin to move.

CUBIC FEET PER SECOND (cfs) - A unit expressing rate of discharge. One cubic foot per second is equal to the discharge of a stream of rectangular cross section, 1 foot wide and 1 foot deep, in which water flows at an average velocity of 1 fps.

DABBLER - A duck that feeds by tipping in shallow water.

DEADMAN - A wooden pile, concrete block, or horizontal timber placed landward of a bulkhead and used to anchor the structure.

DEEP WATER - Water so deep that surface waves are little affected by the bottom. Generally, water deeper than one-half the surface wavelength is considered deep water.

DELTA - Alluvial deposit at the mouth of a river and the geographical and geomorphological unit that results from it.

DESIGN WAVE - Wave used for designing coastal structures such as revetments, breakwaters, jetties, or groins. The wave height and period assist the designer in selecting sizes of armor units and other features of the structure. The design wave is not usually the maximum wave, for economic reasons.

DETRITAL - Related to dead organic tissues and organisms in an ecosystem.

DETRITUS - Any loose material that results directly from rock disintegration, especially when composed of rock fragments--contrasted with soil. In the sediment field, detritus has generally been used to designate the coarser material moved or deposited.

DIFFRACTION (OF WATER WAVES) - The phenomenon by which energy is transmitted laterally along a wave crest. When a part of a train of waves is interrupted by a barrier, such as a breakwater, the effect of diffraction is manifested by propagation of waves into the sheltered region within the barrier's geometric shadow.

DIKE (SILL, GROIN, SPUR, JETTY) - A river training aid constructed of earth, wood, or stone, designed to deflect erosive currents away from a bank and to control movement of bed material.

DISCHARGE - In its simplest concept, discharge means outflow; therefore, the use of this term is not restricted as to course or location and it can be applied to describe the flow of water from a pipe or from a drainage basin.

DISPOSAL, ON LAND - Disposal of dredged material on land at locations where the materials are not subjected to the influence of fluctuations in water stage.

DISPOSAL, OPEN WATER - Disposal of dredged material on islands, marshes, and along riverbanks at locations where these materials are subject to the influence of river stage fluctuations, or are readily washed back into the river by rainfall.

DISPOSAL, THALWEG - Disposal of dredged material in the main channel.

DIVERSION - The removal of water from a stream or other body of water through a canal, pipe, or other conduit.

DOLOS - A type of precast concrete armor unit used for facing rubble mound structures.

DOWNDRIFT - The direction of predominant movement of littoral materials.

DREDGING - A process by which sediments are removed from the bottom of streams, lakes, and coastal waters, transported by ship, barge, or pipeline, and deposited in open water or on land.

DURATION - In wave forecasting, the length of time the wind blows in nearly the same direction over the fetch (generating area).

ELASTOMER - An elastic rubberlike substance.

EMBANKMENT - An artificial bank such as a mound or dike, generally built to hold water or to carry a roadway.

EPILIMNION - The upper, thoroughly mixed warm stratum of water lying above the metalimnion in a thermally stratified lake.

EROSION - The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action or tidal or littoral currents, or by deflation.

EROSION-CONTROL MATTING - Fibrous matting (e.g., jute, paper, fiberglass, etc.) placed or sprayed on a streambank to prevent erosion or to provide temporary stabilization until vegetation is established.

ESTUARY - (1) The part of a river that is affected by tides. (2) The region near a river mouth in which the fresh water of the river mixes with salt water of the sea.

EUTROPHICATION - Process by which waters become more eutrophic (richer in dissolved nutrients required for the growth of aquatic plants such as algae), either as a natural phase in the maturation of a body of water or artificially (as by fertilization and pollution).

EUPHOTIC ZONE - Upper layers of a body of water, into which sufficient light penetrates to permit photosynthesis.

FASCINE - A bundle of brush, sticks, or timber used to make a foundation mat or a revetment to protect a streambank against erosion.

FENCE - A river training structure normally consisting of wire mesh attached to a series of posts, often in double rows; the interstitial space between the rows may be filled with rock, brush, or other locally available materials.

FETCH - The distance over unobstructed open water on which waves are generated by a wind having a constant direction and speed.

FILTER - Layer of sand, evenly graded rock, or cloth, placed between the bank armor and spoil for one or more of three purposes: to prevent the soil from coming through the armor by extrusion or erosion, to prevent the armor from sinking into the soil, or to permit natural seepage from the streambank to occur and thus prevent buildup of excessive hydrostatic pressure.

FINE SEDIMENT - The part of the sediment discharge that consists of particles so fine that they are almost uniformly distributed in the water column and constitute only an inappreciable fraction of the sediment in the streambed. The upper size limit of fine sediment at a particular time and cross section is a function of the flow rate as well as of the sediment particles.

FLOOD - An overflow or inundation that comes from a river or other body of water and causes or threatens damage. Any relatively high streamflow overtopping the natural or artificial banks in any reach of a stream.

FLOOD PLAIN - A strip of relatively smooth land bordering a stream, built of sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current. It is called a living flood plain if it is overflowed in times of high water, but a fossil flood plain if it is beyond the reach of the highest flood.

FLOOD STAGE - The stage at which overflow of the natural banks of a stream begins to cause damage in the reach in which the elevation is measured.

FLOW REGIME - A range of flows producing similar bed forms, resistance to flow, and mode of sediment transport.

FOOD CHAIN - A series of organisms in a community that are dependent, one upon another, for food; it begins with microscopic plants and ends with the largest carnivores. Also called food web.

FREEBOARD - Distance between waterline and top deck of a structure or vessel.

FROUDE NUMBER - The dimensionless ratio of the inertial force to the force of gravity for a given fluid flow. It may be given as Fr = V/Lg where V is a characteristic velocity, L is a characteristic length, and g is the acceleration of gravity; or as the square root of this number.

GABION - A wooden, wire mesh, or cloth basket or cage, filled with earth, stone, or other locally available material, and used as a component of a bank protection structure.

GAGE STATION - A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or discharge are obtained.

GRADIENT (GRADE) - With reference to winds or currents, the rate of increase or decrease in speed, usually in the vertical; or the curve that represents this rate. *See* SLOPE.

GRAVEL - Loose, rounded fragments of rock, 0.75 to 3 in. in diameter.

GROIN (British, GROYNE) - A rigid structure built at an angle (usually perpendicular) from the shore to protect the shore from erosion or to trap sand. A groin may be further defined as permeable or impermeable, depending on whether or not it is designed to allow sand to pass through it.

GROIN FIELD (also Groin system) - Series of groins spaced along the shoreline acting together to protect a section of beach.

GROUNDWATER - Water in the zone of saturation, where all openings in rocks and soil are filled; the upper surface of the zone forms the water table.

GROUT - A fluid mixture of cement and water or of cement, sand, and water used to fill joints and voids.

HABITAT - The specific place where a particular plant or animal lives--where interacting physical and biological factors provide at least the minimum life requirements for one organism or for a group of organisms occurring together.

HABITAT TYPE - All the area that supports a given community of organisms.

HARBOR - Any protected water areas affording a place of safety for vessels; for the purposes of the present study, includes boat basins, marinas, and moorage.

HEAD - (a) The difference in elevation between two points in a body or column of fluid (as between the surface and a submerged orifice at which the fluid flows outward, or when one is pumping fluid into an elevated tank, flows inward) (b) the resulting pressure of the fluid at the lower point, expressible as this height; broadly: fluid pressure.

HIGH WATER LINE - Strictly, the intersection of the plane of mean high water with the shore. The shoreline delineated on the nautical charts of the U.S. Coast and Geodetic Survey is an approximation of the high water line. For specific occurrences, the highest elevation on the shore reached during a storm or rising tide, including meteorological effects.

HYPOLIMNION - Colder stagnant region of heavier water lying below the metalimnion in thermally stratified lakes.

IMPACT - An action producing a significant causal effect on the whole or part of a given phenomenon.

IMPERMEABLE GROIN - A groin through which sand cannot pass.

INVERT - The lowest point in the interval cross section of an artifical channel.

INVERTEBRATE - Animal lacking an internal skeletal structure--e.g., an insect, mollusk, or crayfish.

ISLANDS - Vegetated areas within the channel banks, separated from the mainland by the main channel and side channel or by two side channels.

JACK (KELLNER JACK) - A component of a river training structure consisting of wire or cable strung on three mutually perpendicular metal, wooden, or concrete struts.

JETTY - (1) On open seacoasts, a structure extending into a body of water, and designed to prevent shoaling of a channel by littoral materials, and to direct and confine the stream of tidal flow. Jetties are built at the mouth of a river or tidal inlet to help deepen and stabilize a channel. (2) In British usage, jetty is synonymous with PIER or "wharf."

LEE - Shelter, or the part or side sheltered or turned away from the wind or waves.

LEEWARD - The direction toward which the wind is blowing and waves are traveling.

LENTIC - Pertaining to still waters, such as a lake or pond.

LEVEE - Water-retaining earthwork used to confine streamflow within a specified area along the stream or to prevent flooding due to waves or tides.

LEVEE, NATURAL - Low alluvial ridge adjoining the channel of a stream composed of sediment deposited by flood water which has overflowed the banks of the channel.

LEVEL DITCHING - Construction of ungraded ditches on lands having a high water table; use to create habitat diversity for wildlife.

LIFE CYCLE - The series of successive phases (life stages) or morphological changes through which an organism passes in its development from a fertilized egg to maturity, and ultimately death.

LITTORAL - Of or pertaining to a shore, especially of the sea or a lake.

LITTORAL CURRENT - Any current in the littoral zone caused primarily by wave action--e.g., longshore current, rip current.

LITTORAL DRIFT - The sediment material moved in the littoral zone, under the influence of waves and currents.

LITTORAL TRANSPORT - The movement of littoral drift in the littoral zones by waves and currents. Includes movement parallel to the shore (alongshore transport) and perpendicular to it (onshore-offshore transport).

LOAD, TOTAL SEDIMENT - The sum of the bed-material load and the wash load, or bed load and suspended load, or measured and unmeasured load.

LOG AND CABLE - Trees or timber anchored to a streambank by a series of cables to serve as protection against erosion.

LOTIC - Pertaining to moving water, as in a stream.

LOWER BANK - That portion of a streambank having an elevation less than the mean water level of the stream.

MARSH - An area of soft, wet, or periodically inundated land, generally treeless and usually characterized by grasses and other low growth.

MASS WASTING - Downslope movement of earth and vegetative materials under the force of gravity. The many types of mass wasting include landslides, sloughing, and mudflows.

MAST - Nuts used as forage by birds or other animals.

MATTRESS - A broad flat cage or network of concrete, wood, stone, or other locally available materials used to protect a streambank against erosion.

MEAN HIGH WATER - The average height of the high waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and to reduce the results to the equivalent of a mean 19-year value. All high water heights are included in the average where the type of tide is either seimidiurnal or mixed. Only the higher high water heights are included in the average where the type of tide is diurnal; so determined, mean high water is the same as mean higher high water.

MEAN LOW WATER - The average height of the low waters over a 19-year period. For shorter periods of observation, corrections are applied to eliminate known variations and to reduce the results to the equivalent of a mean 19-year value. All low water heights are included in the average where the type of tide is either semidiurnal or mixed. Only lower low water heights are included in the average where the type of tide is diurnal; so determined, mean low water is the same as mean lower low water.

MEANDER - One curved portion of a sinuous or winding stream channel, consisting of two consecutive loops, one turning clockwise and the other counterclockwise.

MEDIAN DIAMETER - The midpoint in the size distribution of sediment: half the weight of the material is composed of particles larger than the median diameter and half is composed of particles smaller than the median diameter.

MIGRATION - Mass movement of animals to and from feeding, reproduction, or nesting areas.

MUCK - Dark highly organic soil

MUD FLATS - Low, unvegetated mud substrate that is flooded at high tide or river stages and uncovered at low tide or river stages.

NATURAL RIVER - A river that is usually unaffected by backwater curves caused by dams and other hydraulic structures.

NEKTON - Macroscopic organisms swimming actively in water; e.g., fish.

NESTING - Pertaining to brooding eggs or rearing young.

NOURISHMENT - The process of replenishing a beach. It may be brought about naturally, by longshore transport, or artificially by the deposition of dredged materials.

NURSERY - Area where young animals are born or cared for.

NUTRIENTS - Elements or compounds essential as raw material for the growth and development of organisms; e.g., carbon, phosphorus, oxygen, nitrogen.

ORGANIC MULCHES - Any of a number of organic agents (e.g., petrochemicals or vegetative matter) used to stabilize a streambank against erosion by affording permanent protection or temporary protection and nutrients for the establishment of vegetation. These agents, which may be in the form of liquids, emulsions, or slurries, are normally applied by means of mechanical broadcasters.

OVERTOPPING - Passing of water over the top of a structure as a result of wave runup or surge action.

OXBOW - Abandoned part of a former meander, left when the stream cut a new, shorter channel.

P:R ratio - The ratio of the rate of gross primary production to the rate of respiration.

PEAT - Partly decomposed plant matter.

PELAGIC - Pertaining to the open water region of a lake where shore and bottom have lessened influence.

PENSTOCK - Conduit or pipe for conducting water to the turbine at a hydroelectric facility.

PERCHED BEACH - A beach or fillet of sand retained above the otherwise normal profile level by a submerged dike.

PERIPHYTON - Organisms, mostly microscopic and often mostly attached, growing on the bottom or on other submerged substrates.

PERMEABLE GROIN - A groin with openings large enough to permit passage of appreciable quantities of littoral drift.

PHYTOPLANKTON - Minute, suspended aquatic plants. *See* PLANKTON.

PIER - A structure, usually of open construction, extending out into the water from the shore, to serve as a landing place or recreational facility, rather than to afford coastal protection. In the Great Lakes, a term sometimes improperly applied to jetties.

PILE - A long, heavy timber or section of concrete or metal that is driven or jettied into the earth or seabed to serve as a support or protection.

PILE DIKE - Dike constructed of piles.

PILING - A group of piles.

PIPING - Erosional process common to noncohesive soils and stratified banks when groundwater seeps out and down the bank face.

PLANKTON - Suspended microorganisms with relatively little power of locomotion that drift in water and are subject to action of waves or currents.

POINT BAR - The convex side of a loop of a meandering stream where active deposition of bed load and suspended sediment load occurs.

POOL - A deep reach of a stream.

PRODUCTIVITY - Rate of production of offspring, or of fixation of solar energy.

PROPAGULE - A structure that propagates a plant.

REACH - (1) The length of channel for which a single gage affords a satisfactory measure of the stage and discharge. (2) The length of a river between two gaging stations. (3) More generally, any length of river.

REFLECTED WAVE - The part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface.

REFRACTION (OF WATER WAVES) - (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed. The part of the wave advancing in shallower water moves more slowly than the part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents.

RESONANCE - The phenomenon of amplification of a free wave or oscillation of a system by a forced wave or oscillation of exactly equal period. The forced wave may arise from an impressed force upon the system or from a boundary condition.

REVETMENT - A sloped facing built to protect existing land or newly created embankments against erosion by wave action, currents, or weather. Revetments are usually placed parallel to the natural shoreline.

RIFFLES - Shallow rapids in an open stream, where the water surface is broken into waves by obstructions totally or partly submerged.

RIPARIAN - Pertaining to the banks of a body of water.

RIPRAP - Layer, facing, or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of structure or embankment; *see* REVETMENT.

RIVER BED - Lowest part of a river valley shaped by the flow of water and along which most of the sediment and runoff moves in interflood periods.

RIVER MILE - River mile of a section is the mileage between the section and a reference point along the river thalweg or main-flow path.

RIVER TRAINING STRUCTURE - Any structure in a stream, or placed on, adjacent to, or in the vicinity of a streambank, that is intended to deflect currents, induce sediment deposition, induce scour, or in some other way alter the velocity regimen of the stream.

RIVER WIDTH - The distance between vegetated banks taken normal to the general direction of flow in the river.

ROOKERY - Any colony of breeding birds.

RUBBLE - Rough, irregular fragments of random size placed on a streambank to retard erosion. The fragments may consist of broken concrete slabs, masonry, or other suitable refuse.

RUBBLE-MOUND STRUCTURE - Mound of randomly shaped and randomly placed stones protected with a cover layer of stones or specially shaped concrete armor units.

RUNUP - The rush of water up a structure or beach as a wave breaks. The amount of runup is the vertical height above stillwater level that the rush of water reaches.

SACK REVETMENT - A revetment consisting of sacks (e.g., burlap, paper, or nylon) filled with concrete, sand, stones, or other material placed on a streambank to serve as protection against erosion.

SAND - Rock fragments less than 0.75 in. in diameter.

SANDBAR - A dune-shaped bed form whose upstream surface is extremely long in relation to the geometry of the channel (length, 2 to 3 times the width of the channel). The bar may often protrude above the flow.

SCOUR - Erosive action--particularly, pronounced local erosion--of water in a stream, in excavating and carrying away materials from the bed and banks.

SEAWALL - A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action.

SEDIMENT - Fragmental material that originates from weathering of rock and is transported by, suspended in, or deposited by water or air.

SEDIMENT CONCENTRATION - The ratio of dry weight of sediment to total weight of the water-sediment mixture, expressed in parts per million.

SEDIMENT DISCHARGE - The amount of sediment that is moved by water past a section in a unit of time.

SEDIMENTATION - Process of deposition of material, usually soil or organic detritus, in the bottom of a liquid.

SEICHE - (1) A standing wave oscillation of an enclosed water body that continues, pendulum fashion, after the cessation of the originating force, which may have been either seismic or atmospheric. (2) An oscillation of a fluid body in response to a disturbing force having the same frequency as the natural frequency of the fluid system. Tides are now considered to be seiches induced primarily by the periodic forces caused by the sun and moon. (3) In the Great Lakes area, any sudden rise in water of a harbor or a bay, whether or not it is oscillatory. Although inaccurate in a strict sense, this usage is well established in the Great Lakes area.

SHALLOW WATER - (1) Commonly, water of such a depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-half the surface wavelength as shallow water. (2) More strictly, in hydrodynamics with regard to progressive gravity waves, water in which the depth is less than $^{1}/_{25}$ the wavelength.

SHEAR STRESS - The force exerted by flowing water on the bed of a river.

SHOAL (noun) - A detached elevation of the sea bottom, composed of any material except rock or coral, that may endanger surface navigation. (verb) - (1) To become shallow gradually. (2) To cause to become shallow. (3) To proceed from a greater to a lesser depth of water.

SHORE - The narrow strip of land in immediate contact with the sea, including the zone between high- and low-water lines. A shore of unconsolidated material is usually called a beach.

SHOREBIRDS - Any birds of the suborder Charadrii that frequent shorelines.

SHORELINE - The intersection of a specified plane of water with the shore or beach (e.g., the highwater shoreline is at the intersection of the plane of mean high water with the shore or beach.) The line delineating the shoreline on U.S. Coast and Geodetic Survey nautical charts and surveys approximates the mean high water line.

SHORELINE, ERODING - Shoreline that is losing material because of wave action, longshore current, or frequent storm activity.

SIGNIFICANT WAVE - A statistical term relating to the one-third highest waves of a given wave group and defined by the average of their heights and periods. The composition of the higher waves depends on the extent to which the lower waves are considered. Experience indicates that a careful observer who attempts to establish the character of the higher waves will record values that approximately fit the definition of the significant wave.

SIGNIFICANT WAVE HEIGHT - The average height of the one-third highest waves of a given wave group. The composition of the highest waves depends on the extent to which the lower waves are considered. In wave record analysis, the average height of the highest one-third of a selected number of waves, this number being determined by dividing the time of record by the significant period.

SIGNIFICANT WAVE PERIOD - An arbitrary period generally taken as the period of the one-third highest waves within a given group. Note that the composition of the highest waves depends on the extent to which the lower waves are considered. In wave record analysis, this is determined as the average period of the most frequently recurring of the larger well-defined waves in the record under study.

SILT - Sediment particles with diameters of 0.004 to 0.062 mm.

SLIDE - Movement involving failure along discrete planes of weakness, such as a rotational slump.

SLOPE - The degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25 or 1 on 25, indicating 1 unit vertical rise in 25 units of horizontal distance; or given in a decimal fraction (0.04); degrees (2° 18'); or percent (4%).

SLOUGHING - Mass wasting that involves small amounts of material moving as clumps of individual particles.

SOIL CEMENT - A mixture of soil and portland cement of a prescribed moisture content that is compacted to provide stability for a soil surface and to prevent its erosion.

SPAWNING - Deposition of fertilized eggs, by fish and certain other aquatic animals.

STAGE - The height of a water surface above an established datum plane, also gage height.

STANDING WAVES - Curved symmetrically shaped waves on the water surface and on the channel bottom that are virtually stationary. When standing waves form, the water and bed surfaces are roughly parallel and in phase.

STILL-WATER LEVEL - The elevation that the surface of the water would assume in the absence of wave action.

STREAM - A general term for a body of flowing water. In hydrology the term is generally applied to the water flowing in a natural channel, as distinct from a canal. More generally, as in the term stream gaging, it is applied to the water flowing in any channel, natural or artificial.

STRUCTURE - (a) irregularities of substrate or relief either artificial or natural, living or nonliving, which are concave or convex and (b) something constructed or built, such as a dam, bridge, or breakwater.

SUBSTRATE - Solid material upon which an organism lives or to which it is attached.

SUCCESSION - Sequence of communities that replace one another in a given area.

SURFACE AREA, RIVER - The area between the vegetated riverbanks.

SURFACE OF THE RIVERBED - The river surface area minus the area of the islands.

SURGE - (1) The name applied to wave motion with a period intermediate between that of the ordinary wind wave and that of the tide, say from 0.5 to 60 min. It is of low height; usually less than 0.3 ft. (2) In fluid flow, long interval variations in velocity and pressure, not necessarily periodic, perhaps even transient in nature.

SWELL - Wind-generated waves that have traveled out of their generating area. Swell characteristically exhibits a more regular and longer period, and has flatter crests than waves within their fetch.

SYNTHETIC MATTRESS, MATTING, CASING, AND TUBING - A grout- or sand-filled, manufactured, semiflexible casing placed on a streambank to prevent erosion.

TAILWATER - The reach of stream immediately below a dam on a stream.

TERRESTRIAL - Growing or living on or peculiar to the land, as opposed to the aquatic environment.

TETRAHEDRON - Component of river training works made of six steel or concrete struts fabricated in the shape of a pyramid.

TETRAPOD - Bank protection component of precast concrete consisting of four legs joined at a central block, each leg making an angle of 109.5° with the other three.

THALWEG - Line following the deepest part of a streambed, channel or valley.

TOE - The base of a structure, the lowest part.

TOMBOLO - Bar or spit connecting an island or structure to the mainland or to another island.

TOW - String of barges lashed together and pushed by a towboat.

TRAP EFFICIENCY - Ability of a reservoir to trap and retain sediment. Expressed as a percent of sediment yield (incoming sediment) that is retained in the reservoir.

TURBIDITY - Deficiency in clarity; muddiness, murkiness.

UPDRIFT - The direction opposite that of the predominant movement of littoral materials.

UPLIFT - The upward water pressure on the base of a structure or pavement.

UPPER BANK - The portion of a streambank having an elevation greater than the mean water level of the stream.

VEGETATION - Woody or nonwoody plants. In the present study the term applies mainly to plants used to stabilize a streambank and retard erosion.

VERTEBRATE - Animal having an internal skeletal system.

VISCOSITY - (or internal friction) - The molecular property of a fluid that enables it to support tangential stresses for a finite time and thus to resist deformation.

WATERLINE - A juncture of land and sea. This line migrates, changing with the tide or other fluctuation in the water level. Where waves are present on the beach, this line is also known as the limit of backrush. (Approximately, the intersection of the land with the stillwater level.)

WATERSHED - Formerly most commonly used to refer to the divide separating one drainage basin from another. However, over the years, the use of the term to signify drainage basin or catchment area has come to predominate, although the term drainage basin is preferred. Drainage divide, or merely divide, is used to denote the boundary between one drainage area and another. Used alone, the term "watershed" is now ambiguous and should not be used unless the intended meaning is made clear.

WAVE - A ridge, deformation, or undulation of the surface of a liquid.

WAVE CREST - (1) The highest part of a wave. (2) That part of the wave above stillwater level.

WAVE HEIGHT - The vertical distance between a crest and the preceding trough.

WAVELENGTH - The horizontal distance between similar points on two successive waves, measured perpendicular to the crest.

WAVE PERIOD - The time required for a wave crest to traverse a distance equal to one wavelength, for two successive wave crests to pass a fixed point.

WAVE STEEPNESS - The ratio of the wave height to the wavelength.

WAVE VELOCITY - The speed at which an individual wave advances.

WEEP HOLE - Drainage hole in a structure allowing release of groundwater to prevent a buildup of water behind the structure.

WIND WAVES - (1) Waves formed and built up by the wind. (2) Loosely, any wave generated by wind.

WINTERKILL - A die-off of fish that takes place in winter under ice cover caused primarily by oxygen deficiencies.

ZOOPLANKTON - Animal plankton.

PART XII. COMMON AND SCIENTIFIC NAMES

PLANTS[1]

SCIENTIFIC NAME	COMMON NAME
Acer negundo	Boxelder maple
Acer rubrum	Red maple
Acer saccharinum	Silver maple
Acorus calamus	Sweet flag
Alisma sp.	Waterplantain
Alternanthea sp	Chafflower
Asclepias incarnata	Swamp milkweed
Betula sp.	Birch
Brasenia sp.	Watershield
Brasenia schreberi	Schreber watershield
Bromus sp.	Brome
Bromus inermis	Smooth brome
Cabomba sp.	Fanwort
Carex sp.	Sedge
Carya sp.	Hickory
Carya illinoensis	Pecan hickory
Celtis occidentalis	Common hackberry
Cephalanthus sp.	Buttonbush
Ceratophyllum sp.	Hornwort
Ceratophyllum demersum	Common hornwort

[1]Source: Scott and Wasser (1980) and U.S. Soil Conservation Service (1982).

SCIENTIFIC NAME	COMMON NAME
Diospyros sp.	Persimmon
Echinochloa sp.	Barnyardgrass
Echinochloa crusgalli	Common barnyardgrass
Eichhornia crassipes	Water hyacinth
Eleocharis sp.	Spikerush
Eleocharis acicularis	Needle spikerush
Elodea sp.	Waterweed
Elodea canadensis	Canadian waterweed
Fagopyrum esculentum	Common buckwheat
Fagus sp.	Beech
Fraxinus sp.	Ash
Gleditsia aquatica	Water locust
Gleditsia triacanthos	Common honeylocust
Glyceria borealis	Northern mannagrass
Heteranthera sp.	Mudplantain
Heteranthera dubia	Waterstar mudplantain
Hibiscus sp.	Rosemallow; hibiscus
Hordeum vulgare	Sixrow barley
Hydrilla verticillata	Hydrilla
Hydrocotyle umbellata	Pennywort
Hydrolea sp.	Waterleaf
Juncus sp.	Rush
Juncus roemerianus	Needle rush
Justicia sp.	Justicia
Leersia sp.	Cutgrass

SCIENTIFIC NAME	COMMON NAME
Leersia oryzoides	Rice cutgrass
Lemna sp.	Duckweed
Linum sp.	Flax
Lolium multiflorum	Italian ryegrass
Lonicera sp.	Honeysuckle
Ludwigia sp.	Marshpurslane
Megalodonta beckii	Bur marigold
Myriophyllum sp.	Watermilfoil
Najas sp.	Naiad
Najas flexilis	Slender naiad
Nelumbo sp.	Lotus
Nelumbo lutea	American lotus
Nuphar sp.	Cowlily
Nymphaea sp.	Waterlily
Nyssa sp.	Tupelo
Nyssa sylvatica	Blackgum tupelo
Panicum sp.	Panicum
Paspalum	Paspalum
Phragmites sp.	Reed
Pinus sp.	Pine
Pistia stratiotes	Water lettuce
Platanus occidentalis	American sycamore
Polygonum sp.	Knotweed; smartweed
Polygonum coccineum	Marsh knotweed
Polygonum natans	Floating knotweed

SCIENTIFIC NAME	COMMON NAME
Pontederia sp.	Pickerelweed
Pontederia cordata	Common pickerelweed
Populus sp.	Poplar; cottonwood
Potamogeton sp.	Pondweed
Potamogeton amplifolius	Largeleaf pondweed
Potamogeton diversifolius	Waterthread pondweed
Potamogeton epihydrus	Ribbonleaf pondweed
Potamogeton foliosus	Leafy pondweed
Potamogeton gramineus	Grassleaf pondweed
Potamogeton natans	Floatingleaf pondweed
Potamogeton pestinatus	Fennelleaf pondweed
Potamogeton richardsonii	Richardson pondweed
Potamogeton robbinsii	Robbins pondweed
Potamogeton zosteriformis	Flatstem pondweed
Potentilla palustris	Marsh cinquefoil
Pueraria lobata	Kudzu
Quercus sp.	Oak
Quercus sp.	Swamp red oak
Quercus sp.	Cherrybark oak
Quercus bicolor	Swamp white oak
Quercus lyrata	Overcup oak
Quercus michauxii	Swamp chestnut oak
Quercus muhlenbergii	Chinkapin oak
Quercus nuttallii	Nuttall oak
Quercus nigra	Water oak

SCIENTIFIC NAME	COMMON NAME
Quercus palustris	Pin oak
Quercus phellos	Willow oak
Ranunculus sp.	Buttercup
Ranunculus trichophyllus	White buttercup
Robinia pseudoacacia	Black locust
Sagittaria sp.	Arrowhead
Sagittaria heterophylla	Stiff wapoto
Sagittaria latifolia	Common arrowhead
Salix sp.	Willow
Salix interior	Sandbar willow
Salix nigra	Black willow
Salvina auriculata	Salvina
Scirpus sp.	Bulrush
Scirpus acutus	Tule bulrush
Scirpus americanus	American bulrush
Scirpus paludosus	Alkali bulrush
Scirpus validus	Softstem bulrush
Setaria sp.	Bristlegrass
Sium suave	Hemlock waterparsnip
Sparganium sp.	Burreed
Sparganium chlorocarpum	Greenfruit burreed
Spartina sp.	Cordgrass
Spartina pectinata	Prairie cordgrass
Spirodela polyrhiza	Common ducksmeat
Taxodium sp.	Baldcypress

SCIENTIFIC NAME	COMMON NAME
Trapa natans	Water chestnut
Tripsacum dactyloides	Eastern gamagrass
Typha sp.	Cattail
Typha angustifolia	Narrowleaf cattail
Typha glauca	Glaucous cattail
Typha latifolia	Common cattail
Ulmus sp.	Elm
Utricularia sp.	Bladderwort
Utricularia vulgaris	Common bladderwort
Vallisneria americana	American wildcelery
Wolffia sp.	Watermeal; wolffia
Xanthium sp.	Cocklebur
Zizaniopsis sp.	Southern-wildrice

FISHES[1]

SCIENTIFIC NAME	COMMON NAME
Petromyzontidae	Lampreys
Petromyzon marinus	Sea lamprey
Acipenseridae	Sturgeons
Scaphirhynchus platorynchus	Shovelnose sturgeon
Polyodontidae	Paddlefishes
Polyodon spathula	Paddlefish
Lepisosteidae	Gars
Lepisosteus osseus	Longnose gar
Lepisosteus platostomus	Shortnose gar
Amiidae	Bowfins
Amia calva	Bowfin
Anguillidae	Freshwater eels
Anguilla rostrata	American eel
Clupeidae	Herrings
Alosa alabamae	Alabama shad
Alosa chrysochloris	Skipjack herring
Alosa sapidissima	American shad
Dorosoma cepedianum	Gizzard shad
Dorosoma petenense	Threadfin shad
Hiodontidae	Mooneyes
Hiodon tergisus	Mooneye
Salmonidae	Trouts
Coregonus sp.	Whitefish
Oncorhynchus kisutch	Coho salmon
Oncorhynchus tshawytscha	Chinook salmon
Salmo gairdneri	Rainbow trout
Salmo salar	Atlantic salmon
Salmo trutta	Brown trout
Salvelinus fontinalis	Brook trout
Salvelinus namaycush	Lake trout
Esocidae	Pikes
Esox lucius	Northern pike
Esox masquinongy	Muskellunge

[1]Source: American Fisheries Society (1980).

SCIENTIFIC NAME	COMMON NAME
Cyprinidae	Carps and minnows
Ctenopharyngodon idella	Grass carp
Cyprinus carpio	Common carp
Pimephales notatus	Bluntnose minnow
Pimephales promelas	Fathead minnow
Ptychocheilus oregonensis	Northern squawfish
Ptychocheilus umpquae	Umpqua squawfish
Catostomidae	Suckers
Carpiodes sp.	Carpsucker
Carpiodes carpio	River carpsucker
Catostomus commersoni	White sucker
Cycleptus elongatus	Blue sucker
Ictiobus sp.	Buffalo
Ictiobus bubalus	Smallmouth buffalo
Minytrema melanops	Spotted sucker
Moxostoma sp.	Redhorse
Moxostoma anisurum	Silver redhorse
Moxostoma erythrurum	Golden redhorse
Moxostoma macrolepidotum	Shorthead redhorse
Ictaluridae	Bullhead catfishes
Ictalurus sp.	Bullheads
Ictalurus catus	White catfish
Ictalurus natalis	Yellow bullhead
Ictalurus nebulosus	Brown bullhead
Ictalurus punctatus	Channel catfish
Pylodictis olivaris	Flathead catfish
Gadidae	Codfishes
Lota lota	Burbot
Percichthyidae	Temperate basses
Morone americana	White perch
Morone chrysops	White bass
Morone saxatilis	Striped bass
Centrarchidae	Sunfishes
Lepomis cyanellus	Green sunfish
Lepomis macrochirus	Bluegill
Lepomis microlophus	Redear sunfish
Micropterus sp.	Black bass
Micropterus dolomieui	Smallmouth bass
Micropterus punctulatus	Spotted bass
Micropterus salmoides	Largemouth bass
Pomoxis sp.	Crappie
Pomoxis annularis	White crappie
Pomoxis nigromaculatus	Black crappie

SCIENTIFIC NAME	COMMON NAME
Percidae	Perches
Perca flavescens	Yellow perch
Stizostedion canadense	Sauger
Stizostedion vitreum vitreum	Walleye
Sciaenidae	Drums
Aplodinotus grunniens	Freshwater drum
Cichlidae	Cichlids
Tilapia sp.	Tilapia

BIRDS[1]

SCIENTIFIC NAME	COMMON NAME
Family Gaviidae	
Gavia immer	Common loon
Family Phalacrocoracidae	
Phalacrocorax auritus	Double-crested cormorant
Family Ardeidae	
Casmerodius albus	Great egret
Ardea herodias	Great blue heron
Nycticorax nycticorax	Black-crowned night-heron
Family Anatidae	
Dendrocygna autumnalis	Black-bellied whistling-duck
Chen caerulescens	Snow goose
Branta canadensis	Canada goose
Aix sponsa	Wood duck
Anas rubripes	American black duck
Anas platyrhynchos	Mallard
Anas acuta	Northern pintail
Anas discors	Blue-winged teal
Anas strepera	Gadwall
Aythya valisineria	Canvasback
Aythya americana	Redhead
Aythya collaris	Ring-necked duck
Aythya affinis	Lesser scaup
Bucephala islandica	Barrow's goldeneye
Bucephala albeola	Bufflehead
Lophodytes cucullatus	Hooded merganser
Mergus merganser	Common merganser
Family Accipitridae	
Pandion haliaetus	Osprey
Rostrhamus sociabilis	Snail kite
Haliaeetus leucocephalus	Bald eagle
Buteo jamaicensis	Red-tailed hawk
Buteo regalis	Ferruginous hawk
Falco tinnunculus	Eurasian kestrel
Family Phasianidae	
Phasianus colchicus	Ringed-necked pheasant
Bonasa umbellus	Ruffed grouse
Meleagris gallopavo	Wild turkey

[1]Source: American Ornithologists' Union (1982).

SCIENTIFIC NAME	COMMON NAME
Family Rallidae	
Rallus longirostris yumanensis	Yuma clapper rail
Fulica americana	American coot
Family Laridae	
Larus delawarensis	Ring-billed gull
Larus californicus	California gull
Sterna hirundo	Common tern
Sterna antillarum	Least tern
Family Tytonidae	
Tyto alba	Common barn-owl
Otus asio	Eastern screech-owl
Bubo virginianus	Great horned owl
Strix nebulosa	Great gray owl
Family Picidae	
Colaptes auratus	Northern flicker
Family Tyrannidae	
Myiarchus crinitus	Great crested flycatcher
Family Hirundinidae	
Progne subis	Purple martin
Tachycineta bicolor	Tree swallow
Family Paridae	
Parus bicolor	Tufted titmouse
Family Troglodytidae	
Thryothorus ludovicianus	Carolina wren
Troglodytes aedon	House wren
Family Muscicapidae	
Sialia sialis	Eastern bluebird
Family Sturnidae	
Sturnus vulgaris	European starling
Family Emberizidae	
Agelaius phoeniceus	Red-winged blackbird
Family Passeridae	
Passer domesticus	House sparrow

MAMMALS[1]

SCIENTIFIC NAME	COMMON NAME
Didelphidae	New World Oppossums
Didelphis virginiana	Virginia oppossum
Leporidae	Hares and Rabbits
Sylvilagus sp.	Cottontail
Sciuridae	Squirrels
Sciurus sp.	Squirrel
Sciurus carolinensis	Gray squirrel
Glaucomys sp.	Flying squirrel
Castoridae	Beavers
Castor canadensis	Beaver
Cricetidae	New World Rats and Mice
Peromyscus maniculatus	Deer mouse
Ondatra zibethicus	Muskrat
Canidae	Canids
Canis latrans	Coyote
Procyonidae	Procyonids
Procyon lotor	Raccoon
Mustelidae	Mustelids
Mustela vison	Mink
Lutra canadensis	River otter
Cervidae	Cervids
Odocoileus sp.	Deer
Odocoileus virginianus	White-tailed deer

[1]Source: Jones et al. (1979).

PART XIII. SUBJECT INDEX

--A--

Aeration 318-339, 511-513

Aerators, diffuser. *See* Diffuser aerators.

Aerators, mechanical. *See* Mechanical aerators.

Aero-hydraulics gun 321

Aerospray 52 Binder 186

Aerospray 70 Binder 180, 185-186

Aerospray 72 Binder 186

A-Frame breakwaters 149-151, 164

Airfoil breakwaters 160, 162

Alabama shad 278

Ambigrid 86, 107

American black duck 383, 396

American coot 440

American eel 278

American shad 269

American Wind Turbine (AWT) 329

Amitrole 428, 431-433

Anchor chaining 436

ANFO 403-405, 414-415

Angler harvest regulation. *See* Fishing regulations.

Antimycin 369-372, 374-377

Aqua-Beachcomber 350

Aquatain 186

Aquatic plant control. *See also* Vegetation control. 340-362, 513-514

Articulated concrete mattresses 87-88, 110, 112, 497

Artificial nest structures 379-389, 516-517

Artificial reefs. *See* Fish attractors or Spawning structures.

Asphalt mastic 115, 127, 130, 133

Asphalt mattresses 81, 85, 106, 167

Atlanta salmon 269

Atrazine 429-430, 433

Automobile bodies 81, 85, 106, 122, 235, 238, 503

--B--

Backwaters 44-46, 52, 131, 200, 204, 212-213, 217-219, 221, 225-226, 249, 281, 284-287, 510-511

Balanced populations 363-365, 373-374

Bald eagle 386

Bank stabilization (impacts) 33-34

Bank stabilization techniques 52-223, 495-501

Barge traffic. *See also* Boat traffic, regulation . . . 40-51, 58-64, 68, 116, 166, 217-223, 501

Barrels 107

Barrier dams 265-268, 505

Barrow's goldeneye 381

Bayer 73 369

Beach enrichment 158, 206-212, 500

Beach Prisms 208-209, 211

Beaver 312, 408, 464

Beaver pipes 408-409

Berm creation 79, 206-212, 500
Bidim 87
Biological control 347-348, 354, 357, 438-439, 443-444, 513, 519
Birdhouses 381
Bituminous paving 106
Black bass 244, 246-247, 249, 374, 504
Black-bellied whistling-duck 380
Black crappie 81, 129, 366
Black-crowned night-heron 386, 389
Blanket products. *See* Erosion-control mattings.
Blanketing 349, 351, 355, 358, 513
Blue sucker 129
Bluegill 129, 238, 240, 247, 368, 370, 374
Blue-winged teal 383, 385
Bluntnose minnow 247
Boat traffic 40-51, 58-64, 68-69, 166, 389
Boat traffic, regulation 64, 70, 217-223, 501
Boats, old 235, 239, 503
Borland fish lock 274
Bottomland hardwood forests 418-425
Bowfin 37
Breakwaters 64, 70, 82, 99, 109, 135-166, 192, 201, 206, 210, 499
Bromacil 430, 432-433
Brook trout 244
Brown bullhead 238

Brown trout 363

Bufflehead 380

Buffalo 278

Bulkheads 64, 70, 81, 84, 101, 105-106, 108-113, 142, 193, 196, 497-498

Bullhead 318, 369, 424

Burbot 80, 129

Burning 440-443, 445-447

Bypass 258-265, 267-268

--C--

Cabling 436

Caissons. *See* Concrete breakwaters.

Calcium oxide 184

California Gull 396

Canada goose 382-385, 387-388, 395-396, 398, 400

Canvasback 383

Carolina wren 381

Carpsucker 129

Catamaran breakwaters 148-149, 164

Catfishes 32, 46, 244, 247, 249, 278, 374, 504

Cattail control 352, 431, 437-440, 446-447, 513

Cellular concrete grids 85-87, 107, 109, 112-113, 178, 497

Cement blocks 81, 207, 235, 238, 242, 503

Channel catfish 244, 307

Channel enlargement 17-21

Checker dams 284

Checkerblock 86

Chemical control. *See also* Piscicides; Herbicides. . . . . 342-347, 353-354, ... 357, 359, 368-372, 374-377, 427-435, 443-444, 446-447, 514-515, 519

Chemical soil stabilizers 167, 171-172, 184-187, 500

Chemical stabilizers. *See* Chemical soil stabilizers.

Chinook salmon 259, 265, 373

Chute dikes 307-308

Clam beds 229

Clearing and snagging 13, 15-17, 114, 299, 379

Closing dams 29-32, 114, 129, 284, 287, 300, 312-313, 507-508, 510-511

Coho salmon 259, 373

Common barn-owl 381

Common carp . . . . . 32, 37, 80, 129, 265, 278, 363-364, 366, 368, 373, 377, ... 424, 469, 516

Common loon 396

Common merganser 381

Common tern 396, 398

Comprehensive Master Plan for the Management of the Upper Mississippi River System 5, 7, 222

Concrete 81, 85, 106, 497

Concrete blocks. *See* Cement blocks

Concrete breakwaters 141, 201

Construction Reference Plane (CRP) 305, 307-308, 311

Conwed 180, 189-191

"Cookie cutter" 438, 446, 448

Copper chelate 342-343, 346

Copper sulfate 343-346

Core-type embankments 451-452

Cottontail 413

Counterfort design 95-96

Coyote 398

Crappie 32, 37, 238

Crayfish 245, 347

Culverts 97, 269, 275-276, 279, 284-287, 313, 458, 460, 508, 510

Curasol AE 186

Curasol AH 180, 186

Curasol AK 180

Curlex 180, 188-191

Currents. *See* Water currents.

--D--

2,4-D 343-344, 446-347, 428, 431-435

DCA-70 186

Dalapon 428-429, 431-433

Deadmen 121

Deer 413, 423, 518

Deer mouse 381

Denil fishway 270, 273, 506

Destratification 319-324, 331-339, 512-513

Destratification efficiency 319-320

Diaphragm embankments 451-452

Diffuser aerators 330, 337-338, 512

Dikes or levees. *See* Embankments; Stone wing dams; Closing dams; Flood protection levees.

Diquat 344, 346-348, 428, 431-433

Diuron 429, 431-433

Dolos 91-92

Double-crested cormorant 386, 388

Dow Mulch Binder 180

Downflow bubble contact aerator 327

Drawdowns . . . . 42, 291-292, 349-352, 355-359, 367-368, 374-377, 437, 450, ... 464-471, 515, 520

Dredged material disposal . . . . . 17-21, 224-232, 312, 453, 501-502, 517, ... 520-521

aquatic 227, 229, 502

productive upland utilization 228-230, 502

terrestrial 227-230, 502

thalweg 228-230, 502

Dredging . . . . . 11, 17-21, 203, 224-232, 349, 355, 394-395, 501-502, ... 510, 513

Drop inlet spillways 458, 460

Dura-bag 99

--E--

Eastern bluebird 381

Eastern screech-owl 381

Ecotone 288, 292

Electric fences 263, 267

Embankments 450-465, 469, 471-472, 520

Emergency spillways 459

Enclosed pool dikes 306-307

Endangered species 386, 388, 392-394, 399

Endothall 344, 346-347

Energy dissipators 281-283, 286-287

Enhancement (general) 3-4

Enkamat 188, 190-191

Entrainment 256, 267

Enviroblox 88-90, 107, 110, 112, 172, 497

Erosion-control matting 171, 179-181, 188-191, 500

Erosion processes 54-70

Eurasian kestrel 381

European starling 379, 381

Executive Order on the Protection of Wetlands 2

Executive Order on Floodplain Management 2

Exotics 250, 348, 363-364, 373-374, 376-377

--F--

Fabriform 81, 85, 99, 101, 107, 111

Farm implements 436-437

Fathead minnow 247

Fences 114-116, 121-122, 131-134, 498

Ferruginous hawk 386

Filter fabrics 68, 75, 82, 86-87, 93, 97, 99, 167, 192-195, 246, 500

Fish and Wildlife Coordination Act 1-2

Fish attractors 162, 234-243, 503

Fish barriers 256-257, 265-268, 505-506

Fish excluder 257, 267

Fish lifts 270, 273-275, 277-279, 506

Fish locks 270, 273-275, 277-279, 506

Fish passage 269-279, 506-507

Fish populations, manipulation of. 363-377, 514-516

Fish screens 94, 256-265, 267-268, 505-506

Fishways 94, 269-273, 277-279, 506-507

Fishery management techniques. 233-377, 502-516

Fishing regulations 365-366, 374-376, 377, 514

Flathead catfish 129, 131

Flip buckets 282, 283, 507

Floating tire breakwaters (FTB) 102, 153-158, 162-166, 499

Flood protection levees 28-29,35-37, 82, 176, 312

Flooding 339-440, 465-470

Flying squirrel 381

Free overfall and straight drop spillways 455-456

Flow slides 66-67

Freshwater drum 80, 129, 278, 307, 366

--G--

Gabions . . . . . 77, 81, 85, 90, 93-98, 107-110,113, 127, 130, 133, 142, ... 165, 170, 172, 201, 207, 264, 497

Gadwall 382, 395

Garton pump 320, 336

Gate spillways 458

Gated culverts. *See* Culverts.

Gated tube spillways 458-459

Genequa 169 186

Genequa 743 180
Gizzard shad 32, 129
Glyphosate 345, 347-348, 431-433
Gobi block 86
Golden redhorse 32
Goodyear FTB 156-158, 165
Grass carp 347
Grasscrete 86, 172
Gray squirrel 381, 424
Grazing 438-439, 444-445
Great blue heron 386, 388
Great crested flycatcher 381
Great egret 386, 388
Great gray owl 386
Great horned owl 386
Green sunfish 81, 247
Greentree reservoirs 418-425, 518-519
Groins 99, 114-115, 127, 133-134, 142, 144, 192, 207, 210
Grouting 68, 77, 85, 101, 193, 198, 500

--H--

HC-10 350
HC-7 350
Habitat assessment 5-9
Habitat Evaluation Procedures (HEP) 8-10, 12
Harris Floating Breakwater 147-148

Helixor 321-324, 325

Hell's gate fishway 270-272, 506

Herbicides 342-347, 353-354, 357-359, 427-435, 443-444, 446-447, 514, 519

application 433-435

safety precautions 441-442

spray equipment 433-435

Herbivorous fish 347-348

Hexapods 91

High capacity sand filters. *See* Sand filter, high capacity.

Hold/gro 180, 189-191

Hooded merganser 380

Horizontal revolving drum screens. *See* Revolving drum screens, horizonal.

Horizontal traveling screen 258-259, 260-261

House sparrow 381

House wren 381

Hovering breakwater 151-152

Hula dozer 436

Hunting blinds 383, 385

Hydraulic breakwaters 160, 165

Hydraulic drains 192, 196-197

Hydraulic dredges 226, 229-230

Hydraulic wells 192, 196-197

Hydrofoil breakwaters 160, 162

Hydroseeding 171, 176-177, 181-183, 185

Hydrostatic pressure 54, 68, 70, 85, 107, 193, 195, 196-199

Hypolimnetic aeration 319, 324-329, 331-339, 512-513

--I--

Impact assessment 8-12

Impingement 256-257, 262, 267

Impoundments 21-26, 280-281, 290-298, 407-408, 468, 508-509

beaver 408-409

dead timber 418

greentree reservoir 419-423

marsh 407-408

Inclined plane screen 262

Incremental method. *See* Instream Flow Incremental Methodology.

Inlet sediment traps 284

Instream flow 289, 290, 297, 509

Instream Flow Incremental Methodology 10-12, 294

Integrated pest management 352-353, 372, 377, 515

Invertebrate pests 347, 438

Island creation 64, 70, 200-205, 228-229, 390-400, 500, 517-518, 520-521

Islands

avian nesting habitat 390, 391

dredged material 390-395, 396-400, 517

construction 391-395

waterfowl nesting habitat 395-400, 517

--J--

Jacks 114, 115-116, 120-122, 130-134, 498

Jetties 114, 192, 206

Jute netting 180, 189, 190

--K--

Kellner jack field. *See* Jacks.

"Kelp clumps." *See* Plastic strips.

Keokuk Dam 278

--L--

L-head dikes 81, 117, 131, 144, 305, 307-308

Lake trout 244

Land acquisition 2-3

Largemouth bass 163, 238, 240, 247, 374

Least tern 392, 397

Lesser scaup 396

Level ditching 405-407, 412-415, 417, 518

Lime; Liming 184-185, 479, 491, 493

Limno 325

Link belt screen 257, 260

Locks and dams 21-26, 115, 127, 200, 269, 280, 512

Log crib spillways 457

Longard tubes 99-101, 111, 115, 124-126, 130, 133

Longnose gar 32

Louver diverter 265-268

Low-level penstocks 282

--M--

M-145 186

Mallard 382-383, 385, 387, 395, 419, 421

Marsh creation and development 228, 401-417, 475, 518, 521

dredged material 408-414, 416-417, 518

structures 410-411

Mast management 177, 418-425, 518-519

Maximum sustainable yield (MSY) 364-365

McClusky canal screen 257, 263

Mechanical aerators 330, 337-338, 512

Mechanical control 348-349, 354-355, 358-359, 366-367, 374-377, 436-438, 444, 446-449, 513, 515, 519

Mechanical dredges 226-227, 229-230

Methodology, assessment 8-12

Midwater fish attractor 239-240, 243

Minimum pool 291, 296-298, 508

Mink 413

Mitigation

philosophy 1-4

regulations 1-4

techniques 3-4, 52-494

Monoslabs 86-87, 109, 172

Mooneye 32
Mudcat 315
Mud lock 186
Mulches 171
Multi-level penstocks 282, 285-287, 507
Muskellunge 374
Muskrat 38, 312, 403, 407, 413, 440, 449, 454, 464, 466, 470-471, 474
Muskrat damage 464

--N--

National Environmental Policy Act of 1969 (NEPA) 1-2
Natural spillway 457
Navigational markers 385
Nest baskets 382-383, 386-389, 516-517
Nest boxes 379-382, 386-389, 516-517
Nest structures, artificial. *See* Artificial nest structures.
Nest platforms 383-386, 386-389, 395, 516-517
Nets 366, 375
Nitrogen supersaturation 281, 282, 332-333
Northern flicker 381
Northern pike 32, 37, 80, 129, 250, 254-255, 292, 505
Northern pintail 383, 396
Northern squawfish 369
Notched dikes 300-311, 509-510
Nursery coves 250-251, 255, 504-505
Nursery marshes 250-251, 253-255, 504-505
Nursery ponds 250-251, 251, 254-255, 504-505

Nutrient limitation 349, 352, 357, 362, 513

--O--

Occlusive dyes 349, 351, 358, 513

"Offset" breakwaters 159-161

Ogee spillway 457

Optimum sustainable yield (OSY) 364-365, 514

Orifice fishways 270-273, 506

Osprey 383, 385, 388

Overflow pipe spillways 458-459

Oyster beds 229

--P--

Paddlefish 32, 278

Parallel bar screens 257, 260

Passive intake screens 267-263

Penstocks, low-level. *See* Low-level penstocks.

Penstocks, multi-level. *See* Multi-level penstocks.

Perforated pipe filters 257, 264

Perforated plate screens 257, 259

Perma-Bag 99

Petroset SB 180, 186

Physical Habitat Simulation System (PHABSIM) 294-295

Picloram 429, 433

Pike 244, 374, 509

Piping 66
Piscicides 368-372, 374-377, 514-516
Pits 454
Plant pathogens 347
Plastic sheeting 151, 349, 351, 353, 358, 514
Plastic strips 235, 239, 242, 503
Plugs 198, 463
Pneumatic breakwaters 160, 165
Pollution 48-50
Polyfilter X 87
Polypods 91-93, 497
Potholes 401-405, 413-415, 417, 518
Powder A 184
Powder B 184
Propagules 481-489, 493
Pulch 180
Pulse stabilization 288-290
Purple martin 381

--Q--

Quadripods 91-93
Quail 419, 518

--R--

Raccoon 380, 381
Radial well 265

Raft breakwaters 147

Rainbow trout 363

Redear sunfish 240

Redhead 383

Redhorse 129

Red-tailed hawk 386

Red-winged blackbird 381

Reregulating dams 284, 285-287, 507

Retention time 290

Revegetation 176-177, 184, 211, 422, 475-494, 520-521

Revetments 33-35, 71-114, 143, 192, 201, 213-214, 495-498

Revolving drum screens

vertical 257, 259-260

horizontal 257

Ring-billed gull 396

Ring-necked duck 406

Ring-necked pheasant 413

Riprap . . . . . 71-83, 96-97, 108, 165, 170-172, 182, 184, 198-199, 202, ... 495-496

River carpsucker 80, 129

River otter 34

River training structures 13-15, 26-33, 70, 82, 114-134, 498-499

Rock breakwaters 139-140, 144, 499

Root-rap 172

Rootless dike 300-311

Rotating disk screen 257, 259

Rotenone 252, 369-372, 374-377

Rubber ball breakwater. *See* Hovering breakwater.

Rubble-mound breakwaters. *See* Rock breakwaters.

Ruffed grouse 443

--S--

Sand bags. *See* Synthetic bags (sand- or concrete-filled)

Sand filter, high capacity 263-264, 268

Sand pillow 101

Sand traps, vortex tube. *See* Vortex tube sand traps.

Sauger 129, 366

Sawfish 350

Scalping 436

Scrap tires. *See* Used tires.

Sea lamprey 369

Seabreaker floating breakwater 147, 149

Seasonal manipulation 290-292, 295-296

Seawalls 84, 99

Section 32 Program. *See* Streambank Erosion Control Evaluation and Demonstration Act of 1974.

Shading 349, 355, 358

Shear stress 55-57, 75

Shore-all 106, 111

Shore Line cleaner 350

Shorthead redhorse 32

Shortnose gar 32, 278
Shovelnose sturgeon 80, 129, 278
Side channels 281, 284-287, 312-317, 510-511
Side channel modification 284-287, 312-317, 510-511
Side stream pumping system 331-332
Silt fence 285
Silva 180
Silver redhorse 32
Silvex 427
Simazine 345-347, 428, 433
Simple embankments 451-452
Single prism breakwaters 146-147
Skimming weirs 280-282, 286-287, 517
Skipjack herring 129, 278
Slope failure 54, 64-70
Sloughing 54, 67
Smallmouth bass 32, 129, 374
Smallmouth buffalo 32
Snail kite 386
Snow goose 439
Sodium silicate 184
Soil-cement revetment 198-199
Soil saver 189
Soil seal 185
Spawning beds 80-81
Spawning structures 162-163, 166, 244-249, 503-504

Spawning substrate 80-81, 245-247, 250-251, 289, 504

Spillways 455-462, 469, 520

Spotted bass 240, 247

Spotted sucker 37

Squirrel 423, 518

Sta-Bar 91

Sta-Pod 91

Stage filling 291

Stake beds 235, 238, 242, 503

Steel breakwaters 141-142, 144

Steel piling 127, 131

Stilling basins 283, 286, 507-508

Stocking 368, 370, 373-377, 514

Stone wing dams 26-33, 82, 114-118, 127-130, 132-134, 299-311, 498

Stoplog spillways 458

Stream aeration, supplemental 329-331, 334-339, 512

Streambank Erosion Control Evaluation and Demonstration Act of 1974 . . . . . 79, 80, 104, 156, 167, 178, 185

Striped bass 267, 373-374, 376, 514

Structure 234

Sucker 32, 244, 366

Sunfish 240, 247, 307, 424, 509

Supplemental stream aeration. *See* Stream aeration, supplemental.

Synthetic bags (sand- or concrete-filled) . . . . . 99-102, 113, 124-126, 130 . . . . . 142-144, 167, 200, 210-211, 498-499

Synthetic revetments (filled with sand or concrete). *See* Synthetic bags (sand- or concrete-filled).

--T--

T-head dikes 117

2,4,5-T 427

TCA 427

TFM 369

Terra firma 87

Terra tack 180, 186

Tethered float breakwaters (TFB) 158-159, 165

Tetrahedrons 91, 120

Tetrapods 91-92, 140, 200, 203

Threadfin shad 373

Tilapia 347

Timber cribs 105-106, 115, 124, 126, 130-134, 142, 144, 265, 498-499

Timber pile dikes 14-15, 26, 115, 118-121, 128, 498

Timber production and management 419-420, 423-425, 437-438, 444, 448-449, 519

Tin whistle spillway 459, 461, 472

Tires. *See* Used tires.

Tombolos 143, 202

Tow boats *See* Barges.

Tree retards 115-116, 124-125, 131-134, 498

Tree swallow 381

Trees 235, 238

Tribars 91-92, 140

Tufted titmouse 381

Turfiber 180

Turfstone 109

Turtle 312, 347

--U--

U-tubes 326-327, 329-330, 336, 512

Umpqua squawfish 369

Unigreen 86, 172

Used tires. *See* also Floating tire breakwaters (FTB). . . . . 85, 102-104, ... 107, 111-113, 135, 146, 150-158, 167-168, ... 198, 235-236, 241-243, 247, 497, 499, 503

--V--

Vane dike 302-303

Vegetation . . . . . 68, 79, 85, 108, 134, 167, 169-183, 200, 210, 292, ... 340-362, 393, 430-432, 499, 500, 513-514, 520-521

Vegetation Control. *See also* Aquatic Plant Control 426-449, 519

Vertical revolving drum screens. *See* Revolving drum screens, vertical.

Vertical-slot fishways 271-272, 506

Vertical traveling screens. *See* Link belt screen.

Vexar net 180

Virgina oppossum 381

Vitrified clay pipes 235, 238, 242-243, 248, 503

Vortex tube sand traps 284-287, 507-508

--W--

Walleye 32, 80, 129, 244-247, 249, 292, 366, 374

Water control structures 280-287, 455-464, 469, 471-472, 507-508, 520

Water currents 54-57, 133, 161, 170, 276

Water flows 288-290, 292-298, 508-509

Water level control 37-39, 70, 213-216, 288-298, 450-474, 501, 508-509, 520

Water level fluctuation 213-215, 439-440, 465-466, 468-471, 473-474, 520-521

Water pressure 42-46, 166, 217-218

Water velocity 42-46, 80, 217-218

Water Witch 350

Waterfowl nesting habitat 492

Wave action 40-41, 54, 57-65, 76, 84, 109, 137-138, 153, 157, 200, 204,248

Wave-Guard FTB 156-158, 165

Wave-maze FTB 156-158, 165

Weed harvesters 348-350, 354-355, 357-358, 360

Weir fishways 270-271, 506

Weirs, skimming. *See* Skimming weirs.

Wetland farming 489, 494

White bass 80, 129, 240, 366, 373-374, 376

White catfish 238

White crappie 240

White perch 373-374, 376

White sucker 80, 129

Whitefish 244

White-tailed deer 445

Wild turkey 419, 518

Wildlife management techniques 378-494, 516-521

Willows 95, 117, 175-176, 212

Wind-powered aeration system 329, 336, 512

Wing dam modification 117, 129-130, 134, 299-311, 509-510

Wing dams. *See* Stone wing dams.

Winter navigation 50-51

Winterkill 328-329, 337-339, 364, 512-513

Wisconsin log crib 236-237

Wood cribs. *See* Timber cribs.

Wood duck 379-380, 388, 419, 421, 516

--X--

XB-2386 186

--Y--

Yellow bullhead 244

Yellow perch 80, 129, 245, 366

Yuma clapper rail 393-394

GPO 837-677

A list of current *Resource Publications* follows.

133. A Handbook for Terrestrial Habitat Evaluation in Central Missouri, edited and compiled by Thomas S. Baskett, Deretha A. Darrow, Diana L. Hallett, Michael J. Armbruster, Jonathan A. Ellis, Bettina Flood Sparrowe, and Paul A. Korte. 1980. 155 pp.
134. Conservation of the Amphibia of the United States: A Review, by R. Bruce Bury, C. Kenneth Dodd, Jr., and Gary M. Fellers. 1980. 34 pp.
135. Annotated Bibliography for Aquatic Resource Management of the Upper Colorado River Ecosystem, by Richard S. Wydoski, Kim Gilbert, Karl Seethaler, Charles W. McAda, and Joy A. Wydoski. 1980. 186 pp.
136. Blackbirds and Corn in Ohio, by Richard A. Dolbeer. 1980. 18 pp.
137. Handbook of Acute Toxicity of Chemicals to Fish and Aquatic Invertebrates, by Waynon W. Johnson and Mack T. Finley. 1980. 98 pp.
138. Waterfowl and their Wintering Grounds in Mexico, 1937–64, by George B. Saunders and Dorothy Chapman Saunders. 1981. 151 pp.
139. Native Names of Mexican Birds, researched and compiled by Lillian R. Birkenstein and Roy E. Tomlinson. 1981. 159 pp.
140. Procedures for the Use of Aircraft in Wildlife Biotelemetry Studies, by David S. Gilmer, Lewis M. Cowardin, Renee L. Duval, Larry M. Mechlin, Charles W. Shaiffer, and V. B. Kuechle. 1981. 19 pp.
141. Use of Wetland Habitats by Birds in the National Petroleum Reserve—Alaska, by Dirk V. Derksen, Thomas C. Rothe, and William D. Eldridge. 1981. 27 pp.
142. Key to Trematodes Reported in Waterfowl, by Malcolm E. McDonald. 1981. 156 pp.
143. House Bat Management, by Arthur M. Greenhall. 1982. 30 pp.
144. Avian Use of Sheyenne Lake and Associated Habitats in Central North Dakota, by Craig A. Faanes. 1982. 24 pp.
145. Wolf Depredation on Livestock in Minnesota, by Steven H. Fritts. 1982. 11 pp.
146. Effects of the 1976 Seney National Wildlife Refuge Wildfire on Wildlife and Wildlife Habitats, compiled by Stanley H. Anderson. 1982. 28 pp.
147. Population Ecology of the Mallard. VII. Distribution and Derivation of the Harvest, by Robert E. Munro and Charles F. Kimball. 1982. 126 pp.
148. Management of Seasonally Flooded Impoundments for Wildlife, by Leigh H. Fredrickson and T. Scott Taylor. 1982.

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