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VII. Fluvial: Habitat Evaluation

VII. FLUVIAL: HABITAT EVALUATION

EROSION PROTECTION: AN INTEGRATED APPROACH TO MITIGATION

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Abstract: The Upper Yazoo Projects (UYP) is a major flood control effort of the US Army Engineer District, Vicksburg (CELMK), in the Yazoo River Basin of Mississippi. In 1989, work on the uncompleted features of the project was halted because of opposition from landowners, environmental groups, and the State of Mississippi. Continuation of the project was subject to the findings of the UYP Reformulation Study. Construction resumed on the reformulated UYP in 1994 following a comprehensive reanalysis of an array of alternative plans and the development of a Supplemental Environmental Impact Statement by interagency and interdisciplinary teams and the development of an acceptable mitigation strategy by the US Army Engineer Waterways Experiment Station (CEWES). Team members represented the Corps and state and Federal resource agencies. The CELMK requested that CEWES optimize habitat benefits for aquatic, terrestrial, waterfowl, and wetland resources by quantifying advantages and disadvantages of various management alternatives and compensation techniques. The planning objective was 100-percent compensation for unavoidable impacts. Riverbank habitat refers to the riparian trees, logs, woody debris, undercut banks and bank indentations that provide nesting and cover for a variety of fish species and substrate for invertebrates. A systematic ecosystem approach involving project engineering features (e.g., water control structures, borrow pits, and confined disposal facilities) and reforestation of agricultural lands was proposed for mitigation. This paper focuses on the decision to use traditional and nontraditional approaches to compensate for the unavoidable loss of riverbank habitat, while offering requisite erosion protection. A combination of riprap, gravel and trees/logs/woody debris revetments will be employed. The approach used to develop the mitigation strategy, the construction and placement techniques, and the applicability of this approach to other projects are discussed. This systematic ecosystem approach on the UYP employed environmental engineering principles and judgement, demonstrated environmental soundness, cost effectiveness, aesthetic appeal, and used multipurpose design techniques. Post-project management, including all operations and maintenance aspects, will also be simplified.

BACKGROUND

Construction on the Upper Yazoo Projects (UYP) in northwest Mississippi began in 1976 with 203 miles of levees, 179 miles of channel modification (a 75-percent increase in channel capacity), and 108 water control structures. The purpose was to provide flood protection for portions of twelve counties. Significant opposition from nationwide environmental organizations, landowners, and the State of Mississippi, however, resulted in the halting of construction by the US Army Engineer District, Vicksburg (CELMK), after completing 55.7 miles of channel improvements, 3.8 miles of levees, and five water control structures. Continuation was subject to the findings of the UYP Reformulation Study

(USAED Vicksburg 1989). In the Reformulation Study, six alternatives were evaluated. Interagency and interdisciplinary teams evaluated impacts of each alternative on aquatic floodplain, aquatic riverbank, terrestrial, waterfowl, and wetland resources and then cooperatively developed mitigation solutions.

HABITAT IMPACTS

The magnitude of impact to aquatic, terrestrial, waterfowl, and wetland resources varied with the six alternatives. In general, the greater the level of flood protection afforded by an alternative, the greater the expected impacts in the various habitat categories. For each resource category, different impact and compensation units were used. Habitat units (HUs) were used for both aquatic components, average annual habitat units (AAHUs) for terrestrial, duck days (DDs) for waterfowl, and acres for wetland resources. Aquatic habitat was further subdivided into riverbank and floodplain components.

Mitigation strategies were formulated using a cost-effective environmental management plan that maximized the benefits afforded by project features (i.e., water control structures, borrow pits, and confined disposal sites) and land acquisition. Any land acquired for mitigation had to be agricultural tracts within the 2-year floodplain that would either be forested or fallowed depending on the mitigation objectives. Dardeau and Fischenich (1995) provided a description of the proposed systematic ecosystem approach considered by CELMK to achieve UYP mitigation objectives.

Aquatic riverbank structural components evaluated by the aquatic team were logs and debris, live trees, bank indentations and undercut banks (Killgore and Hoover 1993). Removal of this structure during channel enlargement would eliminate important aquatic habitat and necessitate mitigation. An estimated 47 riverbank habitat HUs for the six selected evaluation species would be lost from construction. This paper focuses on the aquatic riverbank structural impacts and the erosion protection plan used to achieve mitigation planning objectives.

INTERDISCIPLINARY APPROACH TO MITIGATION

The Council on Environmental Quality (1978) defined mitigation as any action that includes avoiding, minimizing, rectifying, reducing and/or compensating adverse impacts. The mitigation sequence used in the UYP included avoidance, minimization, and compensation for any unavoidable losses. Dardeau and Fischenich (1995) and Dardeau et al. (1993) described the procedures used by the interdisciplinary and interagency team to determine impacts and the mitigation approaches used to avoid, minimize, and then compensate for these expected impacts.

When developing a mitigation plan, the interdisciplinary/interagency team must integrate the mitigation process with engineering and design objectives (e.g., flood control, navigation, erosion protection, etc.) to produce a well-balanced solution that achieves project objectives. The team should assess the engineering necessity of the various proposed construction activities (avoidance), the possibility of altering the original scope or location of construction (minimization) and, finally, the most efficient yet environmentally sound means of achieving compensation. This process produces alternate proposals or modifications that avoid or minimize habitat losses, minimize compensation requirements, use multipurpose design, and achieve project objectives.

The UYP team's recommendations to avoid or minimize potential impacts to riverbank/instream habitat included a) single-bank modification to minimize channel enlargement impacts especially in areas of high quality habitat and b) use of a hydraulic dredge in lieu of a mechanical dredge (dragline).

All of the logs, debris, live trees, bank indentations and undercut bank structure could not be restored to pre-project conditions. Thus, the team needed to develop acceptable replacement habitat. Investigators (Dardeau et al. 1995, Killgore and Hoover 1993) have noted that where there is a lack of suitable natural hard substrate, such as the Yazoo River basin, populations of fishes and invertebrates are significantly higher at riprap placement sites along streambanks and on flooded graveled roads. Other instances of environmental benefits of erosion protection have been noted by Anderson and Cameron (1980), Boeters et al. (1991), and Henderson (1986).

EROSION PROTECTION/MITIGATION SOLUTION

Both traditional and nontraditional approaches were considered to compensate unavoidable losses of riverbank aquatic habitat. Riprap, the most common traditional approach to bank protection has been documented as beneficial to fishes for spawning, cover, and feeding and to invertebrates as substrate. Road gravel (during high water stages) is also productive spawning substrate (Killgore and Hoover 1993). On the other hand, natural organic substrate and natural bank irregularities were being eliminated. Would riprap and gravel as erosion protection be acceptable as compensation for the 47 lost aquatic HUs, or would some effort have to be made to restore the structure removed from the bank? The team proposed a compromise between traditional and nontraditional approaches: 20 percent riprap, 20 percent gravel, and 60 percent logs/debris revetments. The compromise plan represented tradeoffs among cost-effectiveness, biological productivity, and the intrinsic, aesthetic, and biological values of using natural substrate.

Compensation could have been achieved using only one or a combination of methods. The quantity of riprap associated with project features would have compensated 100 percent of the riverbank aquatic habitat at no additional mitigation cost. Riprap was obviously the most cost-effective alternative, but it ignored the intrinsic, aesthetic, and biological values afforded by using logs and debris for compensation. The team compromised on using 20 percent riprap because the substantial cost savings could not be disregarded, and it represented biologically effective compensation. Use of gravel for riverbank compensation was considered justified by the team because it was documented as highly productive spawning habitat. Gravel will be placed on roads that are at or below the 2-year flood frequency elevation. These roads will be part of the agricultural land that will be acquired and reforested as part of the overall mitigation plan. This tradeoff recognized the biological productivity provided by gravel surfaces, although these areas are not directly associated with the riverbank. The majority of riverbank compensation will be achieved using log and debris revetments. Use of woody substrate was the preferred alternative by the other Federal and state agencies, but they were willing to make cost and productivity tradeoffs associated with the use of rock.

Quarry run limestone was a project feature for erosion and scour protection around water control structures, adjacent to bridge piers, and on some disturbed streambanks. Specifications called for stone with diameters between 8 (10-lb unit weight) and 15 in. (140-lb unit weight) that would be spread to a thickness of between 14 and 21 in. Thus, to achieve the required 20-percent compensation using riprap, an 18-in. layer will require 6,292 cu yd of stone at a 1992 cost of $176,176 (Dardeau and Fischenich 1995, Dardeau et al. 1993).

Gravel placement will require the use of locally available wash gravel, which has a diameter range of 0.25 to 1.25 in. Spread in a layer of 1.5 times the maximum stone diameter, it will be placed "in the dry" on streamside roads provided that these sites are at or below the 2-year flood-frequency elevation. A cubic yard placed in a layer 1.875 in. thick would cover 108 sq ft; thus 655 cu yd would be needed for the 20-percent required compensation at a 1992 cost of $26,255 (Dardeau and Fischenich 1995, Dardeau et al. 1993).

The log/debris revetments will consist of trees, logs, or large woody debris with basal diameters of 10 in. or greater and heights between 50 and 100 ft that are removed during construction. The woody material will be anchored, evenly distributed throughout the mean low water (MLW) portion of the water column, and extend no more than 50 ft from the bank because of navigation constraints. Crowns will be oriented downstream, such that their bases form 20- to 30-deg angles with the bank. This technique will ensure desired scour, maximum sediment deposition, and maximum revetment life, the same engineering logic that is applied to standard revetment construction. The anchored woody material will be placed to provide a similar density to that reported in the UYP study area by Killgore and Hoover (1993) (32.6 sq ft of material per 100 lin ft of bank. Compensation for 60 percent of the impacted aquatic riverbank habitat would require 6,795 lin ft of anchored woody material structure. Dardeau et al. (1993) provided details on anchoring requirements. Figure 1 is a diagram of the proposed UYP erosion protection/mitigation using trees, logs, and woody debris. Construction will begin downstream and proceed upstream. Choice of bendways for placement of anchored woody material will be determined in the field and will be a function of the proximity of construction materials, local site conditions, and engineering considerations.

PROJECT CONSTRUCTION

Even though the interdisciplinary/interagency team proposed a generalized revetment design using trees, logs, and woody debris (Figure 1), plans and specifications will have to be developed. Until FY95, CELMK had never built this type of revetment; therefore, they consulted other districts and agencies. Among those districts that

CELMK consulted was Omaha, who shared their expertise and engineering information from earlier projects.

Similar mitigation but on a smaller scale and not part of the UYP is now being constructed on the Yalobusha River, the left-bank stream that joins the Tallahatchie River at Greenwood, Mississippi, to form the Yazoo River. Approximately 2,600 lin ft of log and debris revetment is being placed at four locations. The size of the Yalobusha, a smaller steam than the UYP rivers (Yazoo and Tallahatchie), necessitated smaller log and debris dimensions.

Tree elements are being cabled to the bank at approximately 20- to 30-deg angles. Each element consists of one or two freshly felled hardwood trees that are approximately 30 ft tall with branches and foliage intact. Elements are being placed approximately 30 ft apart with adjacent canopies touching and tops angled downstream. Tree elements are being anchored at three places: the root end by a cable running approximately 30 deg to the bankline and attached to a deadman to the bank, at the midpoint by a cable running perpendicular to the bank to a second deadman, and by a cable running to a concrete filled 55-gal drum, which is being placed in the channel. As described in the previous section, the UYP mitigation will be on a larger scale than the Yalobusha and will cover 60 percent of the required riverbank/instream compensation.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions: Erosion protection - both traditional and nontraditional - was readily integrated into a mitigation plan. This approach facilitated understanding and communication among various disciplines and agencies involved in the planning process, while providing tangible erosion protection and mitigation benefits. It also focused team members on the need for multipurpose design and tradeoff analysis.

Although the replacement habitat should reflect the impacted natural setting to the greatest extent possible, structural components often cannot be replaced "in kind" and at the same locations because of engineering and operational considerations. Thus, the traditional approaches to erosion control, which provide environmental benefits through artificial structure, may be appropriate and a more effective alternative. The interdisciplinary/ interagency approach afforded better recognition of environmental and engineering limitations and commonalities, which allowed the development of alternate plans that were acceptable to all concerned parties. In areas, such as the UYP, where hard substrate is scarce, rock (riprap and gravel) can be effectively used as compensation for aquatic habitat.

Recommendations: The UYP can serve as a mitigation model for other natural systems that are impacted by water resources projects. Particularly applicable is the erosion protection compensation plan developed for project mitigation. The interdisciplinary/ interagency approach should be used to develop erosion control solutions. Tradeoffs among environmental, engineering, and economic considerations need to be identified and analyzed. Monitoring should be conducted to ensure that the anticipated erosion control and habitat benefits are being achieved.

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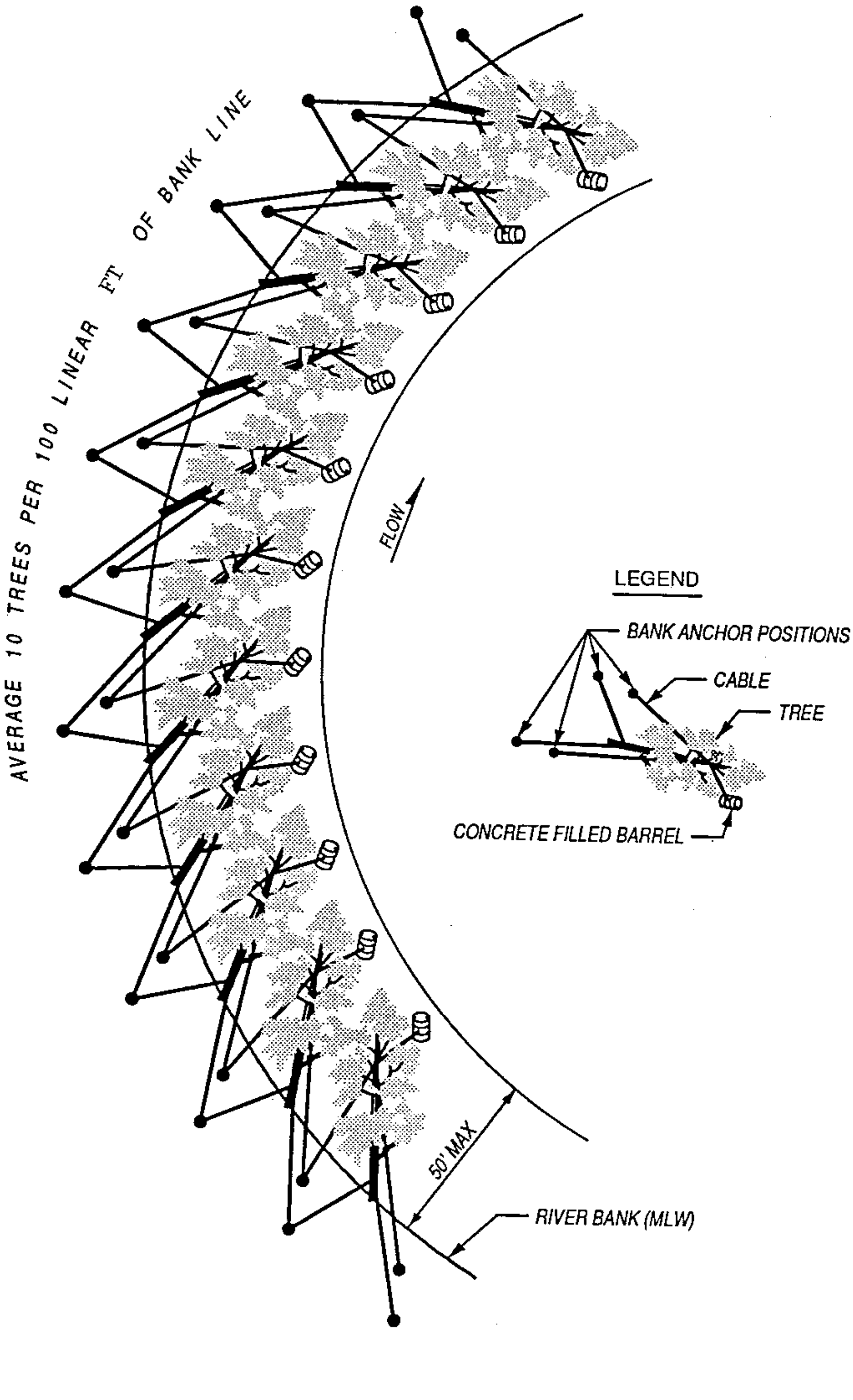

Figure 1. Revetment constructed of trees, logs, and woody debris used as erosion protection and as mitigation for impacted aquatic riverbank habitat

EFFECTS OF HYDROLOGIC DISTURBANCE ON WASHOUT AND RECOLONIZATION OF STREAM BIOTA

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Abstract: Washout and recolonization of macroinvertebrates and algae associated with a spring and summer storm event were measured at three sites in Ohio's Big Darby Creek Basin. Related factors, such as streamflow magnitude and streambed disturbance, were considered when interpreting observed changes in macroinvertebrate and algal densities and community structure.

Streamflows associated with the storm events had little effect on streambed altitudes, but streambed disturbance was documented in the form of shifts in the median particle-size diameters of the bed materials. The streamflow magnitudes did not correlate well with the observed changes in macroinvertebrate and algal-cell densities, but they did generally result in reductions in macroinvertebrate and algal-cell densities.

At each site, macroinvertebrate density and number of taxa were found to vary similarly with time. Local minima of these characteristics (macroinvertebrate density and total taxa) did not generally correspond to the first sample after the storm events, but instead lagged by about 1 to 3 weeks. Other biotic factors such as emergence of Diptera sp. and Trichoptera sp. probably affected the observed mid-July depression in macroinvertebrate densities.

Evaluation of pre-event macroinvertebrate community structure in terms of functional feeding groups and flow-exposure groups showed that, on the basis of percentage of total taxa found, gatherers were the dominate feeding group, and facultative taxa were the dominate flow-exposure group. Densities of gatherers decreased from pre-event levels following all the storm events at all the sites, while facultative and flow avoiding taxa were significantly reduced only after the summer event at Big and Little Darby Creeks.

Algal-cell densities in the first post-event samples were lower than pre-event densities; however, the total number of taxa present generally were not statistically different. In four out of five of the first post-event samples, algal-cell densities were reduced 74 to 84 percent compared to pre-event densities. The exception was at Little Darby Creek after the spring event, where only the stalked cells in the community were significantly reduced. The observed resistance to disturbance of the algal community at Little Darby Creek may result from the relative abundance of the mat forming blue-green algae, *Oscillatoria* sp. The stalked cells were the most consistently reduced in the post-event samples, whereas holdfasts types (such as *Audouinella hermannii*) and epiphytes (such as *Cocconeis* spp.) were the most resistant to washout.

Algal recolonization rates, measured as the change in algal-cell densities over a 7-day period after the summer storm event, ranged from 0.005 to 0.151 million cells/m^2/d. These recolonization rates are expected to be affected by factors, such as the amount of canopy, the initial post-event algae density, and grazing by macroinvertebrates.

INTRODUCTION

Big Darby Creek, a tributary of the Scioto River in central Ohio, drains 555 mi^2 (fig. 1) in the Eastern Corn Belt Plains ecoregion as delineated by Omnerik (1987). The basin is characterized by smooth plains, predominance of cropland, soil parent material of limestone and glacial drift, and potential natural vegetation of Beech-maple forest (Kuchler, 1964). In addition to being among the Nation's most productive agricultural areas for corn and soybeans, the biotic communities of the stream, including more than 86 species of fish and 40 species of freshwater mussels, make Big Darby one of the most biologically diverse streams of its size in the Nation. For this reason, 82 miles of Big and Little Darby Creeks were designated as a "State Scenic River" in 1984 by the Ohio Department of Natural Resources, a "Last Great Place" in

1990 by The Nature Conservancy, and a "National Scenic River" in 1994 by the Department of the Interior.

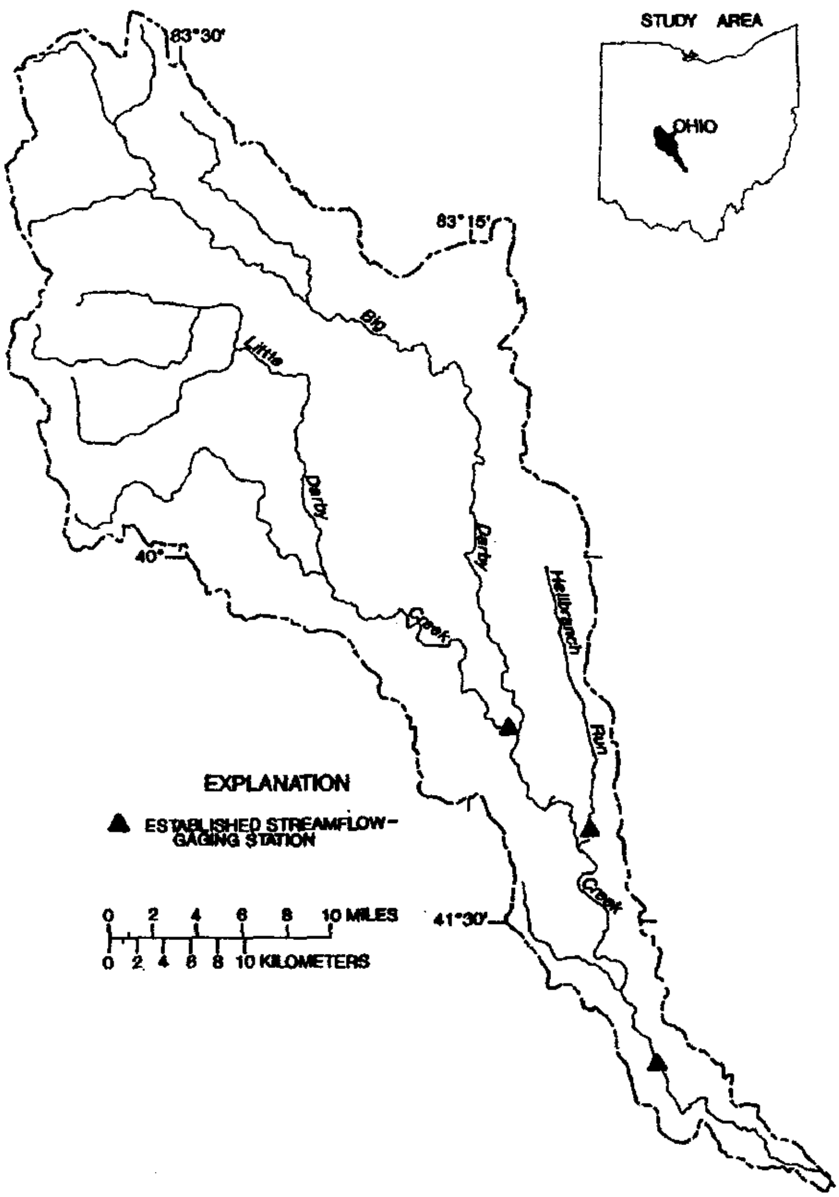

Figure 1. Location of Big Darby Creek Basin and study sites.

The Big Darby Creek Basin is under pressure for residential and commercial development because of its proximity to the city of Columbus. Urban area in the basin increased from 2,146 acres in 1965 to 8,357 acres in 1987 (Gordon and Simpson, 1990). Although urban area in the Big Darby Creek Basin is only a small part of the total drainage area, concern about the potential effects of urban stormwater on such a diverse stream ecosystem prompted a study by the U.S. Geological Survey (USGS) in cooperation with a group of local government agencies and organizations.

Data were collected for this study at three stream sites: Hellbranch Run, a second-order stream whose drainage is undergoing urbanization; Little Darby Creek, a third-order stream with predominately agricultural land use; and Big Darby Creek, a fourth-order stream with predominately agricultural land use representing drainage from 96 percent of the Big Darby Creek Basin.

Purpose and Scope: The paper presents the results of a study to describe the effects of storm runoff and associated physical disturbances on stream biota. Hydrologic conditions and habitat disturbance in a stream benthic community were investigated at the three sites from April 1994 through September 1994. Related factors, such as the streambed sediment particle-size distribution and antecedent streamflow, are discussed in terms of the washout and recovery of macroinvertebrates and algae. The three study objectives were to (1) quantify benthic habitat disturbance by measuring changes in channel morphology and bed material particle-size characteristics before and after storm runoff, (2) measure the washout and recolonization of the macroinvertebrates and algae, and (3) relate the hydrologic factors and disturbance of the streambed morphology and particle-size characteristics to the magnitude of the washout and recolonization rates of the benthic macroinvertebrate and algal communities.

METHODS

Physical and biological data were collected at one riffle site each on Hellbranch Run, Little Darby Creek, and Big Darby Creek before and after a spring storm event and a summer storm event. Data related to the spring storm event, that occurred April 10-13, 1994, and the summer storm event, that occurred in June 27-29, 1994, were collected between April and June, 1994, and June and September, 1994, respectively. In general, samples were collected before the storm events, as soon as streamflow conditions permitted sampling after the events, and periodically thereafter (totalling six samples per site per event, during 8-12 weeks). Samples collected immediately before and immediately after the storm events are referred to as the pre-event samples and first post-event samples, respectively.

Streamflow: A streamflow-gaging station was either established or already present downstream from each of the three riffle sites (fig. 1). Each station was equipped with a pressure transducer and programmable data logger to measure and record stream stage at 15-minute intervals. Standard USGS methods were used to measure and compute streamflow (Rantz and others, 1982).

Streambed mapping: Cross sections with monumented endpoints were established at each riffle site so that a grid (composed of 1-m^2 quadrats) could be formed for bed-material and biological sampling and so that changes in streambed altitude could be monitored over time. Four cross sections were established at riffle sites on Hellbranch Run and Little Darby Creek to demarcate an upper-, middle- and lower-riffle sampling areas. Three cross sections were established at the riffle site on Big Darby Creek to demarcate upper- and lower-riffle sampling areas.

The cross sections were surveyed by means of electronic theodolite before and after each storm. A tagline or surveying tape was strung between the monumented endpoints and used as a guide to ensure that streambed altitudes were always measured along the same cross sections. All altitudes for a given site were referenced to a common datum.

Bed sediment: A freeze-core method was used to collect bed-material samples from three areas at each riffle site during each sampling date. The freeze-core method employs a three-tube device, driven into the streambed, through which a compressed gas is allowed to expand (Everest and others, 1980). The temperature reduction associated with the expanding gas freezes the interstitial water in the bed adjacent to the tubes, allowing the frozen core of relatively undisturbed sediment and organic material to be removed from the streambed. Particle-size distributions of the freeze-core samples, which averaged about 3 kg per sample, were determined at the USGS office in Columbus by use of dry sieve analysis (Guy, 1969).

Macroinvertebrates: A stratified random-sampling design was used within each riffle area to select eight quadrats for collection of macroinvertebrate samples. No quadrat was sampled more than once over the duration of the study.

Surber samplers, fitted with 224-µm nylon-mesh nets, metal bases (2.5 cm in depth), and wooden handles were used to sample 929 cm^2 (1 ft^2) of bed material before and after the spring storm event. The same Surber samplers, equipped instead with 600-µm mesh nets, were used to sample before and after the summer storm event. (The larger mesh was used during the summer event to alleviate clogging problems with the 224 um mesh, which were thought to cause organisms to be washed out of the sampler.)

Rocks, palm size or larger, lying 50 percent or more within the Surber frame, were rubbed by hand and examined for attached macroinvertebrates. Scrubbed rocks and native muss 's were removed from the frame and returned to the stream. The substrate was then raked with a three-prong garden tool. Smaller rocks and sediment were raked upward into the water column to dislodge the organisms and wash them into the Surber net. The substrate was sampled to a depth of about 10 cm, then the material that accumulated on the net was cleaned of debris, split, and preserved in 95 percent ethanol.

The eight macroinvertebrate samples from each riffle site were split in half by use of a Folsom plankton splitter and one half of each sample was reserved for archival purposes. Each remaining half sample was combined with another remaining half sample from the same area (when possible), resulting in four composite samples, each representing 929 cm^2 of stream substrate. Median density of organisms and the relative percentage of each group of organisms were calculated with reference to the four replicates from each sampling date. Preserved macroinvertebrate samples were analyzed by the Ohio Biological Survey and its network of taxonomic specialists to identify the taxa (to the lowest taxonomic level) and determine total number of organisms per sample. The total taxa per sample is a minimum estimate because taxa at higher levels were aggregated at higher taxonomic levels rather than being identified to species.

No mollusks were collected because two species of freshwater mussels — the Clubshell (*Pleurobema clava*) inhabiting Little Darby Creek, and the Northern riffleshell (*Epioblasma torulosa rangiana*) inhabiting Big Darby Creek — are listed as endangered species by the Federal government.

Periphyton: Periphyton samples were collected from rocks found within the same eight quadrats from which the macroinvertebrate samples were collected. Rocks representative of the coarse bed material in the quadrat were gently removed and taken to the streambank for sample processing. The top halfs of the rock surfaces were scraped so that periphyton harvested from each quadrat represented a total surface area of approximately 200 cm^2, as determined by the perimeter method (Graham and others, 1988).

Periphyton samples were chilled and transported to the USGS office for additional processing and preservation. Volumes of the samples collected from the eight quadrats were measured in the laboratory, mixed with a biohomogenizer for 30 seconds, and subsampled with a wide-mouth pipette. The eight samples were composited using 6-mL of sample from each of two quadrats (resulting in four 12-mL composite samples) and were preserved with 2 mL of 25 percent buffered glutaraldehyde. A 0.1-mL aliquot of each composite sample was individually pipetted into a Palmer-Maloney nannoplankton counting chamber. The first 500 algal units were enumerated and identified to genus and species (where possible); then, algal densities were calculated on the basis of sample volumes, area sampled, and dilution factor used.

Ancillary data on tree canopy and light intensity reaching the stream surface were collected at the three riffle sites. The presence or absence of tree canopy was noted at 0.6-m increments along the cross sections used for streambed mapping. The percentage of streambed area where canopy obstructed the sky was determined by superimposing the canopy observations on the sampling grid, interpolating canopy boundaries between cross sections, and counting the numbers of open and obstructed quadrats.

Light intensity was measured in microeinsteins by use of an quantum light sensor held at the water surface. Light-intensity measurements were made along the cross sections used for streambed mapping and from open areas near each site in order to estimate the percentage of ambient light reaching the stream surface.

RESULTS AND DISCUSSION

Benthic habitat disturbance: The bed material at all three sites is composed predominantly of gravel and larger particles with some sand and very little silt. Cross-section surveys indicated that between-measurement variations in streambed altitude during the period April-September 1994 were generally small (about 6 cm or less). However, temporal trends in median grain-size data, obtained from freeze-core samples, indicate that bed materials tended to coarsen at Big and Little Darby Creeks over the period from March to July. In contrast, bed materials at Hellbranch Run tended to become finer over nearly the same period.

The spring storm event produced higher peak streamflows than the summer storm event (fig. 2), however the change in streamflows relative to the 7-day mean antecedent streamflows was generally greater for the summer event (Hellbranch Run being the exception). Peak streamflows at the three sites during the spring storm event (the event with the larger peak streamflows) ranged from 31 to 66 percent of their respective estimated 2-year-recurrence-interval peak streamflows.

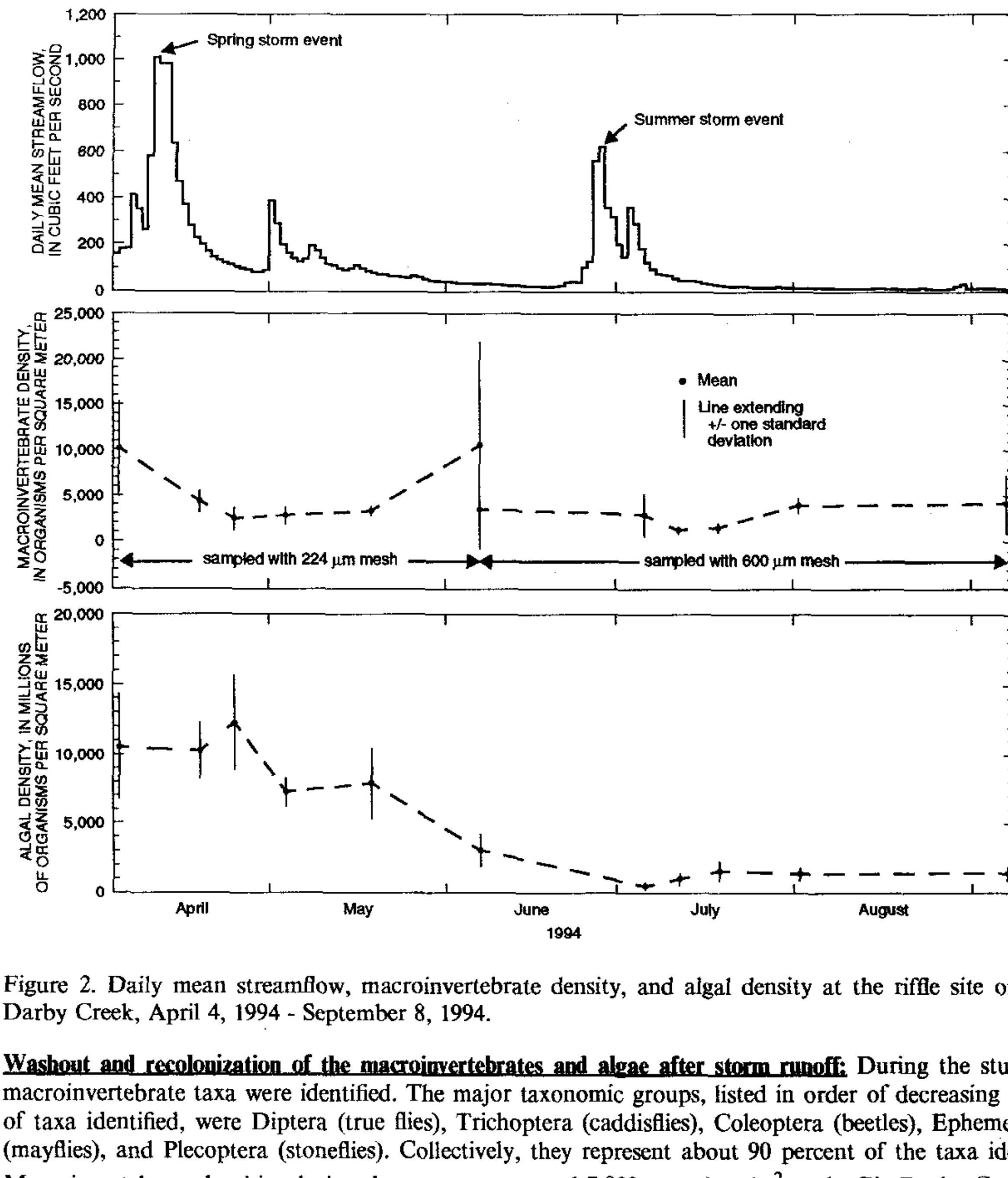

Figure 2. Daily mean streamflow, macroinvertebrate density, and algal density at the riffle site on Little Darby Creek, April 4, 1994 - September 8, 1994.

Washout and recolonization of the macroinvertebrates and algae after storm runoff: During the study, 184 macroinvertebrate taxa were identified. The major taxonomic groups, listed in order of decreasing number of taxa identified, were Diptera (true flies), Trichoptera (caddisflies), Coleoptera (beetles), Ephemeroptera (mayflies), and Plecoptera (stoneflies). Collectively, they represent about 90 percent of the taxa identified. Macroinvertebrate densities during the summer averaged 7,830 organisms/m^2 at the Big Darby Creek riffle site, 3,860 organisms/m^2 at Hellbranch Run and 2,900 organisms/m^{2}at Little Darby Creek. At each site, macroinvertebrate density and number oi taxa found vary similarly with time. Local minima of these characteristics (macroinvertebrate density and total taxa) did not generally correspond to the first sample after the storm events but instead lagged by about 1 to 3 weeks (fig. 2). The depression in macroinvertebrate density that occurred in mid-July is probably a result of emergence of Diptera and Trichoptera taxa that normally occurs in central Ohio from mid-June to mid-July. However, the 1-3 week lag for the macroinvertebrate community to reach its minimum density after both the spring and summer storm events could be due, in part, to biotic factors such as an aberration in food supply (for example, loss of food resource for filterers) or problems with reestablishment.

Macroinvertebrate community structure was evaluated in terms of functional feeding groups based on criteria from Merrit and Cummins (1984) and flow-exposure groups based on criteria from Growns and Davis (1994). In this study, the gatherers were the dominant feeding group in terms of percentage of total taxa found (44 percent) followed by the predators (23 percent), shredders (15 percent), scrapers (10 percent) and filterers (8 percent). Gatherers were also the most abundant group throughout the study, but predators (although relatively high in taxa richness) were frequently the least abundant. The dominant flow-exposure group in terms of percentage of total taxa found was facultative (46 percent), followed by flow avoiders (34 percent) and obligate taxa (20 percent). Densities of gatherers decreased significantly from pre-event levels following most storm events (table 1). Gatherers are represented primarily by Diptera, whose density peaked in the spring, declined until mid-July, then rebounded slightly. Densities of flow avoiders and facultative taxa were significantly reduced by the summer event at Big and Little Darby Creeks.

Table 1. Macroinvertebrate response to storms at three sites in the Big Darby Creek Basin, Ohio
[+, statistically significant change in macroinvertebrate density or total taxa (on-sided p <0.05); -, no significant change in macroinvertebrate density or total taxa; statistics calculated by means of Wilcoxon rank sum test comparing pre-event and first post-event samples]

Storm	Macroinvertebrate density	Total taxa	Density by functional feeding group					Density by flow exposure group		
			Filterer	Gatherer	Predator	Scraper	Shredder	Avoider	Facultative	Obligate
Hellbranch Run										
Spring	+[1]	-[1]	-[1]	+	-[1]	-[1]	-[1]	-[1]	-	+
Summer	-	-[1]	-	-	+	-[1]	+	-	-	-[1]
Little Darby Creek										
Spring	+	+[1]	-	+	-[1]	-[1]	-[1]	-[1]	-	-
Summer	-	+	-[1]	+	-	-	-	+	+	-[1]
Big Darby Creek										
Summer	+	+	-	+	+	-[1]	-	+	+	-

[1] Pre-event median value lower than post-event median value.

During the study, 200 algal taxa were identified. The diatoms were the dominant group (159 taxa), followed by blue-green algae (9 taxa) and green algae (9 taxa). The diatoms, particularly the small, unattached single-cells, also were the most numerous in the algae community. Algal-cell densities varied seasonally and were higher in the spring than in the summer. Algal-cell densities in samples collected after the storm events generally were significantly lower than pre-event densities however, the total number of taxa present generally were not statistically different. In four out of five post-event samples, algal-cell densities were reduced 74 to 84 percent compared to pre-event densities. The exception was at Little Darby Creek after the spring storm event (fig. 2), where only the stalked cells in the community were significantly reduced (table 2). The observed resistance of the algal community at Little Darby Creek may be due to the relative abundance of the mat-forming blue-green algae, *Oscillatoria* sp. Peterson and others (1994) found that filamentous blue-green algae, which develop an interwoven, mucilaginous matrix, are more resistant to disturbance than algae that do not develop a similar matrix. The stalked cells were the most consistently reduced in the post-event samples, whereas holdfast types (such as *Audouinella hermannii*) and epiphytes (such as *Cocconeis* spp.) were the most resistant to washout (table 2).

Table 2. Algal response to storms at three sites in the Big Darby Creek Basin, Ohio
[+, statistically significant reduction in cell density (one-sided $p < 0.05$); -, no significant difference; statistics calculated by means of Wilcoxon rank sum test comparing pre-event and first post-event samples]

			Density by Form			Density by Attachment							Density by Size		
Storm	Cell density	Total taxa	Single cells	Colonies	Filaments	Unattached cells	Stalked	Apical pad	Prostrate	Epiphytes	Mat	Holdfast	Small (<50 µm)	Medium (50-100 µm)	Large (>100 µm)
Hellbranch Run															
Spring	+	-	+	+	+	+	+	+	+	-	-	-	+	+	+
Summer	+	-	+	+	+	+	+	+	-	-	+	-	+	+	-
Little Darby Creek															
Spring	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
Summer	+	-	+	-	+	+	+	+	+	-	+	-	+	+	-
Big Darby Creek															
Summer	+	+	+	-	+	+	+	+	+	-	-	-	+	+	-

Algal recolonization rates measured as the change in algal-cell densities over a 7-day period after the summer storm event were 0.005, 0.088 and 0.151 million cells/m^2/d for Hellbranch Run, Little Darby Creek, and Big Darby Creek, respectively. These recolonization rates are expected to be affected by factors such as the amount of tree canopy overlying the riffle areas (and consequently the amount of light incident on and penetrating the water), the initial post-event algae density, and grazing by macroinvertebrates and snails. The riffle at Big Darby Creek had the least amount of canopy (30 percent canopy), followed by Little Darby Creek (42 percent canopy) and Hellbranch Run (53 percent canopy). The algal cell density in the first set of samples after the summer storm was considerably higher at Hellbranch Run than at the other two sites, so it is possible that the combination of greater canopy and relatively high initial post-event cell densities resulted in the low recolonization rates.

A weak but significant inverse correlation (as determined by Kendall's tau-b; $\tau=-0.40$, $p=0.006$) was found between algal and macroinvertebrate densities at the Hellbranch Run site during the spring decline in algal cell density. No comparable statistically significant relation was found at the other two sites. The riffle site at

Big Darby Creek was characterized by the least canopy and highest growth rate in the summer but the lowest annual mean algal-cell density of the three sites. Even though no inverse relation was found between macroinvertebrate and algal densities at the Big Darby site, the relatively high density of macroinvertebrate organisms may have contributed to the low annual mean algal-cell density.

In summary, the streamflows were not of sufficient magnitude to alter streambed altitudes significantly, but they did generally result in reductions in macroinvertebrate and algal-cell densities. The magnitude of the observed changes in macroinvertebrate and algal-cell densities did not, however, correlate well with streamflow magnitude. Much larger streamflows occurred at all sites during the spring storm event; yet for that storm event, the algal community was not significantly reduced at the Little Darby Creek site, and the macroinvertebrates were not significantly reduced at Hellbranch Run. Although physical disturbance was frequently documented in the form of reductions in macroinvertebrate and algal densities and shifts in the median particle-size of the bed materials, the seasonal patterns of the benthic community as well as the preconditioning of the benthic community to flow may have had a comparatively large effect on the washout and recolonization of stream biota when exposed to these relatively moderate streamflow peaks.

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THE EFFECT OF TRANSIENT LANDSLIDE DAMS ON FISH HABITAT IN THE SALMON RIVER BASIN, CENTRAL KLAMATH MOUNTAINS, CALIFORNIA

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INTRODUCTION

The Salmon River watershed occupies about 485,000 acres in the central part of the rugged and timbered Klamath Mountains of northwestern California [Figure 1]. It is tributary to the Klamath River, a 10 million acre basin which supports one of the most important anadromous fisheries in California. Endemic species in the Salmon River include steelhead (O. mykiss), chinook salmon (O. tshawytscha), and coho salmon (O. kisutch) among others. Though the Salmon River watershed occupies only 5% of the Klamath basin, it provides habitat for the largest wild run of spring chinook salmon in the entire Klamath River system. Several of the anadromous species have experienced dramatic population declines over the past 30 years, and some of them may soon be listed as threatened or endangered species.

The Salmon River was recently designated as a "Key Watershed" as part of President Clinton's Forest Management Plan for the Pacific Northwest. Under this designation, emphasis is placed on managing the basin as a refugia for the preservation of critical species, and gaining a better understanding of how natural processes affect the habitat of these species. Against this backdrop, it is clear that a sound understanding of how the natural river system functions is needed. Large landslide dams play an important role in this system.

The Salmon River Basin is composed of a complex assemblage of accreted geologic terranes. Bedrock consists of a variety of metamorphosed oceanic sediments, lavas, and granitic and ultramafic rock. It is influenced by plate subduction along the Cascadia Subduction Zone, and as a result is tectonically active. Rapid uplift beginning in the Pleistocene Epoch created a steep rugged landscape in which landsliding plays a major role.

The Bloomer and Murderers Bar Landslides blocked the main stem of the Salmon River, forming temporary lakes. The North Russian Landslide dammed the North Fork of Russian Creek, and formed a small lake, a portion of which lasted until about 1980. The Big Elk Landslide blocked the Big Elk Fork of Wooley Creek [Figure 3]. The Nordheimer Pond Landslide is a pre-1900 feature which created a small lake in the west fork of Nordheimer Creek which was destroyed by a flood in 1964.

The purpose of this paper is to compile information on landslide dams and to assess their effects. Understanding the processes involved will provide a soundbasis for future management in the watershed and to enhance our ability to predict the effects of similar landslides when they occur in the future.

METHODS AND OBSERVATIONS

This paper is based on field observations, examination of historical air photos, and conversations with local residents. The five landslides selected for investigation were identified by a previous study of sediment production in the Salmon River Watershed [de la Fuente and Haessig, 1993]. Data for all sites are summarized in Table 1. Plan and profile views are provided in Figures 2 and 3. Topography on Figures 2 and 3 is from U.S. Geological Survey digital elevation model [DEM] data at 30 meter resolution. Data for all cross sections are from field-run profiles, augmented by USGS 7-1/2 minute topographic maps.

Location Map

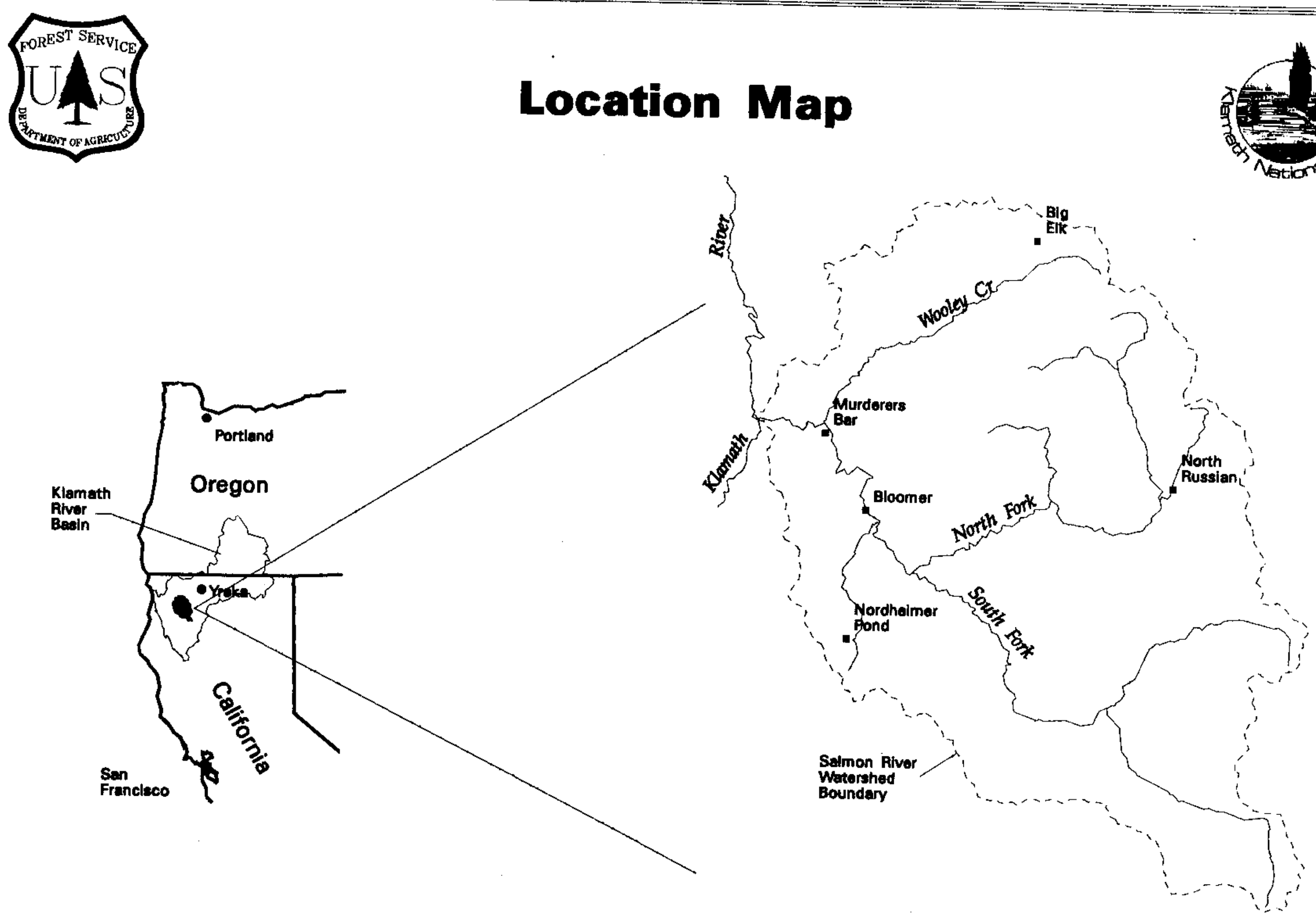
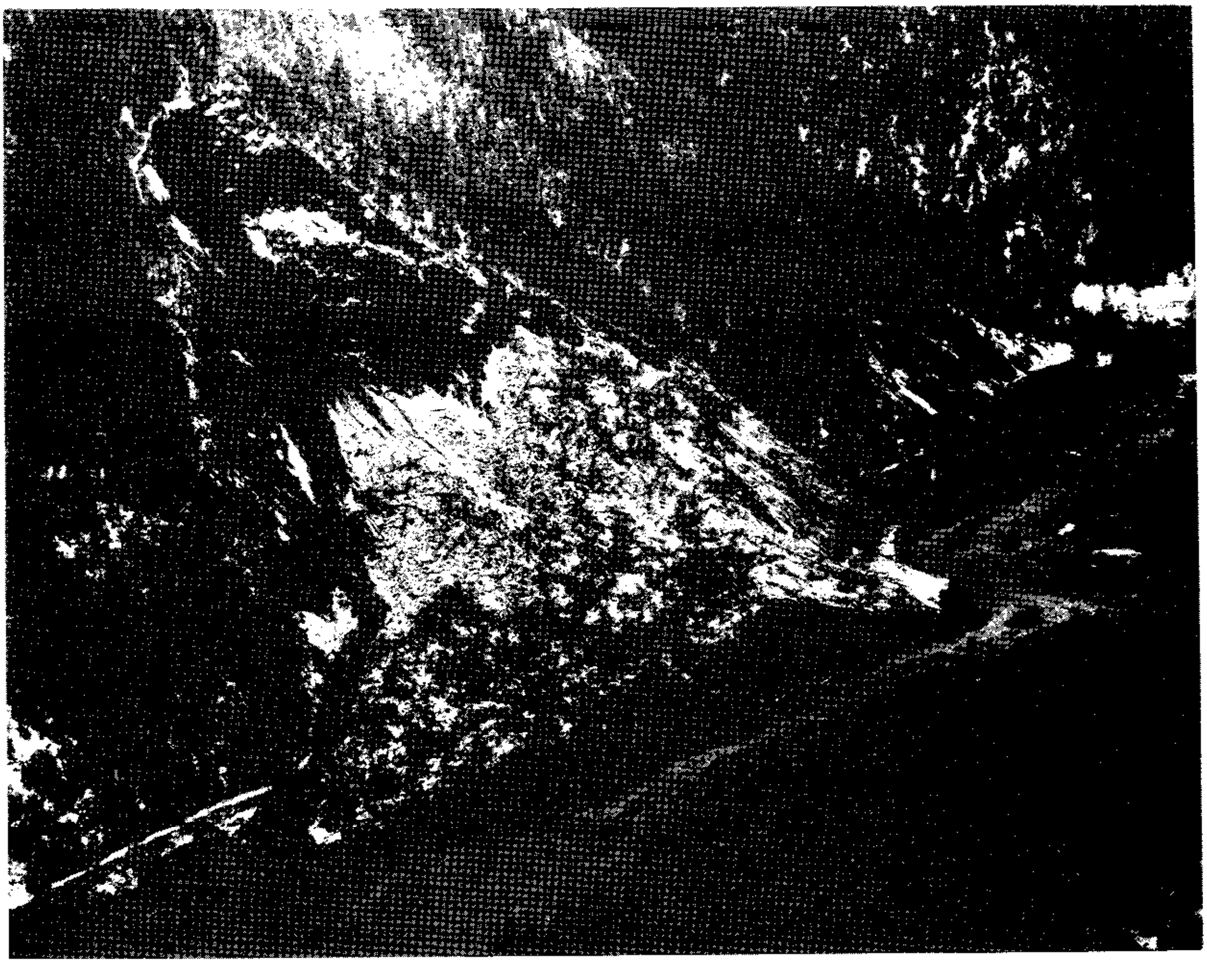


Figure 1



Photograph 1: Bloomer Landslide; USDA Forest Service 1965

Bloomer: This landslide occurred in association with the flood of December 1964. It is a large rock slide/avalanche in metasedimentary rock of the Eastern Hayfork (EHF) unit of the Sawyers Bar terrane (SBT), a melange of chert and argillite with some metavolcanic rock. The landslide failed along planes of weakness in the rock, and they remain clearly visible today in the head scarp. The landslide obliterated 1/4 mile of the county road (Photo 1), and rapidly transported several million cubic yards of rock and debris toward the east bank, burying a broad bedrock terrace in the process [Figure 3]. Debris buried the 1964 river channel to a depth of about 100 feet, the bedrock terrace about 40 feet, and formed a dam 80-100 feet high. An Army Corps of Engineers field team reported that a landslide of 2-3 million yd^3 occurred about 6 miles above the mouth of the Salmon River several hours before noon on December 22, and breached at 5:00 p.m. on December 22 [California Department of Water Resources, 1965]. The Bloomer slide is roughly 12 miles from the mouth of the Salmon River, but in all likelyhood they were referring to this site. Aerial photos taken after the dam broke [Photo 1] suggest that failure was catastrophic, as evidenced by scour high on the east bank and also on the east margin of the landslide debris. The maximum length of the lake is unclear, but local accounts place it on the order of several miles, in the vicinity of Otter Bar (Charlie Snapp, former mail carrier from Etna to Forks of Salmon, pers. com. 1995), and also near Forks of Salmon (Willis Conrad, personal communication, 1995). Failure of the dam was accompanied by a wall of water which is associated with loss of bridges downstream (Willis Conrad, pers. com. 1995; Al Crebbin, narrator of a USDA Forest Service film "The Flood and the Forest" no date, addressing the effects of the 1964 flood). Subsequently, the river was forced to cut a new channel through the bedrock terrace, and a resistant porphyry dike created a water fall which lasted several years. The California Department of Fish

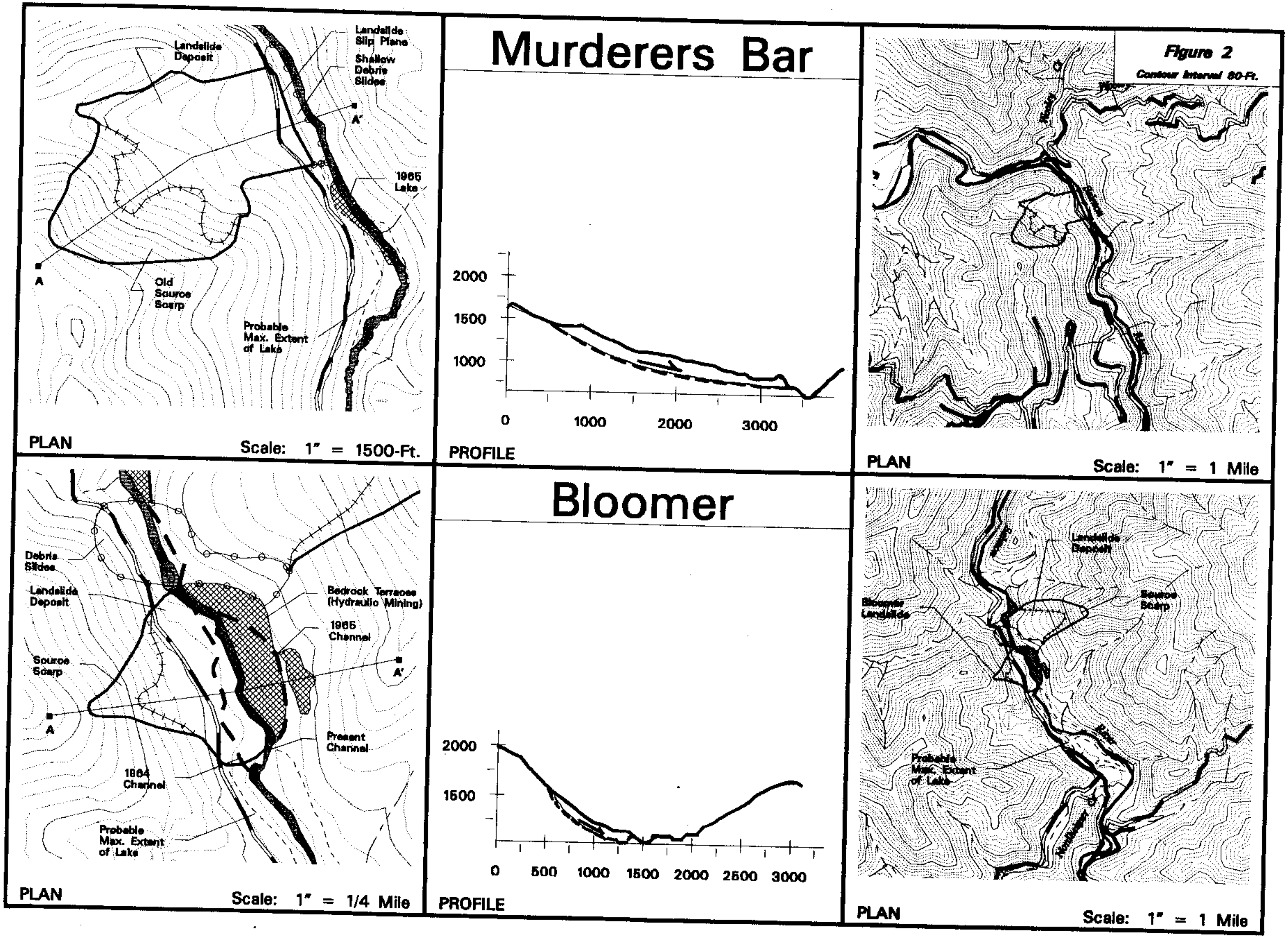


Figure 2
Contour Interval 80-Ft.
Murderers Bar
Landslide Deposit
Landslide Slip Plane
Shallow Debris Slides
A
A'
1965 Lake
Old Source Scarp
Probable Max. Extent of Lake
PLAN
Scale: 1" = 1500-Ft.
2000
1500
1000
0
1000
2000
3000
PROFILE
PLAN
Scale: 1" = 1 Mile
Bloomer
Debris Slides
Landslide Deposit
Bedrock Terraces (Hydraulic Mining)
1965 Channel
Source Scarp
Present Channel
1964 Channel
Probable Max. Extent of Lake
PLAN
Scale: 1" = 1/4 Mile
2000
1500
0
500
1000
1500
2000
2500
3000
PROFILE
Landslide Deposit
Bloomer Landslide
Source Scarp
Probable Max. Extent of Lake
PLAN
Scale: 1" = 1 Mile

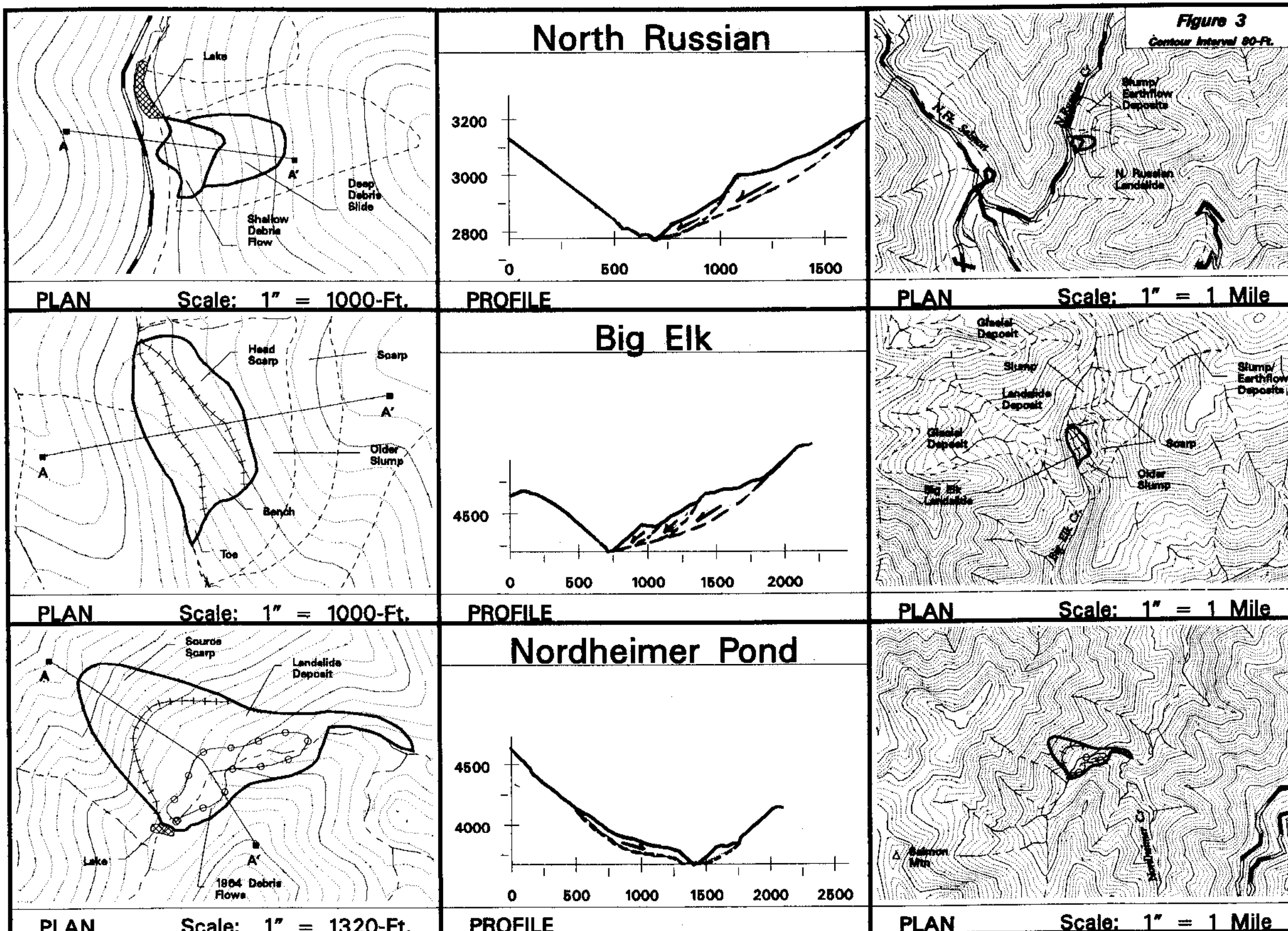


Figure 3
Contour Interval 80-Ft.
North Russian
Lake
A
A'
Deep Debris Slide
Shallow Debris Flow
3200
3000
2800
0
500
1000
1500
N. Fk. Salmon
Slump/ Earthflow Deposits
N. Russian Landslide
PLAN Scale: 1" = 1000-Ft.
PROFILE
PLAN Scale: 1" = 1 Mile
Big Elk
Head Scarp
Scarp
A
A'
Older Slump
Bench
Toe
4500
0
500
1000
1500
2000
Glacial Deposit
Slump
Landslide Deposit
Slump/ Earthflow Deposits
Scarp
Older Slump
Big Elk Landslide
Big Elk Cr.
PLAN Scale: 1" = 1000-Ft.
PROFILE
PLAN Scale: 1" = 1 Mile
Nordheimer Pond
Source Scarp
Landslide Deposit
A
A'
Lake
1964 Debris Flows
4500
4000
0
500
1000
1500
2000
2500
Salmon Mtn
Nordheimer Cr.
PLAN Scale: 1" = 1320-Ft.
PROFILE
PLAN Scale: 1" = 1 Mile

and Game blasted and excavated rock from this channel, with some barrier removal continuing into the early 1980's [Ron Dotson, pers. com., 1995].

Murderers Bar: This deep translational landslide failed catastrophically in association with heavy rains in the spring of 1958. Examination of pre-slide air photos reveals that it is part of a old landslide complex. The river gorge at Murderers Bar is very narrow and exhibits steep walls incised into granitic rock, and the river gradient ranges from 1 to 1-1.5%. The landslide involves rock of the EHF unit [chert, argillite, marble, serpentinite] of the Sawyers Bar Terrane as well as granitic rock of the Wooley Creek Batholith at the base. The slip surface is a planar feature dipping gently NE which separates the underlying competent granitic rock from overlying landslide debris. It daylights about 100 vertical feet above the river [Figure 2]. Field examination suggested that a large dam did not form here, and the river was able to remove most of the debris, leaving a lag deposit of large marble and serpentinite boulders. A lake 1200 feet in length was visible on air photos of September 1964.

This landslide is documented by an article in the Humboldt Standard [Eureka, California] of Tuesday, March 4, 1958 which reports that a 1000-1500 foot wide landslide buried the county road on the afternoon of Monday, March 3, with 50 foot scarps forming 3500 feet up on the hillside. It dammed the river for a time but never very deep, and it muddied the water downstream. A Siskiyou Daily News article [Yreka, California] of early March 1958 by Mabel Nitsche reports that the slide was originally activated by the flood of December 1955, and had re-activated in January of 1958. It suddenly broke loose March 2, sending debris into the river and causing dams to build up periodically. It notes that the river quickly removed dams when they reached 10 feet in height. Twenty feet of aggradation was reported in the river below the slide, and the deep hole at the mouth of Wooley Creek was filled, backing up the creek and forming islands and bars in its channel. A lake was reported to have formed on the body of the landslide "some distance above the road" prior to failure.

Nordheimer Pond: This is a large natural rock slide/avalanche which occurred in sheared argillite and volcanic rock of the Eastern Hayfork unit. The slide failed along weakness planes in the bedrock, many of which remain visible in the head scarp. The slope failed as a rock and debris avalanche, completely filling the channel of a tributary to Nordheimer Creek to a depth of about 100 feet [Figure 3]. A small lake [0.5 acres] is visible on 1964 air photos and local residents describe having fished at the lake. Since the landslide deposit supports trees up to 48 inches in diameter, it is at least 300 years old and may be several thousand years old. In the winter of 1964-65, large debris flows upstream from the dam filled the lake with sediment. During this same time, the stream incised deeply into the landslide dam widening the channel considerably and probably deepening it.

Big Elk: This is a natural slump/debris flow that first appeared on air photos in 1964 [summer] and thus initial activation occurred between 1955 and 1964. The landslide is a series of nested slump blocks on the toe of a large complex of slump and earthflow deposits [Figure 3]. The underlying bedrock is metasedimentary and metavolcanic rock of the EHF unit. The slide grew considerably from 1964-1965 [1964 Flood] and 1965-1971, with heightening head scarps and raw slopes in the toe. Despite its size, field investigation indicates that the stream efficiently removed debris, preventing a large dam from forming.

North Russian: This is a natural debris flow/avalanche in metavolcanic rock of the Salmon River unit of the Sawyers Bar terrane in North Russian Creek. It developed on the toe of a dormant landslide during the winter of 1964-65. Examination of 1965 air photos reveals that in the summer of that year, the channel was filled with debris, but no lake had formed. The 1971 air photos show that the landslide had grown in size, and a lake was present. The lake formed in 1968 or 1969 [Jack Herr, personal communication, 1995]. In 1971, the lake was 550 feet long and had maximum width at its lower end of about 110 feet. By the time the 1975 air photos were taken, the lake was only 160 feet long and 100 feet wide. The 1980 photos display a lake only 30 feet in diameter. In the summer of 1995, the lake area was completely filled with gravel and cobbles, and a prominent exposed bar occupied its former location. The gravel deposits extend for about 700 feet above the landslide exhibiting a gradient of about 1.5%. Below the landslide, the channel gradient steepens to about 2.5% and is lined with boulders and minor gravel deposits.

	Murderers Bar	Bloomer	Nordheimer Pond	Big Elk	North Russian
Year of Failure	1955, 1958	1964	Pre-1650 1964	1955-1964 1964-1971	1964 1965-1971
Ave. Length	1800 ft.	1300 ft. [with scarp]	1800 ft. [with scarp]	600 ft.	1200 ft.
Ave. Width	1300 ft.	1000 ft.	1400 ft.	1300 ft.	400 ft.
Area [acres]	58.0	31.0	50.0	17.0	8.5
Ave. Depth	120 ft.	75 ft.	50 ft.	65 ft.	60 ft.
Volume Mobilized yd^3	10,396,000	2,889,000	5,540,000	2,080,000	1,066,700
Volume Delivered to Stream yd^3	599,000	1,469,000	1,666,000	320,000	23,000
Floodplain Width [ft.]	100 ft.	Ave. 500 feet	240 ft.	35 ft.	120 ft.
Channel Gradient	1.2%	1.5%	+7%, -25%	15%	2.5%
Est. Lake Lgth	2800 ft.	5400 ft.	240 ft.	100 ft.	550 ft.
Lake Width	100 ft.Ave	400 ft.Ave	90 ft.Ave	50 ft.Ave	50 ft.Ave
Lake Depth	20 ft.Max	80 ft.Max	15 ft.Max	20 ft.Max	15 ft.Max
Lake Area	13.0 ac.	50.00 ac.	0.50 ac.	0.11 ac.	0.63 ac.
Tributary Watershed Area	730 sq. mi.	680 sq. mi.	2 sq. mi.	3 sq. mi.	18 sq. mi.
Geologic Terrane	Sawyers Bar [Eastern Hayfork unit]	Sawyers Bar [Eastern Hayfork unit]	Sawyers Bar [Eastern Hayfork unit]	Sawyers Bar [Eastern Hayfork unit]	Sawyers Bar [Salmon River unit]
Failure Process	Translation/ debris flow	Rock slide/ avalanche	Rock slide/ avalanche	Slump	Debris slide/flow

Table 1: Data Summary

DISCUSSION AND CONCLUSIONS

All the Salmon River landslide dams formed in relatively low-gradient stream reaches, immediately adjacent to the channel, and debris was delivered perpendicular to the direct on of stream flow. Effects were generally localized to a relatively short stream segment. The dam at Bloomer was an exception in that the dam failed catastrophically, and the water removed a 500 foot wide segment of the dam on the east margin (Figure 2). The largest dams were formed by bedrock avalanches at Bloomer and Nordheimer Pond, while those involving slump and slide processes were smaller. In the spring of 1995, a slump/earthflow occurred on the Klamath River near Lone Pine Bar, about 13 air miles NW of Murderers Bar. This landslide displaced Highway 96 about 140 feet overnight, and formed a partial dam. Had the landslides at Murderers Bar or Big Elk moved this rapidly, they too would probably have formed large dams. Four of the five landslides investigated were linked to periods of high precipitation or major floods, such as those of 1955 and 1964. None with seismic triggers were documented. The landslides at North Russian, Big Elk and Nordheimer Pond are natural features which occurred on vegetated hillslopes, with no known human influence. Prior to failure, the landslides at Murderers Bar and Bloomer were crossed by a narrow road (15-20 feet wide). The destabilizing effect of the road at Murderers Bar was probably small, but at Bloomer Slide, the road undermined a possible rockslide bench immediately above the Salmon River. The road cuts had a destabilizing effect but the magnitude of this effect is unknown. The length of time during which these landslides obstructed flow patterns was influenced by: volume of debris relative to the power of the stream to transport sediment; size of particles; width of floodplain; and strength of underlying bedrock. Studies of landslide dams around the world indicate that about 1/4 of them fail within one day of formation, and about half within 10 days [Costa and Schuster, 1988]. Three of the five Salmon River landslide dams followed this pattern. All the slides investigated caused short term turbidit and downstream sedimentation (pool filling). They also delivered large boulders and logs to the stream. The boulders remain to this day, creating rearing habitat for fish. Some of the temporary lakes and aggraded areas may have caused increases in late summer water temperatures, but quantitative data are not available.

Landslide dams in the Salmon River have affected two habitat characteristics which influence life history events of cold water fish; (1) upstream migration passage, and, (2) spawning and rearing conditions. The presence of two runs of chinook salmon (spring and fall) in the Salmon River suggests that seasonal barriers to migration were common features in the past. Seasonal barriers favor development of two runs of fish by allowing passage to the spring run, but obstructing the fall run. The landslide dams at Bloomer and North Russian inhibited upstream migration of fall runs for up to 18 years. Since permanent barriers favor development of a single run, they were probably rare in the Salmon River. Grade changes and constrictions associated with landslide dams caused extensive aggradation upstream of the Bloomer and North Russian barriers, and at the mouths of some tributaries like Nordheimer Creek. Grade changes and constrictions remain at Bloomer (where the channel remains about 10 feet higher than it was in 1964), Nordheimer and North Russian. The overall effects of these dams on fish habitat are complex and can't be characterized as "good" or "bad". Aggradation above some of the dams has resulted in the formation of spawning gravels, but this has occurred at the expense of rearing habit which was buried by the gravels. This is the case at Bloomer and North Russian. Also, we don't yet know subtle downstream effects of accumulating gravel at one site and loss of gravel at another. When gravel is stored in one area, it is prevented from replenishing spawning areas downstream.

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SEDIMENT AND SPAWNING HABITAT IN THE LOWER GUNNISON RIVER, COLORADO

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Abstract: The Gunnison River is a large river with a mean discharge of 73 m^3/s located in Southwestern Colorado, USA. The lower reach of the river is habitat for Colorado Squawfish, an endangered species. The flows of both sediment and water in the river have been modified by the construction of reservoirs and by major diversions for irrigation. A major impact of the reservoirs has been a reduction of the capacity of the river to cleanse the stream bed of fines and sand. The flow needed to maintain the spawning habitat for the Colorado Squawfish by removing fines and sand from the bars (riffles) is 480 m^3/s (17,000 cfs); and the flow needed to remove sand and fines from the pools is 226 m^3/s (8000 cfs). These flushing flows are probably not required each year but they are required periodically. An index to the capacity of the river to transport sediment (Sediment Transport Capacity Index, STCI) has been developed based on average daily streamflows. The frequency of flows available to remove sediment from the pools has been reduced from 92% of the years up to 1936, to 46% of the years between 1966 and 1993. The frequency of the flows with the capacity to clean the potential spawning bars was 50% for the years up to 1936; in comparison, the frequency was 12% in the 1968-1993 period. The annual STCI for pool cleaning has been reduced from 58.9 to 10.6, an 82% reduction; and for bar cleaning reduced from 6.62 to 0.26, a 96% reduction.

INTRODUCTION

The Gunnison River, a Southwestern Colorado river, has a mean discharge of 73 m^3/s and a 75 meter width just upstream of its junction with the Colorado River. The lower reach of the river is habitat for Colorado River Squawfish (*Ptychocheilus lucius*), an endangered species. The flows of sediment and water in the river have been modified by the construction of reservoirs and by major diversions for irrigation, and for municipal and industrial purposes. The upper (eastern) part of the Gunnison basin is in the Rocky Mountain physiographic province and the rest in the Colorado Plateau province. The drainage area of the basin above Whitewater is 20,534 km^2. Downstream of Whitewater the river enters the Grand Valley before joining the Colorado River in Grand Junction. About 94,300 hectares are irrigated in the basin above Whitewater.

There was a significant increase in major storage capacity in the Gunnison River basin between 1917 and 1993. The water storage history of the basin can be divided into three periods. The period from the beginning of discharge records (in 1896 but with missing years before 1917) until the completion of Taylor Park Reservoir (137 hm^3) in 1937, the period following construction of Taylor Park Reservoir until completion of Blue Mesa Reservoir (1020 hm^3) in 1965 (in 1966 there was 1187 hm^3 of major reservoir capacity), and the period from 1965 until 1993 (reservoir capacity increased to 1475 hm^3).

The reservoirs in the upper Gunnison basin and the use of water for irrigation have had a significant impact on the daily streamflows in the lower river but less impact on the total flow during a water year. The average daily discharge for two periods are given in Figure 1. The reservoirs have reduced the daily discharges during the spring runoff period and increased significantly the discharges during the summer, fall, and winter. The various uses of water have reduced mean annual flows by roughly 20 m^3/s at the present time. The early 1980's were very wet compared with previous periods. The bankfull discharge is about 500 m^3/s.

The lower Gunnison River can be characterized as a cobble and gravel river, with considerable sand and fine sediment on the surface of, and among, the cobbles and gravel. The median (D50) size of the armour layer is 63 mm, of the substrate below the armour 31 mm, and of a fine material on the surface of the armour in some locations 0.025 mm.

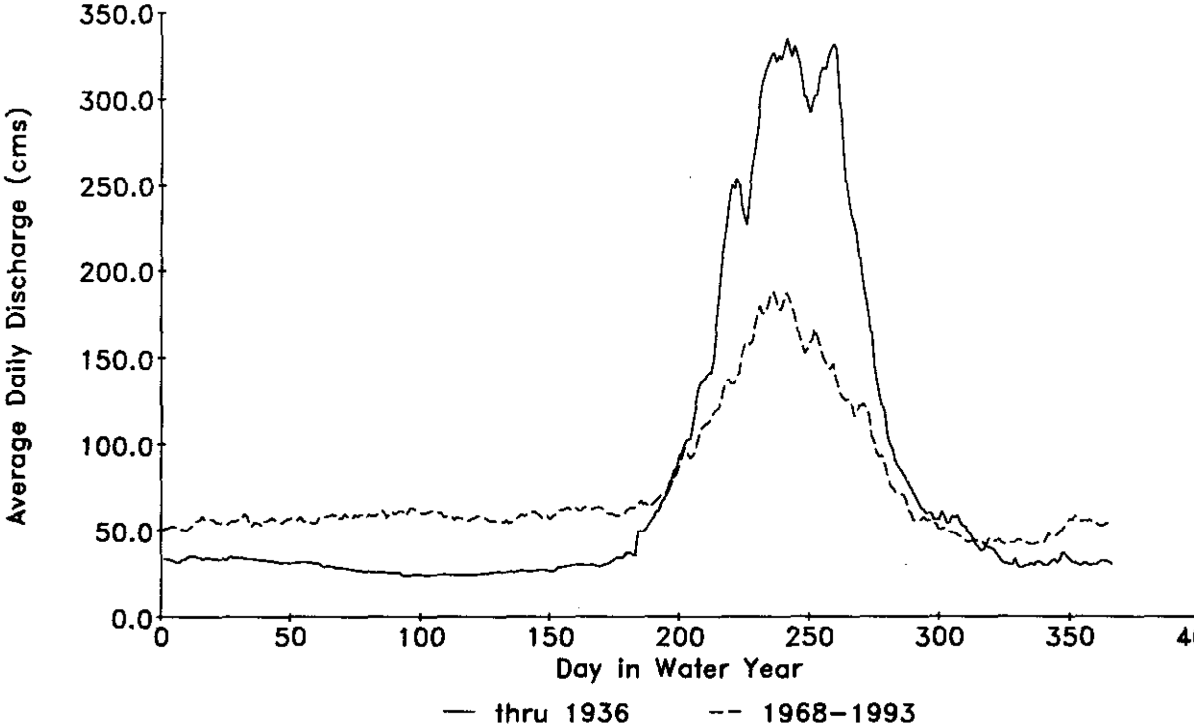

Figure 1. Average daily discharge in the Gunnison River. The period up to 1936 is prior to major reservoir construction in the basin. There was significant water use for irrigation during this period. In 1965 the major storage capacity in the basin could hold about sixty percent of the mean annual discharge of the river.

The National Biological Service and the U.S. Bureau of Reclamation have a joint project to develop techniques for the management of sediment for the benefit of the aquatic ecosystem. This paper is a product of the joint effort. A site (Dominguez Flats) in the lower Gunnison River about 61 km upstream of the junction with the Colorado River and about 38 km upstream of the Whitewater gage is being used as a test study reach.

SEDIMENT AND SQUAWFISH HABITAT

The Colorado Squawfish is an endangered fish native to the warmwater reaches of the Colorado River. The Colorado Squawfish is a predator; the adults feed on other fish. Young fish feed on small invertebrate animals, but as they grow they become increasingly dependent on fish. (Behnke and Benson, 1980).

Colorado Squawfish spawning behavior has two phases (Tyus, Jones, and Trinca, 1987): 1) a staging phase in pools or large shoreline eddies where the fish rest and feed between spawning forays or where males gather around females until they are ready to deposit eggs; and 2) a deposition-fertilization phase on cobble bars (riffles) where the females deposit adhesive eggs on and among the cobbles and males fertilize them. Spawning occurs between late June and mid-August. A clean substrate is needed because the eggs stick to the surface of cobbles.

There are other aspects of the Squawfish habitat that are important from the viewpoint of sediment in the stream. This paper considers only the two items above. The sedimentation analysis must consider 1) the critical discharge required to clean the fines and sand from the bars (riffles) and 2) the discharge needed to cleanse fines and sand from the pools.

BED SEDIMENT IN THE DOMINGUEZ FLATS REACH

The bed material is quite variable with considerable quantities of sand on, and among, the gravel and cobbles on the surface of the stream. The variation in the sizes across one diagonal bar are shown in Table 1. The large sizes on the left are in an area of fast water at all discharges. The samples on the right are from an area of low velocity, or are dry, at low discharges but with reasonably fast water during the spring runoff period.

Table 1. Median (D50) Sizes of the bed material of the Gunnison River along one bar in the Dominguez Flats Reach (diagonal bar between cross section 6 on the left and cross section 7 on the right). Left side is looking upstream

	Armour (mm)	Sub-surface (mm)	Surface (mm)
Left Side	90.4	33.7	
Middle Left	70.1	31.6	
Middle Right	29.8	23.2	0.019
Right Side	29.7	15.1	0.032

The surface material is representative of the sizes of material that must be removed from the bars (riffles) and from the pools.

REMOVAL OF FINES AND SAND FROM BARS (RIFFLES)

One of the two flushing flow objectives considered in this paper is the removal of fines and sand from the parts of the river that may be used as spawning sites by the Colorado Squawfish.

Criteria for flushing of gravel and cobble rivers was previously (Milhous and Bradley, 1986) developed using a substrate movement parameter (called beta parameter in the 1986 paper). The equation for the substrate movement parameter (ß) is:

$$\beta = \frac{R * S_e}{D50_a * (G_s - 1)}$$

where R is the hydraulic radius, S_e is the energy slope, $D50_a$ is the median size of the armour on the bed surface, and G_s is the specific gravity of the armour material.

For removal of fines and sand from the surface of a cobble and gravel stream bed, beta should be at least 0.021 (Milhous and Bradley, 1986). Surface flushing, and not depth flushing, is needed because the eggs stick to particles. The relationship between the sediment transport parameter and discharge is shown in Figure 3. The average relation was used to select a discharge of 480 m^3/s as the required discharge to remove fines and sand from the riffle areas. Only riffle cross sections were used to develop the functions shown in Figure 3. The functions in Figure 3 are based on a one-dimensional model of the river and a constant median size of the armour material of 94 mm (the maximum of the median sizes found on the :iffles) was used to calculate the movement parameter. The WSP program in the Physical Habitat Simulation System (Milhous et al, 1989) was used to simulate water surface elevations. The WSP model was calibrated to 6200 cfs (175.6 m^3/s).

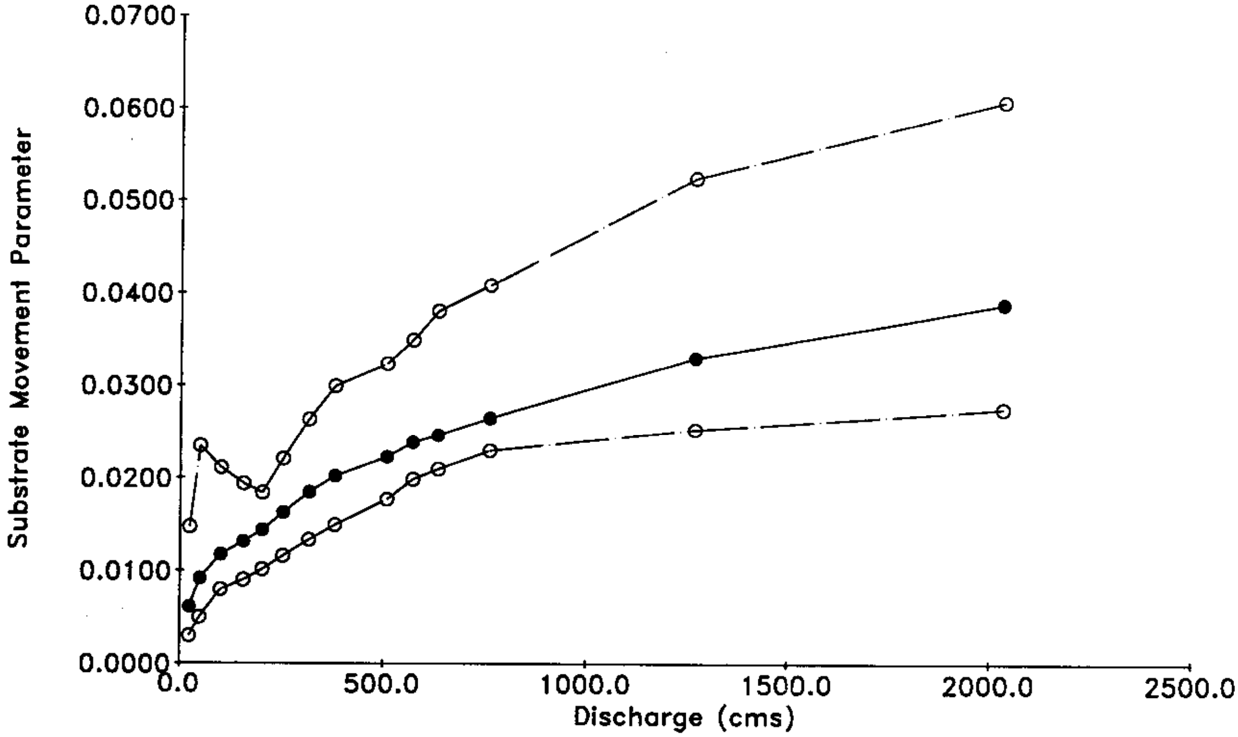

Figure 3. The substrate movement parameter as a function of discharge in the Dominguez Flats reach of the Gunnison River. The maximum, average, and minimum value found on bar (riffle) sections are shown.

The variation in the substrate movement parameter along the river is shown in Figure 4. The use of the average value of the movement parameter means some of the bar cross sections do not have a value of at least 0.021. This is assumed to be acceptable because the section average of the hydraulic radius and maximum of the median sizes of the armour material was used to calculate the substrate movement parameter.

The use of a sediment transport capacity index (Milhous, 1995a) can be used in investigating impacts of water projects and water management on the ability of a river to move sediment when little to no measured sediment load data exists. The sediment transport capacity index (STCI) is calculated using the equation:

$$STCI = \sum((Q\text{-}QCRT)/QREF)^b$$

where Q is the daily discharge, QCRT is a critical discharge, QREF is a reference discharge, and b is the power term in the sediment load vs. discharge equation (2.0 for Gunnison River). The summation is over a period of interest; in this paper the summation period is a water year. The STCI provides an index to the capacity of the stream to transport sediment and not the actual sediment loads.

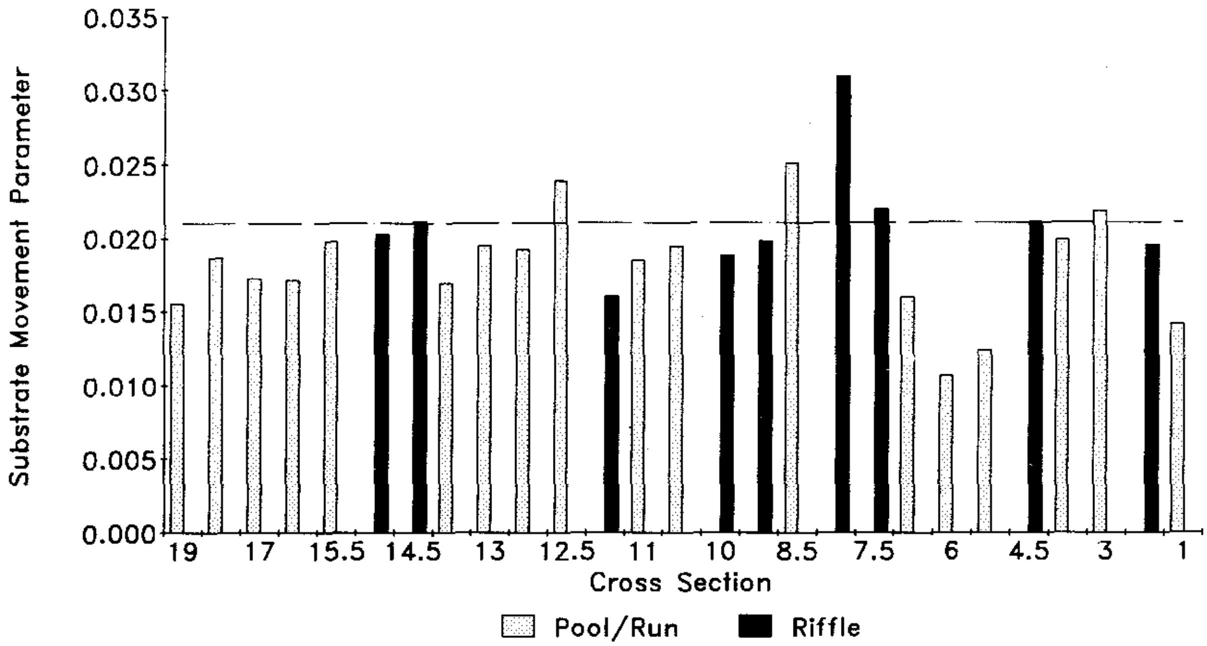

Figure 4. Variation of the substrate movement parameter at a discharge of 480 m^3/s along the Dominguez Flats reach of the Gunnison River. The specific gravity was 2.65, the median size of the bed surface (armour) material used in the calculations was 94 mm.

The critical discharge for the removal of fines and sand from the Gunnison River is 480 m^3/s. The variation of the annual sediment capacity index over the period from water year 1917 to 1993 is shown in Figure 5.

Changes in the water resources system and in the management of the system have had a significant impact on the ability of the river to clean the cobble and gravel bars of sand and fine sediment. These impacts are summarized in Table 2.

Table 2. The frequency of years with sediment transport capacity (STCI) adequate to flush bar (riffle) areas needed by Colorado Squawfish for spawning. Each Period has 26 years. The 1898-1936 period is the 26 years of the record backward from 1936. Minimum discharge for flushing of bars is 480 m^3/s.

Period	Percent of Years With Flushing Flows	Average STCI	Percent of 1898-1936 STCI
1898,1902-06,1917-36	50	6.62	100
1940-1965	31	1.85	28
1968-1993	12	0.26	4

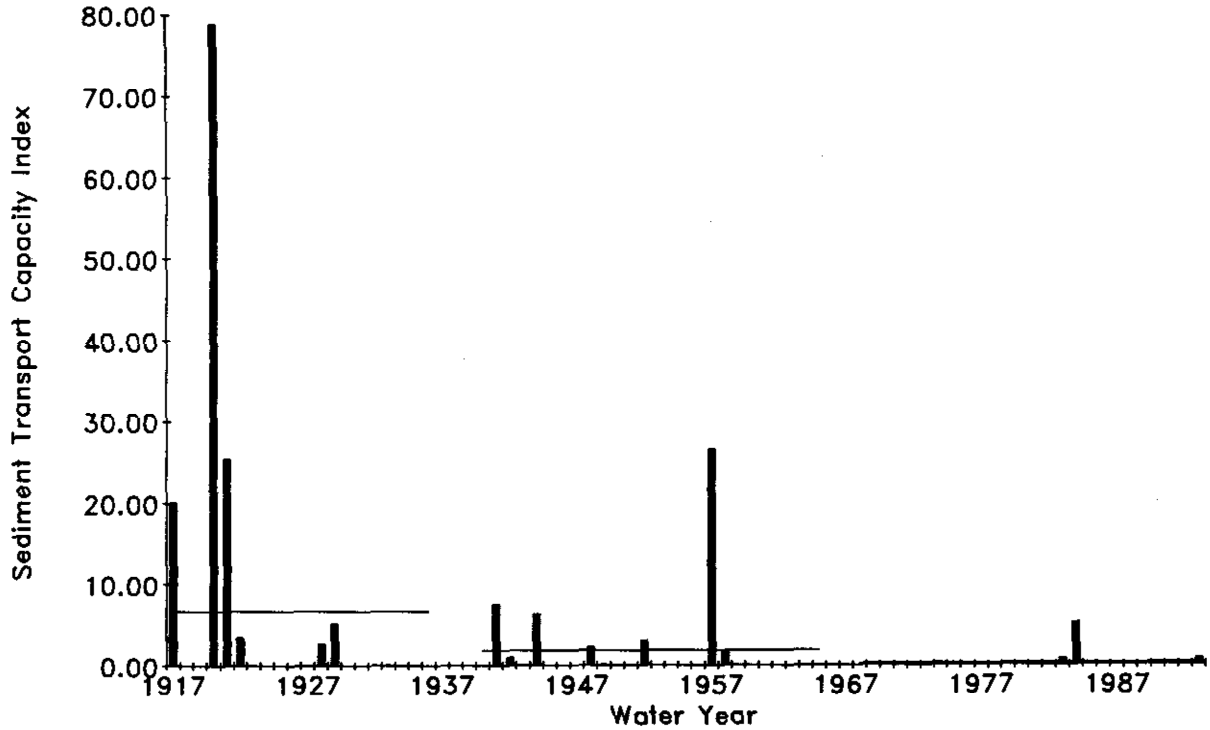

Figure 5. The annual sediment transport capacity index for removal of fines and sand from the bars (riffles) of the Dominguez Flats reach of the Gunnison River. The critical discharge was 480 m^3/s and the reference discharge 150 m^3/s. The lines on the figure are the mean for the period.

REMOVAL OF FINES AND SAND FROM POOLS

The calculation of a critical discharge for removal of sand and fines used the maximum wash load size analysis presented in Milhous (1995b). The critical discharge required to remove sizes up to 2 mm was found to be 226 m^3/s. The sediment transport capacity index was calculated using a critical discharge of 226 m^3/s. The change in the frequency and the magnitude of the sediment capacity to clean pools is shown in Table 3.

Table 3. The frequency of years with sediment transport capacity (STCI) adequate to flush pool areas needed by Colorado Squawfish. Each Period has 26 years. The 1898-1936 period is the 26 years of the record backward from 1936. Minimum discharge for flushing of pools is 226 m^3/s.

Period	Percent of Years With Flushing Flows	Average STCI	Percent of 1898-1936 STCI
1898,1902-06,1917-36	92	58.9	100
1940-1965	77	30.4	52
1968-1993	46	10.6	18

DISCUSSION

The conclusions of this paper are that the discharge needed to maintain pools in the condition needed by Colorado Squawfish is 226 m^3/s and to maintain bars in the state needed by the Colorado Squawfish for spawning is 480 m^3/s. The frequency of the flows with the capacity to clean the potential spawning bars was 50% for the years up to 1936, in comparison to 12% in the 1968-1993 period. The frequency of flows available to remove sediment from the pools has been reduced from 92% of the years up to 1936, to 46% of the years between 1966 and 1993. The sediment transport capacity index for pool cleaning has been reduced from 58.9 to 10.6, an 82% reduction; and the STCI for bar cleaning reduced from 6.62 to 0.26, a 96% reduction.

In 1993 the sediment transport capacity was adequate to remove fines and sand from both pools and riffles. (The STCI for bar flushing was 0.81, and for pool flushing 55.56.) This runoff event did cause flushing of the pools as is shown in Figure 6.

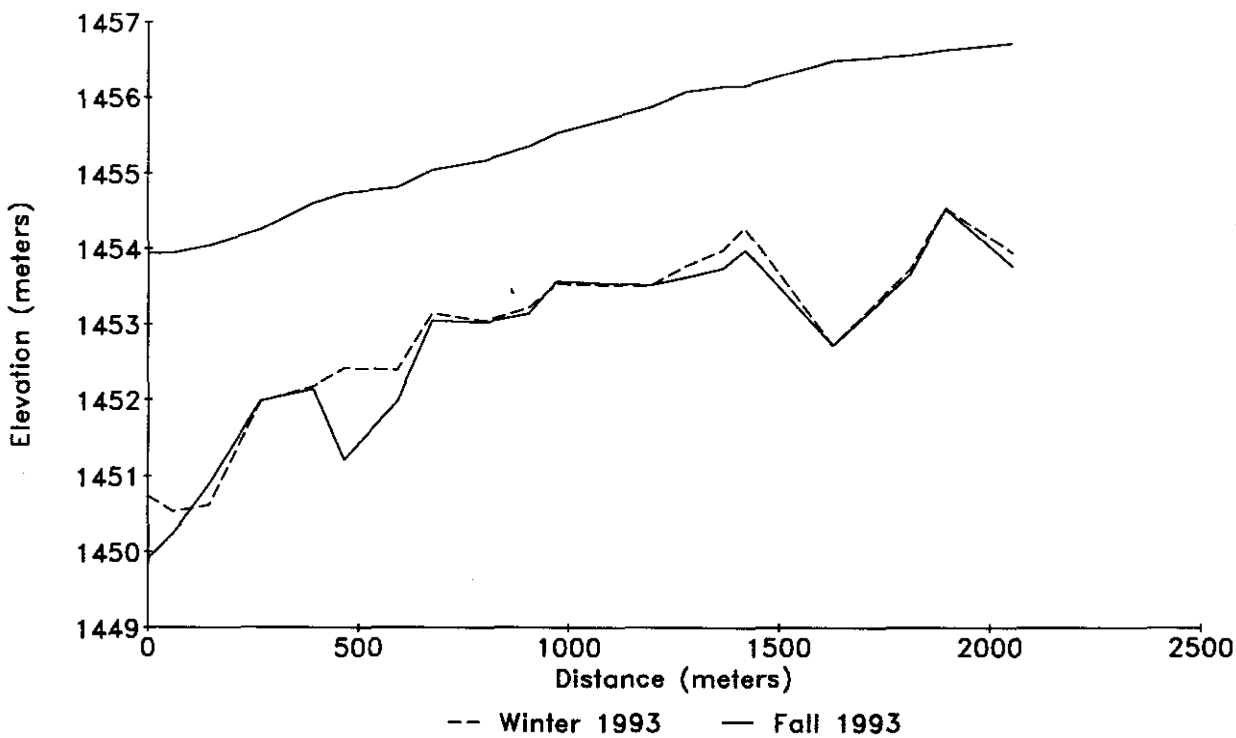

Figure 6. Change in the thalweg of the Dominguez Flats reach of the Gunnison River caused by the 1993 spring runoff. The upper line is the water surface for a discharge of 171 m^3/s.
There was also an inportant change in at least one bar. Measured bulk density in February 1993 was 2.61 kg/m^3 which means few voids existed. The measured bulk density after the 1993 runoff event was 2.08 kg/m^3. The sediment transport capacity needed to clean the bars was zero for each of the previous eight years.

The observed scour of the thalweg and the change in bulk density suggest the conclusions of the paper are at least reasonable.

Two considerations should temper these conclusions. The first is that the spawning needs of the Colorado Squawfish are poorly understood. The second is that a one-dimensional analysis was used. The spawning needs of the fish should be better understood and a two-dimensional analysis technique used that relates the specific locations in the stream that have the bed conditions needed for spawning with the two-dimensional velocity structure before definitive conclusions can be made. The conclusions from this paper can be used on an interim basis.

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2-D MODEL OF SEDIMENT TRANSPORT AND APPLICATION IN ESTUARINE AND COASTAL ENGINEERING

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Abstract: Under the joint action of tidal currents and waves, the sediments in the silty estuaries and coastal regions are easily suspended and the main form of sediment transport is as the suspended load. It is necessary to study the sedimentation problems when the harbours and navigation channels are to be constructed and dredged in such arias. Based on the non-equilibrium sediment transport equation, bed deformation equation and transport capacity formula developed by the first author, a 2-D suspended sediment model is established and applied to study the sedimentation problem for deepening navigation channel in Yangtze estuary and building Huanghua big coal harbour. The verification of calculations shows that the sediment concentration distribution and bed deformation in the Yangtze estuary and Huanghua coastal region can be successfully simulated by the model.

INTRODUCTION

It is well known that the rivers in China are rich in sediments and many estuaries and coastal regions are covered by silts. Such fine particles are easily suspended by the joint action of tidal currents and waves, and the main form of sediment transport is as the suspended load. It is important to study the sedimentation problems when the harbours are to be built and the navigation channels to be dredged.

In past, the study on the sediment transport under the joint action of tidal currents and waves is very limited and, therefore, it is difficult to establish a suspended sediment transport model. Because of lack of modeling method, the study on the sedimentation problems for the estuarine and coastal engineering is still limited to empirical or semi-empirical analyses and approximate estimations.

In this paper, an attempt is made to present a horizontal 2-D mathematical model of suspended sediment transport under the joint action of tidal currents and waves on the basis of all necessary equations developed by the first author.

CONTROL EQUATIONS

In the process of the suspended sediment transport, the sediments are uninterruptedly exchanged between the particles suspended in water and those on the bed. The quantity of sediments settled down to the sea bed of unit area in the interval of unit time from the water is denoted by q_d, and it can be determined as

$$q_d = \alpha \omega S \tag{1}$$

where α is the probability of particle settling, ω is the fall velocity of sediments and $\alpha\omega$ can be considered as the fall velocity in the moving water, S is the sediment concentration of water. When the sediment concentration, S, is equal to the sediment transport capacity of tidal currents and waves, S_*, the sea bed is under the equilibrium condition and the incoming quantity of sediments from sea bed into the water, q_u, is equal to the quantity of sediments settled down to the sea bed from the water. This condition leads to

$$q_u = \alpha\omega S_* \tag{2}$$

In general cases, the sediment concentration of water is not equal to the sediment capacity, and the deposition occurs if $S > S_*$, and the scouring occurs if $S < S_*$ and the bed particles can be suspended by the joint action of tidal currents and waves; and there is no scouring or deposition if $S = S_*$ or $S < S_*$ and the bed particles can not be moved by the action of tidal currents and waves. Therefore, for general cases the quantity of sediments suspended from the bed has to be rewritten as

$$q_u = \alpha\beta\omega S_* \tag{3}$$

where

$$\beta = \begin{cases} 1, & \text{when } S > S_*; \\ 1, & \text{when } S \le S_* \text{ and bed particles can be moved;} \\ S/S_*, & \text{when } S < S_* \text{ and bed particles can not be moved.} \end{cases} \tag{4}$$

Based on the conservation of sediment quantity, the non-equilibrium suspended sediment transport of tidal currents and waves can be obtained (Dou,1995b)

$$\frac{\partial(hS)}{\partial t} + \frac{\partial[h(u+u_w)]}{\partial x} + \frac{\partial[h(v+v_w)]}{\partial y} + \alpha\omega(S - \beta S_*) = 0 \tag{5}$$

Where h is the water depth; u and v are the velocity components of tidal currents in the directions of x and y respectively; u_w and v_w are the orbital velocity components of waves.

As is usually the case, one-directional sediment transport caused by waves can exist only within a semi-period. Within a period the sediments are transported alternately in two contra directions, and the sediments transported by mass transport velocity are negligible in comparison with the sediments transported by tidal currents. When the observation period is much greater than the wave period, one can average Eq.(5) over a wave period. As the tidal velocity is basically independent of the orbital velocity of waves and the mean value of the orbital velocity in a wave period is equal to zero at neglecting the mass transport velocity, the integration between a wave period makes Eq.(5) simplified as

$$\frac{\partial(hS)}{\partial t} + \frac{\partial(hSu)}{\partial x} + \frac{\partial(hSv)}{\partial y} + \alpha\omega(S - \beta S_*) = 0 \tag{6}$$

This equation is just the same in apparent as the sediment transport equation for tidal currents obtained by the first author before (Dou,1963), and the difference between them is in the transport capacity. The sediment transport capacity, S_*, in Eq.(6) is the capacity under the joint action of both tidal currents and waves. Based on the consideration of the exchange between the sediments in water and on the bed, the bed deformation equation can be written as

$$\gamma_0 \frac{\partial \eta}{\partial t} = \alpha\omega(S - \beta S_*) \tag{7}$$

where γ_0 is the dry unit volume weight of sea bed materials, η is the elevation of sea bed surface. It can be mentioned that the deposition occurs if η increases and the scouring occurs if η decreases.

The sediment transport capacity of tidal currents and waves is dependent on the tide and waves energy. Both tidal currents and waves make the sediments suspended by their turbulent energy and a part of this energy is dissipated by suspending sediments. As the turbulent energy of tidal currents and waves is provided by the time-averaged energy, the turbulent energy dissipated by suspending sediments is included in the time-averaged energy dissipation. Therefore, the energy dissipation for suspending sediments is a little part of the time-averaged energy dissipation. Based on this conception, one can write out (Dou,1995a)

$$\beta_1\beta_2\gamma\frac{H^2}{T} + \alpha_0\gamma\frac{V^3}{C^2} = (\gamma_s - \gamma)h\omega\frac{S_*}{\gamma_s} \tag{8}$$

where β_1, β_2, α_0 are coefficients; γ and γ_s are unit volume weights of sea water and sediment particles respectively; H is wave height, T is the wave period, V is the mean velocity of tidal currents, C is Chezy coefficient. The first and second terms on the left of Eq.(8) are the wave and tide energy respectively dissipated for suspending the sediments, and the term on the right is the energy needed for sustaining a certain quantity of sediments in suspension, i.e. the energy needed to form the sediment transport capacity S_*. From Eq. (8) one can obtain

$$S_* = \alpha_0\frac{\gamma\gamma_s}{\gamma_s - \gamma}\left(\frac{V^3}{C^2h\omega} + \beta_0\frac{H^2}{hT\omega}\right) \tag{9}$$

where $\beta_0 = \beta_1\beta_2 / \alpha_0$. According to a lot of laboratory and field data, we can take $\alpha_0 = 0.023$ and $\beta_0 = 0.04 f_w \approx 0.0004$, here f_w is the sea bed friction coefficient for wave propagation.

In the silty estuaries and coastal regions the sediment particles are very fine and flocculated under the influence of salt. These particles are transported in the form of flocs. Therefore, the problem of particle-size distribution in above equations are not considered. In the case when the influence of flocculation is very small and the non-uniform distribution of particle sizes has to be considered, the sediment concentration and fall velocity in Eq.(6) and (7) can be considered as those for some one particle-size group, and Eq. (6)and (7) have to be written as

$$\frac{\partial(hS_n)}{\partial t} + \frac{\partial(hS_nu)}{\partial x} + \frac{\partial(hS_nv)}{\partial y} + \alpha_n\omega_n(S_n - \beta_nS_{*n}) = 0 \tag{10}$$

$$\gamma_0\frac{\partial \eta_n}{\partial t} = \alpha_n\omega_n(S_n - \beta_nS_{*n}) \tag{11}$$

solutions of sediment transport equation and bed deformation equation can be obtained on the basis of dynamic factors given by the wave and flow models, and then the dynamic factors are recalculated on the basis of consideration of the bed deformation given by the sediment transport model.

For mathematical modeling of sediment transport, the various methods and grids can be adopted, and the finite difference method and triangular grids are adopted in the paper in order to fit well the engineering boundary and to be economic of the volume of work. The finite difference form of the sediment transport equation and bed deformation equation can be written as

$$\frac{h_i^{n+1}S_i^{n+1}-h_i^nS_i^n}{\Delta t}+\frac{\partial}{\partial x}(hSu)_i^n+\frac{\partial}{\partial y}(hSv)_i^n+\alpha_i^n\omega_i^n\left(\frac{S_i^{n+1}+S_i^n}{2}-\beta_i^n\frac{S_{*i}^{n+1}+S_{*i}^n}{2}\right)=0 \tag{17}$$

$$\frac{\eta_i^{n+1}-\eta_i^n}{\Delta t}=\frac{\alpha_i^n\omega_i^n}{\gamma_0}\left(\frac{S_i^{n+1}+S_i^n}{2}-\beta_i^n\frac{S_{*i}^{n+1}+S_{*i}^n}{2}\right) \tag{18}$$

where i is the computation node in model region, Δt is the time step, and n and $n+1$ denote the values at time $n\Delta t$ and $(n+1)\Delta t$ respectively. The partial derivatives can be expressed by using the area weighted method, and the up-wind scheme has to be adopted (Dou,1995b). This model has been applied to study the sedimentation problems for navigation channels and harbours.

APPLICATION IN NAVIGATION CHANNEL

The navigation depth of Yangtze Estuary in natural conditions is only about 6 m, and it reaches at present to 7 m by dredging the sediments of 10 ~ 15 million cub meters per year. In order to deepen the navigation channel to 12.5 m, a regulation project is developed, which includes two guide jetties and some dikes. The length of each guide jetty is about 50 km. The dredging work is also proposed. The model is made to predict the siltation in the deepened navigation channel. The grid system of the model is presented in Fig.1. Before the model is used for the siltation prediction, the verification is made by the field data in order that the parameters and initial and boundary conditions in the model are determined correctly. The verification of calculations shows that the velocities and directions of clockwise rotation of tidal currents are well simulated. Based on the dynamic factors given by the tidal flow model and wave model, the sediment concentration distribution field in every moment of a tidal period is calculated and compared with the field measurements (Fig.2). In Tab.1 the quantities of siltation given by the sediment transport model are compared with the data measured in the field. Fig.2 and Tab.1 show a good agreement between the model and the prototype.

Tab. 1 Siltation in navigation channel

Time period	Quantity of siltation ($10^3 m^3$)	
	Calculated	Measured
Feb.2 ~ Feb.16,1990	304.1	329.0
Aug.3 ~ Aug.16,1990	545.9	528.0

APPLICATION IN BUILDING HARBOUR

A big port of coaling is to be built in the Huanghua coastal region, Hebei Province, where Dakouhe river comes in. The sea bed is covered by silts. Under the joint action of tidal currents and waves, the bed materials are easy to be suspended and transported. However, the sea bed is basically in equilibrium with some slight erosion. The proposed layout of the harbour can be seen in Fig.3, where a closed basin and entrance jetties are illustrated.

The model verification is carried out for the natural conditions. The calculated velocities and directions of anti clockwise rotation of tidal flow is in good agreement with the measured data. Presented in Fig.4 is the comparison of sediment concentration between field measurements and calculated curves. The field data were measured when the mean wave height was 0.2 ~ 0.25 m.

In Huanghua coastal region the action of waves on suspending sediments is strong, and under their action the sediment concentration in the shallow water is much greater than that in the deep water. This phenomenon is well simulated by the model, and the calculated curves and measured data are presented in Fig.5. Based on the topographic maps measured in 1985, 1989 and 1992, the verification of bed deformation is made and presented in Fig.6. In the model the initial topography was taken from the map measured in 1985, and then the bed elevation is calculated for 1989 and 1992. All kinds of verification show that the suspended sediment transport model can successfully simulate the concentration distribution and bed deformation under the action of tidal currents and waves. At present, the model is used for the optimization of the harbour entrance and navigation channel siting.

CONCLUSION

On the basis of the sediment transport equation and bed deformation equation developed by the authors, 2-D model of suspended sediment transport under the joint action of tidal currents and waves is established. All kinds of verification shows that the sediment transport and bed deformation in estuaries and coastal regions can be successfully simulated by the model. By using this model, the sedimentation problems in deepening navigation channel of Yangtze Estuary and building Huanghua coal harbour are studied, and a lot of important information are obtained for optimizing the projects. Therefore, a new practical means is provided for studying the sediment problems of the estuarine and coastal engineering.

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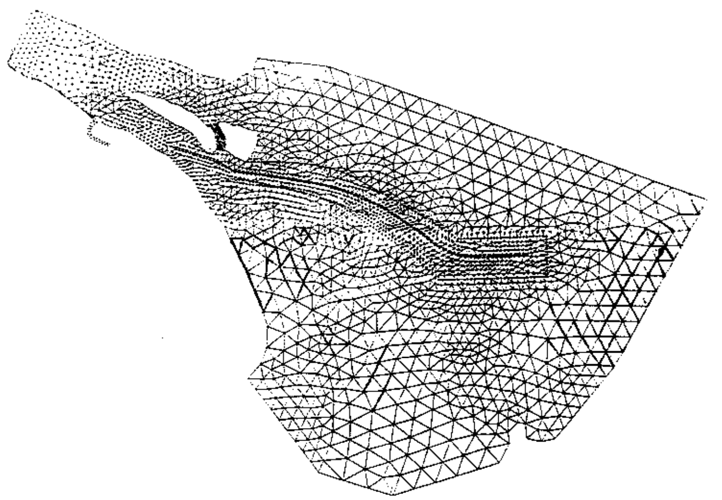

Fig.1 The grid system of Yangtze Estuary model

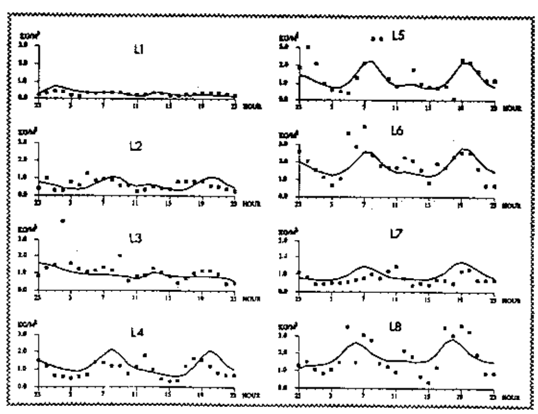

Fig.2 Comparison of concentration calculated with measured in Yangtze Estuary

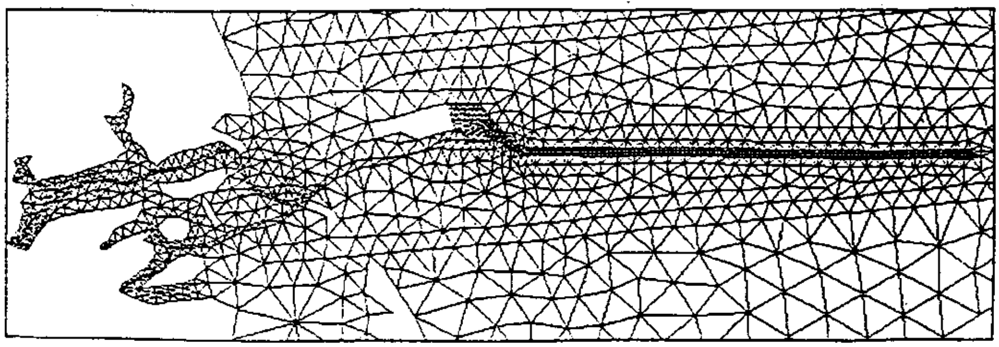

Fig.3 The model grids of Huanghua harbour

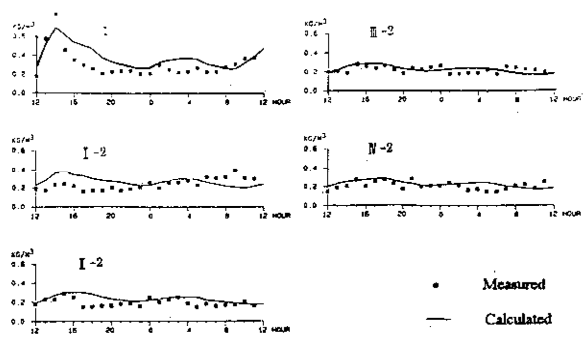

Fig.4 Comparison of concentration between calculated curves and measurements in Huanghua region

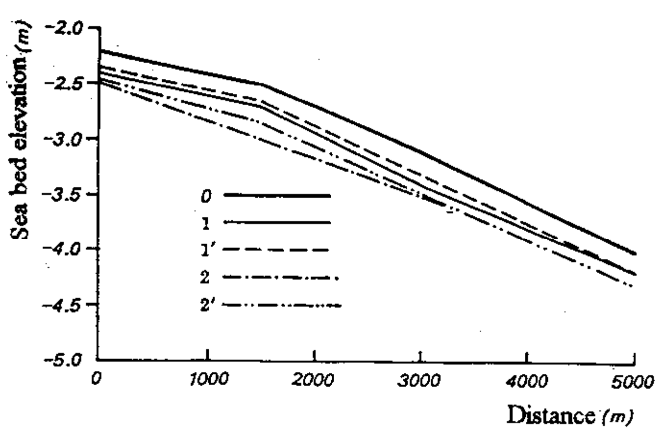

Fig.5 Comparition of bed deformation between calculated and measurement

0-1985.5. Initial topography

1 Measured in July, 1989 1' July, 1989 calculated topography

2 Measured in Aug., 1992 2' Aug., 1992 calculated topography

NOTES

HYDRAULIC IMPACTS OF IN-STREAM HABITAT AND EROSION CONTROL MEASURES

By R. Seal, Research Scientist; B.R. Hall, Hydraulic Engineer; R.R. Copeland, Research Hydraulic Engineer; Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi

Abstract: We are developing a methodology for assessing the effect of habitat enhancement measures on water-surface profiles and local scour. After selecting several habitat enhancement structures to evaluate, we are establishing field data collection sites to measure their hydraulic effects directly. We are constructing a flume model of the structures to study their impact on flood stages and velocity distributions. Habitat enhancement features are frequently used in groups. Flume experiments will allow us to determine the effect of individual and multiple structures under a wide range of flow conditions. In the future, we will develop a methodology for using the HEC RAS backwater program to calculate water-surface profiles in the flood channels around the structures. Our goal is to formulate guidance for the selection and design of habitat enhancement features that optimize flood conveyance and environmental value.

INTRODUCTION

Background: Originally, most flood control channels were constructed and managed for the primary purpose of optimizing flow conveyance and reducing the impacts of flooding. However, the aesthetic, recreational, and habitat value of the flood control channels and their floodplains have all become important and fundable management objectives. Since the 1970's, and with increasing frequency, these flood control channels have been modified to reflect the changing priorities of communities and local partners. A new design philosophy has emerged. It may be described as " designing with nature in all of its dimensions--ecological, visual, and human-cultural--rather than against or onto it.". (Nunnally and Shields, 1985) One focus of efforts and resources is the in-stream habitat, especially, but not exclusively, as it pertains to fish populations. Variables that are generally recognized as being important indicators of the quality of fish habitat include: water depth, diversity of flow velocities, water temperature, organic matter both in and overhanging the channel, and water quality.

In-stream habitat enhancement structures directly affect the water depths, flow velocities, and when natural woody materials such as root wads are used, organic content. Structures placed in flood control channels affect the conveyance and planform properties of the river directly as roughness elements and indirectly as flow diverters. While many of these structures are being placed in streams nationally and internationally in the effort to improve the environmental quality of managed rivers, little, and often no, data have been collected to quantify either the intended effects or the indirect effects on water level, scour, and channel stability. This lack of data affects the process of improving the habitat quality of rivers in two fundamental ways. Firstly, it is difficult to design an enhancement program that optimizes environmental goals while assuring flood conveyance to design or acceptable levels. Adding roughness to a channel will increase the water level so that at some point habitat measures may conflict with maintaining flood level criteria. Secondly, without quantification of the environmental impacts of these structures one cannot reasonably estimate levels of success or failure or identify the important limiting and contributing factors in each physiographic environment. For example, what is effective in a highly variable flow gravel bed stream may not be the best choice in a sand bed stream of relatively moderate perennial flow characteristics.

The Flood Control Channels Research Program, sponsored by Headquarters, US Army Corps of Engineers (HQUSACE), established a work unit to address and quantify effects of many types of habitat restoration measures both in-stream and in the surrounding riparian corridor. The preliminary field and laboratory studies for the work unit, Hydraulic Effects of In-stream Habitat Measures and Hydraulic Structures for Channel Restoration, are described herein. This is the first year of funding for the work units so the effort has concentrated on identifying and beginning to instrument field sites.

IN-STREAM HABITAT ENHANCEMENT STRUCTURES

Types of Structures: Historically, flood control channels have been constructed to be relatively uniform in cross-section with low sinuosity. This has resulted in channels with uniform depths and little variation in velocity in the cross or downstream directions. It is believed in the fisheries community that diversity of species, sizes, and ages within species, correlates strongly with diversity of habitat parameters including depth and velocity. A variety of in-stream structures are used in channels to create this diversity. The primary function of the structures outlined below is the creation of habitat diversity characterized by variations in channel depths and velocities especially at low flow. The descriptions given below are drawn from the projects we have visited for this study. The terminology and definitions of habitat enhancement structures vary with locale and have not been standardized to date.

Deflectors: Deflectors are typically triangular in shape and are keyed into the channel bank. The deflectors are typically made of boulders that may be held in place with logs on the stream side. Deflectors are sometimes known as low flow deflectors because they have a low profile with only the top surface exposed at low flows and are entirely submerged at medium and high flows. Their principle effect is to concentrate the flow toward the center of the channel, increase velocities, and sometimes cause a scour hole to develop. They can be used in pairs that are directly opposing each other on a single cross section or on alternating sides on adjacent cross sections. When directly opposing each other they have the effect of concentrating the flow in mid-channel for an increased effective velocity, and in an erodible bed, increased depth. Alternating deflectors are used to encourage a meandering pattern in an otherwise straight channel. These deflectors are often complemented with some bank cover or protection measures on the opposite bank.

Weirs: Weirs are structures that completely span the low flow channel, are generally perpendicular to the flow, and often are exposed at low flow such that most of the flow is directed through a center notch. They can be made of many materials ranging from cement to boulders, to logs. They usually have a fairly substantial base and hence can perform as a grade control structure as well. They are used to concentrate flows, providing a corridor for fish in extremely shallow flows, and a plunge pool on the downstream side.

Sills: Sills are similar to weirs in that they extend the full width of the low channel. However, they are generally entirely submerged, being only a log or two diameters in height. They may be straight, diagonal, or combined to form V-shapes in the up or downstream directions. Their function is to direct the flow and create plunge pools.

Boulders: Boulders that protrude from the water at low flows are used to create flow variation, cover, and scour to improve the fish habitat. They can be placed in groups, called clusters, or singly in a more random pattern. The minimum rock size is usually meant to withstand the maximum flows. The maximum size in the rivers in this study is about four feet in diameter, with three feet being the average.

Scour Holes: Scour hole formation is a measure that is taken rather than a structure that is added to the stream. Scour holes can develop naturally as a result of the addition of structures as described above or may be created or enhanced by removal of material during construction. Pre-forming the scour holes immediately generates habitat diversity that may be maintained by the accompanying structures.

FIELD DATA COLLECTION

Locations/Reconnaissance: Basic field reconnaissance and data collection has been conducted for eight different rivers this field season with some information gathered on an additional four rivers. The sites include: Guadalupe River, CA; Wildcat Creek, CA; Zumbro River, MN; Twenty Mile Creek, MS; Harland Creek, MS; Lower Saddle River, NJ; Sammamish River, WA; and St. Regis River, MT. Detailed topographic surveys of cross sections and habitat enhancement measures, velocity profiles, surface bed-material grain size distributions, and installation of pressure sensors for water surface elevation changes have all been conducted on the Sammamish, St. Regis, and Zumbro Rivers. The data is being collected in cooperation with the following agencies that have design and/or oversight responsibilities: King County and the Seattle District Corps of Engineers; the US Forest Service and Department of Transportation; and the St. Paul District Corps of Engineers; respectively. Twenty Mile Creek and the Lower Saddle River are sites where habitat structures have not yet been constructed and are being considered for pre-and post-construction monitoring.

Water Surface Levels: As stated earlier, one of the principal goals of the project is to quantify the effects of in-stream habitat structures on water surface profiles. To determine the effects where the structures are already in place, we are monitoring both developed and control reaches. Control reaches are chosen to be as similar as possible in hydraulic, geometric, and length aspects as the reach that contains structures. A water level pressure sensor is placed at both the upstream and downstream ends of each reach with no apparent rapid deposition or erosion. The sensor is connected by cable to a data logger (Fig. 1) that can be downloaded in the field to a laptop computer. The memory in the data logger is sufficient to allow two to three months of continuous logging between data retrievals.

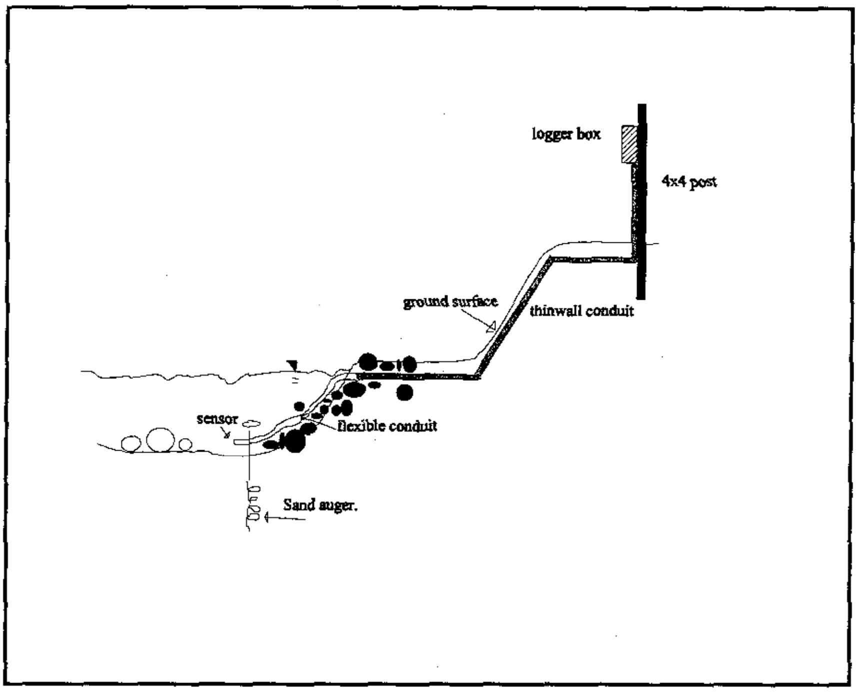

Figure 1 Schematic of Pressure Sensor and Data Logger Field Installation.

Field Variables: The purpose of monitoring the water surface levels is to determine whether or not the habitat enhancement measures have a measurable effect on the channel conveyance and, if so, to develop the data necessary to back calculate the Manning 'n' value for the reach. The field data alone will not allow us to assign a discrete roughness value to individual types of structures, because in all cases there are other physical roughness elements within the reach which can only be estimated. Flume experiments which will isolate the variables are described in a later section. Of the three rivers studied, the St. Regis River field site affords the best possibility of effect isolation because only one type of structure, boulder clusters, is used in the study reach and because the vegetation and channel geometry were not altered as part of the enhancement process. The addition of the boulder clusters is the only difference between the enhanced and control reaches. In the other two rivers, multiple types of structures were used within each enhanced reach including deflectors, boulder clusters, weirs, and sills. The Sammammish River has the most differences between control and enhanced reaches including drastic changes to the bankline vegetation and cross section geometry. A variety of structures, including deflectors, sills, and rootwad bank stabilization were used. The Zumbro River has the largest variety of structures, including rock weirs, deflectors, and boulder clusters, but is uniform between reaches with respect to vegetation and cross-sectional geometry.

Topographic Surveys: Detailed topographic surveys of the channel geometry, bathymetry, structures, and surrounding flood plain were performed on the three rivers. Standard cross sectional surveys every fifty feet between each structure, as well as immediately upstream, downstream, and around the outside perimeter of each structure were measured with a total station that defined each point in x, y, and z space relative to arbitrary or known datums. The data will be used to determine planform and structural changes through time due to the changing hydrograph and to facilitate stage-discharge calculations for each reach. Each of the three field sites was surveyed during the same low flow season that the structures were installed. In each case, there was already evidence of changes in bottom geometry caused by the placement of the structures. Comparison surveys are planned for all of the reaches as soon as possible after the high flows recede to a navigable level in order to document the topographic changes due to flood stage hydraulics. The water level recordings, and US Geological Survey discharge records will enable us to model the channels for the different discharges.

Velocities: Low flow velocity measurements have been taken at each of the cross sections using a Marsh-McBirney flow meter at either 0.6 or 0.2 and 0.8's depth at multiple locations on the cross section. Velocities were also measured around the structures to document the local changes due to the in-stream measures. An attempt will be made to gather similar data at the peak and moderate flows when most of the channel forming discharges are active. However, this may prove logistically difficult in the field, and changes in velocity distributions due to changes in water-surface elevations may be relegated to the flume experiments.

Grain-size Distributions: Grain-size distribution data was collected on cross sections around the structures. Patches, as defined by Seal and Paola (1995) wherein a bounded area containing material of similar mean grain size distinct from the surrounding areas, were identified. These patches present a significantly different apparent roughness to the flow. Patches of material with a mean size coarser than 16 millimeters were sampled using a modified Wolman pebble count method (Wolman, 1954). Finer patches were surface sampled for laboratory sieve analysis. Grain-size information is critical for estimating surface roughness as well as critical shear stresses. Bed material grain size distributions are also and indicator of habitat diversity. Substrate diversity is important for macro-biotic life and as spawning material for different fish species.

FLUME EXPERIMENTS

Purpose: The purpose of the flume experiments is to allow isolation of variables and to test the limits of stability of various structures and configurations of structures. As described earlier, it is impossible to find a field site that isolates roughness elements and is accessible at the full range of flows for detailed measurements of the velocity and bed profiles. The laboratory facilities of the Waterways Experiment Station are being used to provide an experimental environment to meet those measurement needs.

Experimental Setup: The Hydraulic Research Facility immobile bed flume is approximately 40 meters in length, 1.5 meters wide, 0.25 meter deep, and is capable of tilting through an angle of 1.5 degrees about a pivot point at the headbay. The upstream 20 meters of the flume has a preformed channel geometry from a previous experiment. The cross-sectional geometry is uniform over the first 20 meters but is asymmetrical about the channel centerline as is shown in Figure 2. At the downstream end this form ends abruptly with a 5 centimeter drop to the flume floor and the cross sectional geometry becomes a rectangle. An expanded steel mesh with diamond shaped holes covers the bottom of the upstream channel form and has an approximate

Manning's roughness coefficient of 0.02 based on earlier calibration experiments. A Sontek, three-dimensional velocity probe is used to measure velocity profiles at cross sections. This probe was chosen for its small cross-sectional area and hence small disturbance to the flow and its ability to measure velocities in shallow flows and record them automatically on a PC. Water surface elevations are measured using a point gauge suspended from a cart that rolls on rails adjusted to be parallel with the flume slope. The velocity meter is also suspended from the cart. Discharges are measured through a standard venturi meter that was calibrated with a v-notch weir prior to the experiments.

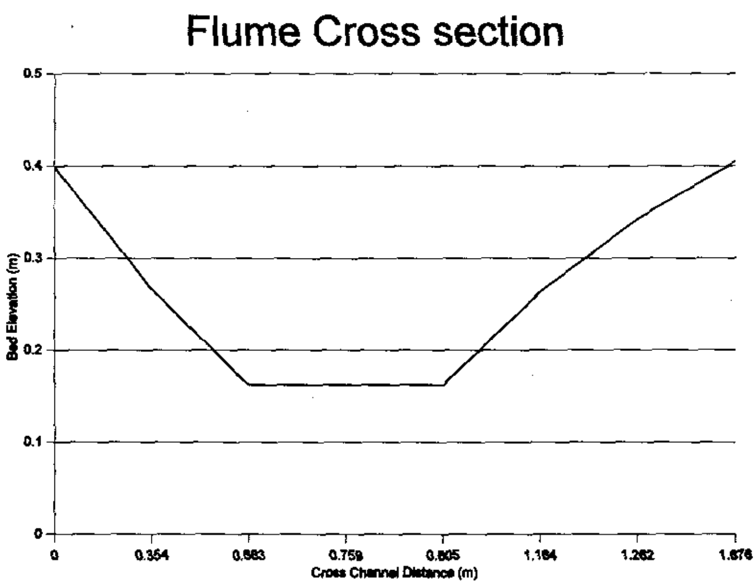

Figure 2 Plot of Flume Cross Section Geometry

Initial Experiments: Initial experiments are underway to determine velocity profiles and water surface elevations without structures, with one boulder, and with one boulder cluster. Because of scale effects we will be comparing the relative velocity changes around the structures and throughout the channel between flume and field experiments. If the initial experiments produce results that cannot be compared to the field because of the scaling effects the experiments will be moved to a larger, outdoor flume.

FUTURE WORK

Field Work: Field work at existing sites will continue for at least the next 2 years. Water surface elevation data will be collected continuously throughout the year. Topographic surveys will be taken following the high flow season and perhaps immediately before if the low flow discharges are responsible for significant geomorphic changes.

Additional Sites: Additional sites are under consideration for instrumentation. Currently all of the rivers monitored are perennial and affected heavily by spring snow melts. Their substrates vary from mostly sand and clay to primarily coarse gravel to cobble. There is interest in studying the stability of structures in more ephemeral flood control projects where high flow events are more flashy and dramatic with varied substrates and channel planforms that are relatively unstable. There is also the possibility of monitoring a few sites pre-construction to record actual variations in the conveyance of the same reach of channel with and without the structures. This would eliminate many of the frustrating variables introduced by choosing a representative control channel.

HEC-RAS Modeling: The initial geometry and discharge data is being entered into the recently released River Analysis System Model (USACE,1995) for each of the surveyed field sites and the laboratory flume. HEC-RAS is a one-dimensional model for water surface profiles similar to HEC-2. Currently there is no tested and accepted procedure for incorporating specific types of habitat enhancement structures into one dimensional models for predicting conveyance properties of channels. We hope to develop and verify a systematic methodology for using the backwater model to predict the one-dimensional hydraulic effects of in-stream habitat enhancement structures in flood control channels.

SUMMARY

The field, laboratory, and modeling components of research to study the hydraulic effects of in-stream habitat enhancement measures are well underway. Three rivers with different structure types, substrates, and climates, have been instrumented. A methodology for measuring the hydraulic effects of individual structures and groupings in a flume has been established and is being tested. And finally, HEC-RAS will be utilized at each step of the field and laboratory research effort to improve our ability to predict channel water-surface elevation changes in the future. This is an ongoing research project that is scheduled for funding through fiscal year 1997.

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SEDIMENT MANAGEMENT STRATEGIES FOR HABITAT RESTORATION, MISSOURI RIVER, IOWA AND NEBRASKA

By John I. Remus II, River and Reservoir Engineering Section, Hydrologic Engineering Branch, USACE, Omaha District

Abstract: Channelization of river and streams for navigation, streambank stabilization and flood control has lead to the destruction of thousands of acres of wetlands and related upland habitat throughout the United States. Agencies at all levels of government have just begun to address the complex process of preserving remaining wetlands and restoring lost habitat. The Corps of Engineers', Omaha District has been planning habitat mitigation projects along the Missouri River from Sioux City, Iowa to Rulo, Nebraska since 1984, and has completed design work on six sites and construction of two. This paper documents sediment transport issues related to wetland restoration including: (1) design objectives such as isolated wetland development and connection of old river chutes; (2) data requirements; (3) the relative value of mathematical modeling (HEC-2, HEC-6); and (4) risk management related to operation and maintenance costs. Lessons learned and future strategies are also presented.

INTRODUCTION

The lower Missouri River Streambank Stabilization and Navigation Project, like most river development projects of the time, was designed and constructed with little or no consideration for fish and wildlife. Environmental conservation was not a concern at the time of construction. Original design efforts concentrated on maximizing the project benefits related to navigation, flood control, water supply, etc. Tools such as mathematical and physical models were developed to aid in the planning and design of the project. Original mitigation efforts concentrated on the negative aspects of the existing project and were viewed by project users as trying to undo what was done. In recent years efforts to develop new techniques that allow for expansion of existing projects to include environmental restoration and preservation have advanced, and design tools are being developed.

The Missouri River Streambank Stabilization and Navigation Project is a 735 mile self scouring channel that extends from Sioux City, Iowa to the mouth near St Louis, Missouri. Construction began in the early 1900s, however, the majority of the construction was accomplished from 1940 to 1970. The objectives of the project were to provide a reliable 9-foot deep by 300-foot wide navigation channel and to prevent the channel from meandering across the flood plain. This would promote commercial navigation, allow for increased agricultural development in the flood plain, and protect Federally constructed flood control projects (levees). To accomplish these goals the Corps of Engineers constructed a series of transverse dikes and revetments in each bend of the river. These structures cut-off minor or side chutes and forced the river into a single narrow channel (Fig. 1). Where natural alignment was poor and in-efficient, pilot channels were dredged to shorten or straighten the river. From Sioux City to the mouth approximately 75 miles or 10 percent was removed from the rivers length. The cut-off chutes, stabilized point bars, and isolated oxbow lakes rapidly filled with sediment from floods, became over grown with vegetation, and were subsequently cleared for agricultural purposes. The Corps of Engineers (1981) completed a feasibility report and Final EIS for the project that quantified the environmental, recreational, and commercial fishing losses associated with the project. It was estimated that 500,000 acres of flood plain habitat (aquatic and riparian) would be lost from Sioux City to the mouth by the year 2000. These losses are mainly attributed to agricultural development associated with the stabilized channel.

The Corps of Engineers has utilized two authorizations to begin mitigation of the environmental losses. These are the Missouri River Bank Stabilization and Navigation Fish and Wildlife Mitigation Project (FWMP), and the Section 1135 Program. Both programs were authorized by the Water Resources Development Act of 1986 (P.L. 99-662). The FWMP authorization was based on the Final EIS and called for the Corps of Engineers to purchase and develop nearly 30,000 acres in the four downstream states, and develop approximately 18,000 acres of habitat on existing public lands (state and Federally owned lands). The corps will operate and maintain these sites as part of the original stabilization and navigation project. The Section 1135 program is a continuing authority which allows the Corps of Engineers to construct environmental restoration projects at existing water resources projects. This program requires partnership with a non-Federal sponsor who must provide 25 percent of the construction cost (including real estate interest), and agree to maintain the project after construction.

CASE STUDIES

<u>Boyer Chute</u>: Boyer Chute is located between river mile 637.5 and 633.5 in eastern Washington County, Nebraska (Fig. 2). This project, constructed under the Section 1135 Program, was completed in March 1993 prior to the Flood of 1993. The project consist of reconnection of a historic chute to the main channel in order to provide slower moving, shallower aquatic habitat for native river fish species. The major issues to consider during planning and design were, costs both initial and operation and maintenance (O&M), stability of the existing navigation project, and minimizing the disturbance to the existing terrestrial habitat.

Boyer Chute is approximately 3.5 miles long and was cut-off from the main channel of the river by constructing a stone closure across the upstream end of the chute. Sediment deposition was further enhanced by construction of a second closure structure in the downstream portion of the chute. Through successive flooding the chute filled with sediment except for a large scour hole immediately downstream of the downstream closure structure and a very small trough that allowed flow through the chute only during very high flows (Corps 1991).

Initial design efforts concentrated on determining how much flow could be removed from the main channel without negatively impacting the navigation channel. This was accomplished by using the split flow option in the HEC-2 backwater model (Table 1). These discharges were then removed from the existing flood plain model to determine if there were significant changes in the velocities and water surface elevations in the main channels that may cause changes in the main channel depositional patterns which may lead to hazards to navigation. The maximum change in the main channel average velocity and water surface elevation were 0.4 feet per second and 0.1 feet respectively. A qualitative assessment indicated neither would pose a threat to navigation.

Table 1. Predicted Discharge and Velocity Relationships in the Fully Developed Boyer Chute.

Missouri River Discharge (cfs)	Boyer Chute Discharge (cfs)	Average Chute Velocities (fps)
20000	150	0.7-0.9
31000 *	1250	1.6-2.1
40000	2300	1.9-2.5
50000	3500	2.1-2.9
60000	4800	2.4-3.2
70000	6100	2.7-3.4
80000	8200	3.1-3.9
90000	11300	3.6-4.8

* - Normal Missouri River Discharge.

Minimizing both construction and O&M costs were primary concerns for both the Corps of Engineers and the local sponsor. The discharges in Table 1 were used to determine the most likely channel width that would be self maintaining. Although no controlled soil samples were obtained, field reconnaissance indicated that the prevailing soil types would be fine sands, silts and clays with sands dominating. Empirical analysis indicated that an average velocity of 1.5 feet per second would be required to maintain the chute channel. HEC-2 calculations indicated that

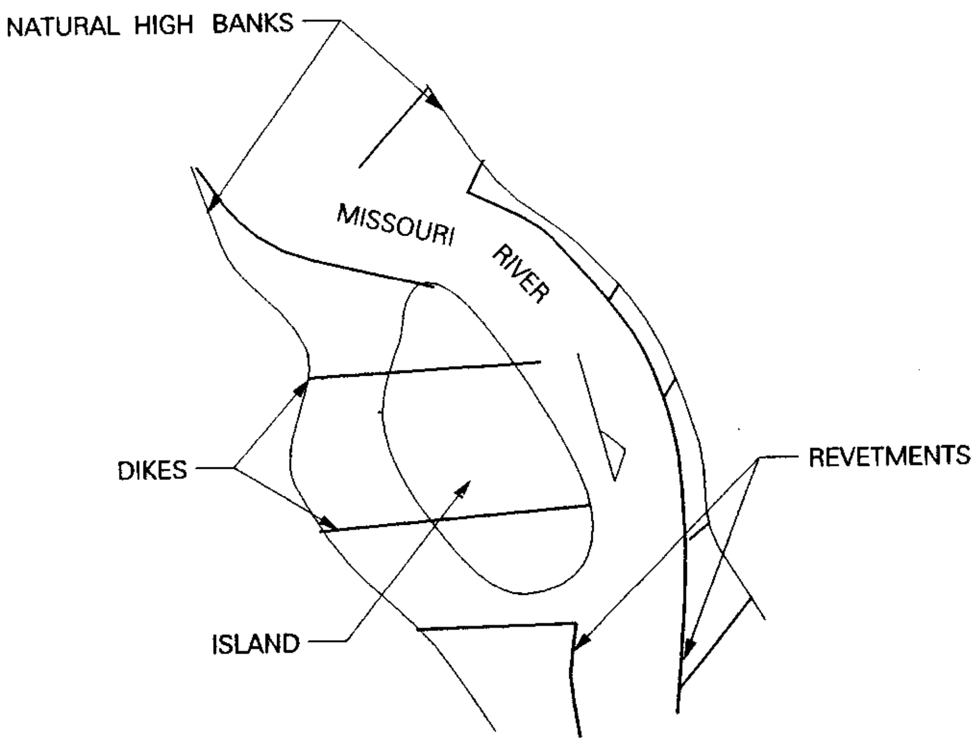

Figure 1. Typical Construction of Transverse Dikes and Revetments, Missouri River, Sioux City, Iowa to the Mouth.

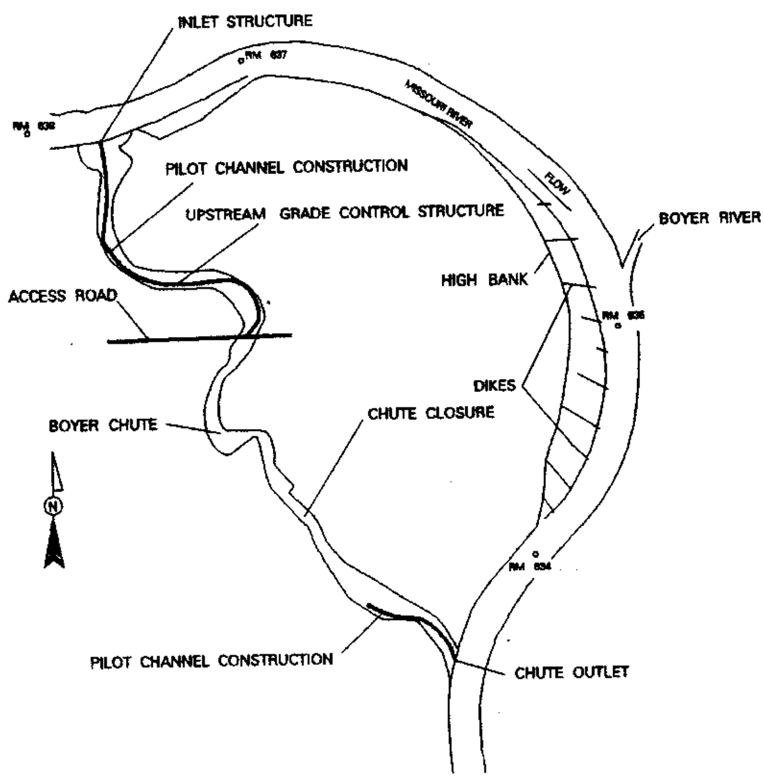

Figure 2. Boyer Chute, General Plan View.

the stable channel width would be approximately 150 feet wide at normal Missouri River discharges. The next step was to determine the smallest pilot channel that could be constructed that would produce high enough velocities to scour the channel to the stable width. This would minimize both excavation and construction cost. The local sediments indicated the threshold velocity for erosion was approximately 5 feet per second. A number of channel bottom widths were analyzed ranging from 10 to 50 feet with side slopes from 1:10 to 1:2. The configuration that minimized excavation was a 10-foot bottom width with 1:2 side slopes.

To insure that erosion of the channel bed did not capture the main river, a stone grade control structure was constructed approximately 1/3 of the way from the upstream end and the existing closure structure was modified to operate as a grade control structure. Also the inlet and outlet structures were strengthened to add additional stability to the channel.

The total project cost was just less than $1,000,000 with about 65 percent being pilot channel construction. Savings were realized by side casting the excavated material adjacent to the channel and allowing higher flows to erode the material from the chute. This also eliminated the need to dress-up/reshape or seed the spoil piles which further reduced the costs.

The project has operated through two full seasons and the channel banks have eroded. Top width increases range from 30 to 100 feet. The flood of 1993 eroded some of the spoil piles, however, vegetation has begun to cover the spoil piles which will slow the erosion considerably. Thalweg profiles indicate areas of shallow and deep water and that there is some movement of the thalweg. This was expected and is desirable for habitat. Post construction environmental monitoring indicated that velocities in the chute were approximately half of those in the main river channel. However, velocities across the chute channel were nearly constant which is not favorable for attracting native river fish. Trees were anchored in the chute and along the banks in an attempt to cause flow disruptions that would attract fish. Continued monitoring indicated that native fish species, that are scarce in the main river channel, are relatively abundant in the chute (Hesse). The Omaha District will continue to monitor the project to document long term channel development.

Because the channel is expected to be self maintaining, except for debris removal at the bridge, the only maintenance expected is replacement of stone in the inlet, outlet and grade control structures. Average annual O&M is estimated to be $2,100.

Louisville Bend: Louisville Bend is a 1100 acre wildlife management area located along the left bank of the Missouri River between river miles 685 and 681 in Monona County, Iowa (Fig. 3). The project , constructed under the FWMP, consist of an isolated lake area that will be managed primarily for water fowl and upland species. Water will be supplied by two 3000 gallon per minute pumps. Pool levels in the lake are controlled by a stoplog and culvert structure at the downstream end. When all of the stoplogs are removed fish can access the area. The stoplogs will be placed in the structure in late summer or early fall and the pumps will begin to fill the lake area. The maximum lake area of approximately 219 acres will be available for the migratory water fowl season (Corps, 1993).

Initial planning and design efforts centered on maximizing the lake area while keeping construction and operational costs at a reasonable level. Major areas of concern were water evaporation and seepage losses, sedimentation from overbank flooding, and flood plain impacts. To maximize the lake area, water control structures needed to be designed as high and as near the river as possible. Flood plain analysis concluded that levees and closure structures could be built to the 50-year elevation and as close as 400 feet from the left bank of the main river channel without negatively impacting flood elevations. This provided for the maximum lake area of 219 acres.

Once the lake surface area was determined a water budget was developed by adding the seepage and evaporation losses and several different filling rates to arrive at the most desirable pump configuration from an operability and cost point of view. Two pumps were selected instead of one to provide both flexibility in fill rates and reliability in case one pump were to require repairs.

Sedimentation during flooding, will over time, decrease the size of the lake area. A levee between the river and the lake, constructed to the 50-year flood elevation, was analyzed. This would protect the lake from all but the most serious flooding. The cost for this protection ranged from $1,000,000 to $5,000,000 depending on the design of the levee cross section. This cost was determined to be prohibitive when compared to dredging costs and the overall budget for the project. Also some sediments may be able to be flushed through the lake area during pool draw down.

This project will require a greater degree of management as the stoplogs will have to be inserted and removed, and the pumps will be operated manually. Also O&M costs are relatively high for this type of development. Average annual O&M is estimated to be $70,400, with $42,800 being the annualized cost of maintenance dredging and structure repair. However, this plan does provide the means to manage for specific species, even during hydrologic extremes on the Missouri River, and can be more accessible for recreational purposes.

Hamburg Bend: Hamburg Bend is also a Missouri River Mitigation site and is located along the right bank between river miles 556 and 552 in Otoe County, Nebraska (Fig. 4). The project consist of two components. The first is a chute reconnection that is almost identical to the Boyer Chute Project. The second component is modification of the river control structures (dikes) along the right bank of the main channel (Corps, 1994). The chute portion of the project is scheduled for construction during the winter of 1995/1996. The dikes were lowered in August of 1995. The following discussion will concentrate on the design considerations for determining river control structure (dike) modifications.

The river control structures along the right bank of the main channel are transverse dikes constructed of stone and wooden piling. The alignment and adequacy of the navigation channel has been very stable since the completion of the project. Navigation problems related to shoaling have been very infrequent, temporary and usually associated with extreme hydrologic events. A qualitative assessment of the area indicated that the dikes could probably be modified in some manner to allow for more shallower water habitat and some pool and riffle areas. A review of recent maintenance activities, and the rivers response to these activities, indicated that the most likely structure modification would be to lower the dikes to an elevation 2 feet below the normal navigation stages. The length of the dike to be lowered would very depending on the results of the analysis.

Initial modeling efforts were conducted using the HEC-6 Sediment Transport Model. This is a one-dimensional model that distributes scour and accretion evenly across the section. It was thought that by mechanically modifying the river cross section to represent the structure modifications, a point could be identified when significant changes in the sediment transport capacity occurred. However, when the modeling was complete, it did not compare favorably with observed results of natural dike lowering in other reaches of the river. The HEC-6 model predicted very little deposition and nearly no change in sediment transport through the bend. Also the results of the modeling could not quantify the changes in shallow water areas to the extent necessary for habitat evaluation. For these reasons the modeling results were discounted and alternate strategies were developed.

Three dimensional mathematical modeling and physical modeling were considered as alternatives to the HEC-6 analysis. Three dimensional modeling would require extensive data collection for calibration and verification of the model, and would delay the project at least one year. Also the cost of a three dimensional model would be $85,000 to $130,000 which is approximately 30 percent of the estimated construction costs. Physical modeling would cost $250,000 to $400,000 depending on the number of alternatives modeled and the detail needed, and would delay the project by two to three years. It was further determined that regardless of the method of analysis the structure modification scheme would have to be heavily monitored for a number of years to verify the results of any model and to insure no adverse impacts to the navigation project. Therefore, it was decided to pursue the dike modification in a phased approach over a number of years without modeling. This would allow the river to adjust slowly, which minimizes the chances of for rapidly developing or unmanageable navigation hazards to occur.

This project, like the Boyer Chute Project, requires no management perse. Maintenance activities above those currently being done would include removal of trash from the tops of the modified dikes to ensure flow over the structures. The depositional pattern in the modified dike field should be dynamic and respond to changes in the

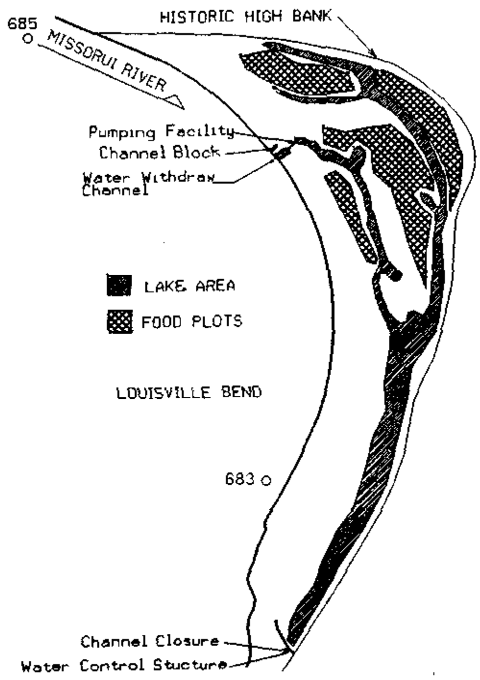

Figure 3. Louisville Bend, General Plan View.

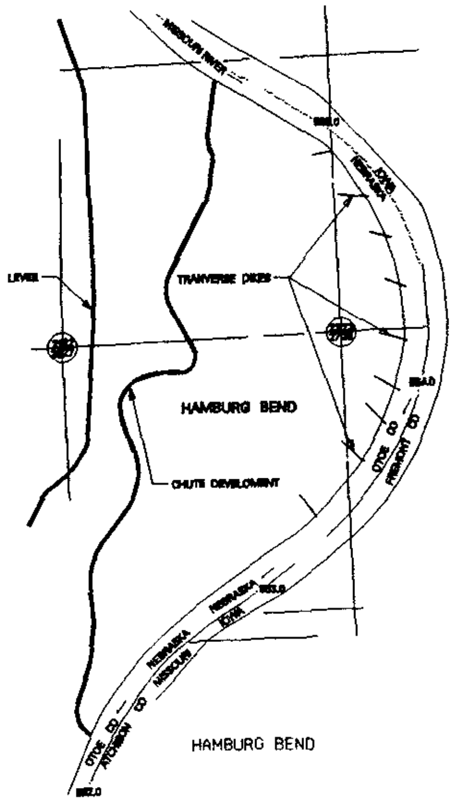

Figure 4. Hamburg Bend, General Plan View.

hydrograph. This could become a problem if certain species (i.e. Piping Plover or Least Tern) were to nest on any exposed sandbars. If this were to occur additional modifications may be necessary to encourage nesting in safer areas.

MONITORING PLAN

Monitoring for the overall project will consist of developing data bases to be used for future design efforts and coordination of all project sites to ensure individual projects are as complementary as possible, and do not conflict with other project uses and other restoration efforts along the river. The data bases will include physical data such as channel geometry changes, sedimentation rates, sediment characteristics, discharge and velocity distributions, and ground cover types. This data can be used for developing cause and effect relationships (design tools). Biological data will also be collected on a site specific basis to verify the design criteria for future projects and documenting project performance.

Monitoring programs will be customized for each individual project and will be designed to verify the original assumptions and justify any modifications to the original plan. Physical and biological data will be gathered at key points on the project site and during critical times of the year to ensure that the total project is performing as planned. Proper planning of monitoring activities is essential. Although the increased use of GPS, satellite image processing, and other remote sensing techniques have lowered the cost of collecting and processing data, it remains quite expensive. Data should be collected which can directly measure project performance relative the intended goals and objectives.

SUMMARY

The three case studies presented above demonstrate that restoring aquatic habitat on a channelized river system is very expensive and involves a great deal of risk. Models used to design the original development projects do not provide the same type of certainty for mitigation efforts. This is due mainly to the fine detail associated with habitat evaluation. Obtaining a comparable level of risk when designing mitigation projects usually requires greater initial investment and more intensive management of the site, and more often offers benefits for only a small range of species. Projects that offer a more diverse and dynamic physical environment require accepting a greater amount of risk. This is due to the lack of affordable analysis tools. Detailed and coordinated monitoring is essential to measure project performance and develop the necessary design and evaluation tools for future restoration projects.

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