Methodology for River-Quality Assessment with Application to the Willamette River Basin, Oregon

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GEOLOGICAL SURVEY CIRCULAR 715-M

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By David A. Rickert, Walter G. Hines, and Stuart W. McKenzie

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FOREWORD

The American public has identified the enhancement and protection of river quality as an important national goal, and recent laws have given this commitment considerable force. As a consequence, a considerable investment has been made in the past few years to improve the quality of the Nation's rivers. Further improvements will require substantial expenditures and the consumption of large amounts of energy. For these reasons, it is important that alternative plans for river-quality management be scientifically assessed in terms of their relative ability to produce environmental benefits. To aid this endeavor, this circular series presents a case history of an intensive river-quality assessment in the Willamette River basin, Oregon.

The series examines approaches to and results of critical aspects of river-quality assessment. The first several circulars describe approaches for providing technically sound, timely information for river-basin planning and management. Specific topics include practical approaches to mathematical modeling, analysis of river hydrology, analysis of earth resources–river quality relations, and development of data-collection programs for assessing specific problems. The later circulars describe the application of approaches to existing or potential river-quality problems in the Willamette River basin. Specific topics include maintenance of high-level dissolved oxygen in the river, effects of reservoir release patterns on downstream river quality, algal growth potential, distribution of toxic metals, and the significance of erosion potential to proposed future land and water uses.

Each circular is the product of a study devoted to developing resource information for general use. The circulars are written to be informative and useful to informed laymen, resource planners, and resource scientists. This design stems from the recognition that the ultimate success of river-quality assessment depends on the clarity and utility of approaches and results as well as their basic scientific validity.

Individual circulars will be published in an alphabetical sequence in the Geological Survey Circular 715 series entitled "River-Quality Assessment of the Willamette River Basin, Oregon."

J. S. Cragwall, Jr.
Chief Hydrologist

Cover: Willamette River as it winds through Portland, Oregon. Photograph taken by Hugh Ackroyd.

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CONVERSION FACTORS

Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric (SI)*
in. (inches)	2.540×10^{1}	mm (millimetres)
ft (feet)	3.048×10^{-1}	m (metres)
ft/mi (feet per mile)	1.894×10^{-1}	m/km (metres per kilometre)
ft/s (feet per second)	3.048×10^{-1}	m/s (metres per second)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic metres per second)
Mgal/d (million gallons per day)	4.381×10^{-2}	m^3/s (cubic metres per second)
acre-ft (acre-feet)	1.233×10^{-3}	hm^3 (cubic hectometres)
mi (miles)	1.609	km (kilometres)
mi/mi^2 (miles per square mile)	6.212×10^{-1}	km/km^2 (kilometres per square kilometre)
mi^2 (square miles)	2.590	km^2 (square kilometres)
lb/d (pounds per day)	4.536×10^{-1}	kg/d (kilograms per day)
ton (short, 2,000 lbs)	9.072×10^{-1}	t (tonne)
tons/acre/yr (tons per acre per year)	2.242	$t/hm^2/yr$ (tonnes per square hectometre per year)

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SUMMARY OF CONCLUSIONS AND IMPLICATIONS

Comprehensive river-quality assessments are critically needed in most areas of the country. Resource managers will soon be faced with major decisions concerning advanced waste treatment without having the necessary background information. The achievement of desirable river quality at acceptable cost will require that resource-management decisions be based on sound information, not on arbitrary assumptions.

At present, scientific water-quality assessments are hindered by a scarcity of appropriate data and the absence of a unifying national framework for study methodology. Several years ago, this limitation was recognized by the Department of the Interior Advisory Committee on Water Data for Public Use. At that time the committee recommended the Geological Survey conduct a pilot interdisciplinary river-quality study. The objectives set forth for the study were to: (1) define a framework for designing and conducting comprehensive assessments of river-quality problems, (2) determine the data required to analyze different types of problems, (3) develop techniques for evaluating such data and for presenting it so as to promote better public understanding of its significance (4) develop and document methods for assessing resource-management alternatives in terms of the potential impacts on river quality, and (5) apply the framework, data programs, and methods to assess the critical river-quality problems of a major river basin.

In January 1973, the Survey responded by initiating a prototype river-quality assessment of the Willamette River basin, Oregon. Reasons for selecting this basin included the availability of formalized basin-management plans and the existence of several land-use projections. The study therefore allowed for an evaluation of existing planning and management alternatives.

Furthermore, the Willamette was the largest river in the Nation on which all major point-source, municipal and industrial discharges received secondary waste-water treatment. Also, during summer, riverflows were augmented by releases from a system of 11 reservoirs. Thus, by choosing the Willamette, it was possible to appraise the relative importance of waste-water treatment and flow augmentation on the quality of a major river.

In establishing a framework for the prototype assessment, the Survey gave particular consideration to optimal study duration, staffing, and the specific problems to be evaluated. Regarding the duration, a compromise was sought between taking enough time to do a research-oriented study and so little time that unexpected problems and questionable results could not be evaluated. A study duration of 2½ years, beginning in January and allowing two summer field seasons, was finally selected. In this time, problems could be identified, studied, evaluated, and rechecked. The 2½-year duration also provided a reasonable time frame for response to the needs of resource managers.

Staff needs were based on an interdisciplinary team-oriented approach. The selected team was comprised of scientists and engineers experienced in river work and trained in the discipline categories of hydrology, sanitary chemistry, aquatic biology, mathematical modeling, and geology.

Specific work elements for the program were selected in discussions with State, interstate, and Federal agencies concerned with river-quality management. Eight existing or potential problems were identified. Following evaluation and ranking, the following four were selected—dissolved-oxygen (DO) depletion, potential for algal problems, trace-metal occurrence, and the impact of land-use activity on erosion.

CONCLUSIONS FOR THE WILLAMETTE RIVER BASIN

Detailed results of the four project elements are described in a series of chapters in U.S. Geological Survey Circular 715. Here, brief conclusions drawn from the results illustrate their impact on resource planning and management in the Willamette River basin.

DISSOLVED-OXYGEN (DO) DEPLETION

Historically, severe DO depletion during summer has been the critical quality problem in the Willamette. In recent years, summer DO levels have increased dramatically. This increase is the result of secondary biological treatment of all point-source wastes (municipal and industrial) and of streamflow augmentation from storage reservoirs.

Although secondary treatment improved river quality, it resulted in continuous discharge of pulp- and paper-mill effluents rather than the previously used program of summer storage (in lagoons) and winter discharge. The advent of biological treatment also resulted in the use of ammonium hydroxide for neutralizing the raw waste waters at certain pulp and paper mills. During the summers of 1973 and 1974, the ammonia in the effluent of one mill caused a large DO depletion between river miles 86 and 50 which previously had not occurred. Reduction of ammonia loading from this one source offers a relatively simple alternative for achieving a large (as much as 20 percent) improvement in summer DO levels.

In contrast, at foreseeable levels of development, further reduction in the point-source discharge of organic wastes beyond that achieved by efficient secondary treatment would produce only limited improvement in DO concentrations. Only about half the summertime loading of organic, oxygen-demanding wastes presently comes from point sources. The other half represents natural background demand from essentially pristine streams. This demand cannot be removed by pollution-control programs.

Even with basinwide secondary treatment and a reasonable limitation on ammonia loading, flow augmentation will be needed to maintain the Willamette's high DO standards. As basin development continues, reservoir augmentation will continue to be necessary even if an advanced waste-treatment program is implemented.

POTENTIAL FOR ALGAL PROBLEMS

A potential for algal problems may exist in the Willamette River because point-source discharges cause the concentrations of nitrogen and phosphorus to be high. To date, however, nuisance algal growths have not occurred, and results indicate that the primary reason for maintenance of favorable algal populations in the Willamette is the short detention time of water in the river.

Perhaps the most important aspect of the short detention time is the constant nutrient influx that prevents depletion of major nutrients. The maintenance of a balance in major nutrient contents favors the growth of desirable rather than undesirable types of algae. Thus, in the Willamette the key to keeping algal growth at its present balance appears to be control of those factors that maximize summertime flow and minimize water-detention time. Such control would require maintenance of present levels of flow augmentation and avoidance of large increases in summertime diversions.

The results imply that national or regional standards for permissible nitrogen and phosphorus concentrations represent a poor management tool. The need for advanced waste treatment to remove point-source nitrogen and phosphorus should be assessed on a river-by-river basis.

TRACE-METAL OCCURRENCE

When present in critical concentrations, many materials discharged into rivers are toxic to aquatic organisms. A review of records for the Willamette River basin showed there was little possibility that toxicity problems could result from pesticides and other organic chemicals. However, few data were available on the discharge of trace metals and their possible accumulation in sediments and food chains.

To partly fill this void, a study was designed to determine the concentration and distribution of selected metals in river-bottom sediments. The objectives were to establish baseline data for future comparisons and to provide an alert to possible accumulations of toxic metals. The study approach involved the sampling of bottom sediments under stable low-flow conditions, fractionation of samples to obtain fine-grained materials prior to metal analysis, and interpretation of trace-metal data through the use of probability plots.

The results suggested that no metals were present at levels that might represent an ecological threat. There were moderate enrichments of zinc, resulting from industrial discharges, and slight enrichments of lead, resulting from urban runoff.

The procedures developed in the study are considered suitable to detect the extent of trace-metal pollution in almost any river.

LAND USE AND EROSION

Great increases in population and industry over the next 50 years are predicted for the Willamette River basin. At present (1976) the potential impacts of this development on land and water quality have not been appraised.

To permit an initial assessment, a synoptic approach was devised to delineate the relationships between physiographic factors, land-use activities, and resultant erosional-depositional problems. The approach involved the development of a basin-wide erosional-province map and a matrix for rating erosional impacts. Data on geology and slope were collated to delineate eight units of terrain having different natural potentials to erode or receive sediment. Infrared aerial photography was used to identify land-use activities and to map existing erosional and depositional features. The matrix was formulated by placing order-of-magnitude erosional factors for geology and slope as columns and similar factors for land-use activities as rows.

Together, the map and matrix serve as tools for estimating the erosional impact of human activities on different types of terrain. The tools have already proven useful for land- and water-resource planning and also for the design of improved data-collection programs.

IMPLICATIONS FOR THE SCIENTIFIC AND ENGINEERING COMMUNITY

The Willamette Study emphasized the development of approaches, methods, and data programs that would be useful in the assessment of other river basins. From this effort, and from the study results, certain findings emerged that are pertinent to programs of the scientific and engineering community.

THE NEED FOR SYNOPTIC DATA-COLLECTION PROGRAMS

Except for flow records, the large data base that existed for the Willamette River was found to be unsuitable for assessment of the three in-river problems of DO depletion, algal-problem potential, and trace-metal occurrence. The unsuitability resulted primarily from the fact that existing data were collected under routine monitoring-and surveillance-type programs. Such programs are designed, not to assess specific problems, but to provide a general indication of water-quality trends and to check for compliance with stream standards. Data generated for these purposes are generally inadequate for defining the critical cause-effect relationships that control most river-quality problems. This was true for the Willamette, and indications are that it is true for most other rivers in the United States.

Short-term, intensive synoptic-type studies were found to provide the kinds of data required for assessing the three in-river problems. In contrast to monitoring- and surveillance-type programs, the synoptic approach can provide a sound understanding of cause-effect relationships. This permits the critical temporal and spatial changes in river quality caused by hydrologic factors and waste-water loadings to be more easily recognized and quantified.

From experience gained on the Willamette, we believe that intensive synoptic studies will be required in most river basins to develop an adequate information base for managing key river-quality problems.

UTILITY AND LIMITATIONS OF MATHEMATICAL MODELS

Mathematical models can be used effectively in the practical assessment of certain river-quality problems. However, the models must be based on sound data and reliable assumptions, with mathematics and the computer used as tools rather than as ends in themselves. Because of past experiences, the Oregon Department of Environmental Quality was skeptical at the outset of the DO study that a mathematical model could be formulated for practical use. The project staff determined the reasons for skepticism and devised a framework for avoiding the potential pitfalls. As a result, the Department of Environmental Quality has accepted the DO model as a sound tool for evaluating pollution-control alternatives.

The Willamette project team found that there were several river-quality problems that currently are too complex to model in a practical and useful manner. Such problems include trace-metal distribution and the relationship of nutrients and algal growth. The project assessed these problems through the development of qualitative descriptive approaches. The results clearly demonstrated that qualitative approaches can provide adequate and reliable information for the management of certain river-quality problems.

THE NATURE OF DISSOLVED-OXYGEN DEPLETION IN A RIVER HAVING COMPLETE SECONDARY TREATMENT

The secondary treatment of point-source discharges has drastically changed the self-purification characteristics of the Willamette River. The loadings, in-river concentrations, and rates of exertion of biochemical-oxygen demand (BOD) were all much lower than in previous times.

The results generally indicate that once efficient secondary treatment has been achieved on all waste discharges, other causes of DO depletion may become more important than the remaining point-source BOD. Also, the rate of carbonaceous decay can become so low that, depending on a river's hydrologic character, further reduction of point-source BOD may have little or no effect on DO concentrations.

Measured BOD concentrations and rates of exertion in the Willamette River are approaching those in natural, unpolluted waters. This means that the 5-day BOD test can no longer be used to estimate the impacts of pollution loadings. It is now necessary to conduct 20-day (or other long-term) BOD tests to adequately measure concentrations and to determine rates as a basis for modeling carbonaceous decay.

As previously noted, nitrification is now a prominent DO sink in the Willamette River. The process was found to occur only in shallow high-velocity reaches, and within biological slimes attached to rocks (not in the water column). This finding supports a recently proposed hypothesis and indicates that assessment of nitrification impacts must consider the physical nature of rivers in addition to ammonia loadings and water temperature.

IMPLICATIONS FOR RIVER-QUALITY PLANNING AND MANAGEMENT

Certain of the Willamette Study findings are highly significant to national programs for the planning and management of river quality.

THE NEED FOR LOCALIZED STUDIES

Rivers and their basins are dynamic, and the processes within them result from the interaction of complex natural factors with man's activities and alterations. This interaction creates unique local problems which, once adequately assessed, often have unique local solutions. Examples in the Willamette River are the relative roles of (1) BOD and nitrification as causes of DO depletion and (2) nutrient concentrations and flow as controllers of algal growth.

Without the understanding provided by this study, Federal and basin planners might logically have assumed that further BOD removal was a critical priority and that treatment of all point sources was necessary to reduce the loading of nitrogen and phosphorus. However, the study showed first that nitrification, induced largely by ammonia loads from one industrial source, was a more important cause of DO depletion than waste-water BOD loads and second that water detention time, rather than the concentration of nitrogen or phosphorus, was the primary controller of algal growth.

These examples illustrate the fact that rigid nationwide standards and regulations are likely to result in unneeded expenditures in some basins and in undesirable quality in others. The proper balance can be attained for each river only through an intensive, coordinated assessment that is keyed to local problems and conditions.

THE NEED FOR ALTERNATIVE STRATEGIES TO ADVANCED WASTE TREATMENT

While wastewater treatment always will play an important role, it is not the sole means of river-quality enhancement. Other defensive and offensive strategies are also needed. For example, in the Willamette River basin, two critical needs are reservoir low-flow augmentation to maintain desirable summertime conditions of DO and land-use planning to alleviate the wide-spread problems that arise from erosion and deposition.

Flow augmentation from storage reservoirs is largely responsible for the remarkable improvement in summertime DO concentrations witnessed in the Willamette. Even with the excellent pollution control program mounted over the years, standards would still be violated in certain subreaches during most summers without low-flow augmentation. During dry years, violations would occur under natural flow conditions over much of the lower half of the river for up to two months. These results generally show that low-flow augmentation must be recognized as both a viable alternative and as a complement to advanced-waste treatment programs.

The quality of a river is largely determined by the interaction between climate, basin-terrain characteristics, and land-use activity. At present, the controlling interrelationships are poorly defined because of (1) inadequate recognition of the linkages between land-use activity and river quality and (2) until recently, lack of a suitable basis for synoptic terrain analysis of entire river basins. Today, however, there is awakening recognition that an economic linkage exists between land development and river-quality management. The situation is now such (in the Willamette and all other river basins) that either land-use activity and land runoff are brought into the planning picture, or else the ultimate reality will be land-imposed constraints on river quality.

THE COST OF CONDUCTING RIVER-QUALITY ASSESSMENTS

The cost of conducting the Willamette Study was about $500,000. Although a considerable investment, this sum is small compared to the amount that will be spent for pollution control in most large river basins over the next 10 to 20 years. The information obtained in the Willamette Study provided a sound basis for (1) ascribing planning and managing priorities and (2) generating potential savings in pollution-control programs by identifying ineffective management strategies. As costs for waste-treatment facilities continue to rise, the latter consideration is important in keeping public support for environmental management and pollution-control programs.

ACKNOWLEDGMENTS

Because the Willamette River Quality Assessment was undertaken as a cooperative venture with State and local interests, it is difficult to acknowledge fully the many organizations and individuals who have contributed. Here it is only possible to mention a few.

From the beginning, the Oregon Department of Environmental Quality has been a constant advisor and contributor. Many members of the agency have enthusiastically provided support, and we wish to especially acknowledge Jack Weathersbee, Warren C. Westgarth, and Glen D. Carter. The U.S. Army Corps of Engineers participated in the development of a reservoir model and also assisted financially in the development of the photomosaic base. David M. Rockwood and George Holmes were largely responsible for the excellent cooperation of the Corps.

Tom J. Lucus of the Columbia Region Association of Governments provided valuable insight and important information throughout the study. John D. Beaulieu, Oregon Department of Geology and Mineral Industries, assisted in the development of criteria for the erosion-potential map and was a constant source of geologic information. Fred A. Limpert, Bonneville Power Administration, aided early in the development of the project through his excellent contacts with State and Federal agencies.

High altitude photographs were provided by the National Aeronautics and Space Administration, NASA-Ames Research Center, Moffett Field, California. Arrangements for the photography were facilitated by the Environmental Remote Sensing Applications Laboratory (ERSAL) at Oregon State University and by Ernest H.

Lathram, U.S. Geological Survey. ERSAL also provided financial assistance for the production of the photomosaic base.

Richard Petersen of Portland State University was instrumental in the design and conduct of the algal study, and Lolita Carter, together with Douglas Larson, provided valuable aid in data interpretation. Joseph V. Hunter and Thomas J. Tuffey, both of Rutgers University, helped in the design and interpretation of work on dissolved oxygen and nitrification. Trace-metal analyses were made by Kam W. Leong and Raymond G. Havens of the Geological Survey.

Invaluable aid in all phases of the project was given by the Oregon District Office of the U.S. Geological Survey, under the direction of Stanley F. Kapustka. Individuals who became deeply involved with the project included David J. Lystrom, Alexander H. Gonsalves, Nyra A. Johnson, Frank A. Rinella, Joseph F. Rinella, and Timothy L. Miller.

Thoughtful criticisms and suggestions concerning other circulars in this series were made by several members of the Geological Survey including John H. Feth, Robert M. Beall, Vance C. Kennedy, Keith V. Slack, and Phillip E. Greeson.

The project was initiated in response to a recommendation to the Geological Survey by the Advisory Committee on Water Data for Public Use. Our special thanks go to the Advisory Committee's Ad Hoc Working Group on River-Quality Assessment which provided constant encouragement, positive criticism, and manuscript review. During the study, the members of the group included Howard B. Brown, Robert A. Canhan, Edward J. Cleary, Laurence R. Jahn, John E. Kinney, Walter A. Lyon, John A. Roller, and Clarence J. Velz.

Clarence Velz was also instrumental in the design and conduct of the dissolved-oxygen modeling study, and he continually provided encouragement, insight, and professional criticism of high excellence on all elements of the project.

INTRODUCTION

Today there is an urgent need for comprehensive resource assessment in most river basins of the United States. In response to this need, many planning groups have prepared reports that project future demands for water supply, wastewater treatment, and other services, and suggest possible alternatives for meeting the demands. Implicit in these reports is the acceptance of economic and population growth, but in a manner assumed consistent with some desired level of land and river quality.

Virtually all forms of growth and development exert some impact on river quality. Achievement of desirable river quality at acceptable cost requires that management decisions be based on sound impact assessments, not on arbitrary assumptions. Thus, the vital link between resource-development plans and management decisions is scientific assessment to predict the probable impacts of each planning alternative. At present, the impact-assessment link represents a stumbling block to the overall process. The difficulty in appraising impacts results from (1) absence of a rational framework for structuring such work, (2) lack, poor development, and misapplication of assessment methods, and (3) scarcity of reliable data. The concept of river-quality assessment as developed and used in the present study provides a mechanism for overcoming each of the three deficiencies.

In 1964, the Bureau of the Budget (now Office of Management and Budget in the Executive Office of the President), issued Circular A–67 which designated the Department of the Interior as the lead Federal agency in water-data acquisition and prescribed creation of Federal and non-Federal committees to assist the Geological Survey (Interior's designated bureau) in coordinating the designated functions. The non-Federal committee was officially named the Advisory Committee on Water Data for Public Use.

Several years ago, the Advisory Committee voiced concern at the lack of suitable information for adequate river-basin planning and, in 1971, formally recommended that the Geological Survey conduct a pilot, interdisciplinary river-quality study. The recommended objectives were (1) to define a practical framework for conducting comprehensive river-quality assessments; (2) to determine the kinds and amounts of data required to adequately assess various types of river-quality problems; (3) to develop techniques for evaluating such data and for presenting it so as to promote better public understanding of its significance; (4) to develop and document methods for assessing planning alternatives in terms of potential impacts on river quality; and (5) to apply the framework, data programs, and methods to assess the critical river-quality problems of a major river basin.

The Geological Survey responded to the committee's recommendation by starting in January 1973 a prototype river-quality assessment study in the Willamette River basin, Oregon. The Willamette River basin was selected for several reasons. First, there was an excellent base of background data, particularly on hydrology. Second, social and political attitudes in Oregon reflected a keen interest in environmental quality. This suggested that the people and agencies would welcome the study and that results would be used at the State and local levels. Third, a river-basin management plan already existed, as did several land-use projections (Willamette Basin Task Force, Main Rept., 1969). Thus, the study could evaluate existing planning alternatives to provide a realistic test of assessment approaches. Fourth, the Willamette was the largest river in the Nation on which all major point-source discharges received secondary waste-water treatment (Oregon Department of Environmental Quality, 1970). The quality was above the stringent State standards, and the river was considered a national success story (Gleeson, 1972). Thus, the study could include appraisal of the factors to which past improvement was attributed, in addition to evaluating the factors that needed to be managed to maintain or improve the quality.

This report summarizes both the development of a framework for conducting intensive river-quality assessments and the results obtained from applying the framework to four river-quality problems in the Willamette River basin, Oregon. The assessed problems were: (1) the effect of population and industrial growth and resulting waste discharges on dissolved oxygen (DO), (2) the potential for nuisance algal growth, (3) the possibility of trace-metal accumulation in river-bottom sediments, and (4) the potentially harmful effects on land and river quality of accelerated erosion resulting from intensified land use.

Detailed results for each element of the study are presented in lettered chapters in Geological Survey Circular 715. To acquaint the reader with the series, the brief titles of the chapters are:

A. A Practical Framework for River-Quality Assessment (Rickert and Hines, 1975)
B. Formulation and Use of Practical Models (Hines and others, 1975)
C. Project Development (Rickert and others, 1976)
D. Hydrologic Analyses (Hines and others, 1976)
E. General Aspects of Streamflow and Reservoir Release Modeling (Jennings and others, 1976)
F. A Synoptic Survey of Trace Metals (Rickert and others, 1976)
G. The Potential for Algal Problems (Rickert and others, 1976)
H. A Reservoir-System Model (Shearman, 1976)
I. Dissolved-Oxygen Conditions (Hines and others, in preparation)
J. A Dissolved-Oxygen Model (Hines and others, in preparation)
K. Planning Implications of Dissolved-Oxygen Conditions (Rickert and others, in preparation)
L. Analysis of Erosional Processes and Problems (Brown and others, in preparation)

These circulars are referred to as lettered chapters throughout the present report, and complete citations are given in the reference section for those published or in press.

RIVER-QUALITY ASSESSMENT AND ITS RELATION TO RIVER-BASIN PLANNING

River-quality problems stem basically from two factors, the unique hydrology of a river basin and man's development and use of the land and water resources. Depending on the interrelation of these factors, a wide variety of quality problems can result. Each river basin, therefore, is *unique*, and it follows that each one must be subjected to individual and intensive river-quality assessment to provide a proper basis for judicious management of the land and water resources.

In the broadest context, river-quality assessment is a problem-oriented approach for developing information that is appropriate and adequate for sound resource management. In a more specific sense, river-quality assessment is the science and art of identifying the significant resource problems, defining them with adequate relevant data, and developing methods for evaluating the impacts of planning alternatives on each specific problem. In order to predict the consequences of any plan of action, it is essential to have a fundamental understanding of *cause-effect* relationships. Assessment, therefore, extends far beyond basic data on the physical, chemical, and biological quality of water to measurement of pollution sources and the prevailing hydrologic conditions that cause the observed effect. When, by scientific analysis, cause-effect relationships are defined and verified, then assessment becomes a powerful predictive tool by which alternative plans of action can be evaluated. Such evaluations then become a rational guide for the planner and the decision-maker in establishing priorities.

In keeping with this philosophy, the approach developed for the Willamette study includes the seven steps outlined across the bottom of figure 1. Each of these steps was fully described in Chapter A.

Within figure 1, the planning components are outlined by solid lines to symbolize a more or less standard process, whereas the assessment components are portrayed in dashed lines to represent an undeveloped potential. To place the figure in perspective, it must be noted that river quality is but one of many factors that decisionmakers consider in choosing among alternative plans. River quality is a single component of the natural-resource system, which, in turn, is only one aspect of the socioeconomic-political-environmental structure of river-basin management. In many basins, demographic and economic uncertainties may be greater than the river-quality uncertainties. Such a situation actually increases the need for assessment, because a sound understanding of river quality provides a starting point for systematic evaluation of the socioeconomic and political options and of the technical alternatives for control of land and water resources development.

PHYSICAL SETTING

The detail provided here to describe the physical setting of the Willamette River basin offers an illustration of the types and scope of data required for designing a river-quality assessment. The manner of presentation was considered more effective than a simple outline of data needs but is offered with the recognition that key factors and data availability may vary from basin to basin.

The Willamette River basin, a watershed of nearly 11,500 mi^2 (29,800 km^2) (fig. 2), contains the State's three largest cities, Portland, Salem, and Eugene, and approximately 1.4 million people, representing 70 percent of the State's population (1970 census). The basin supports an

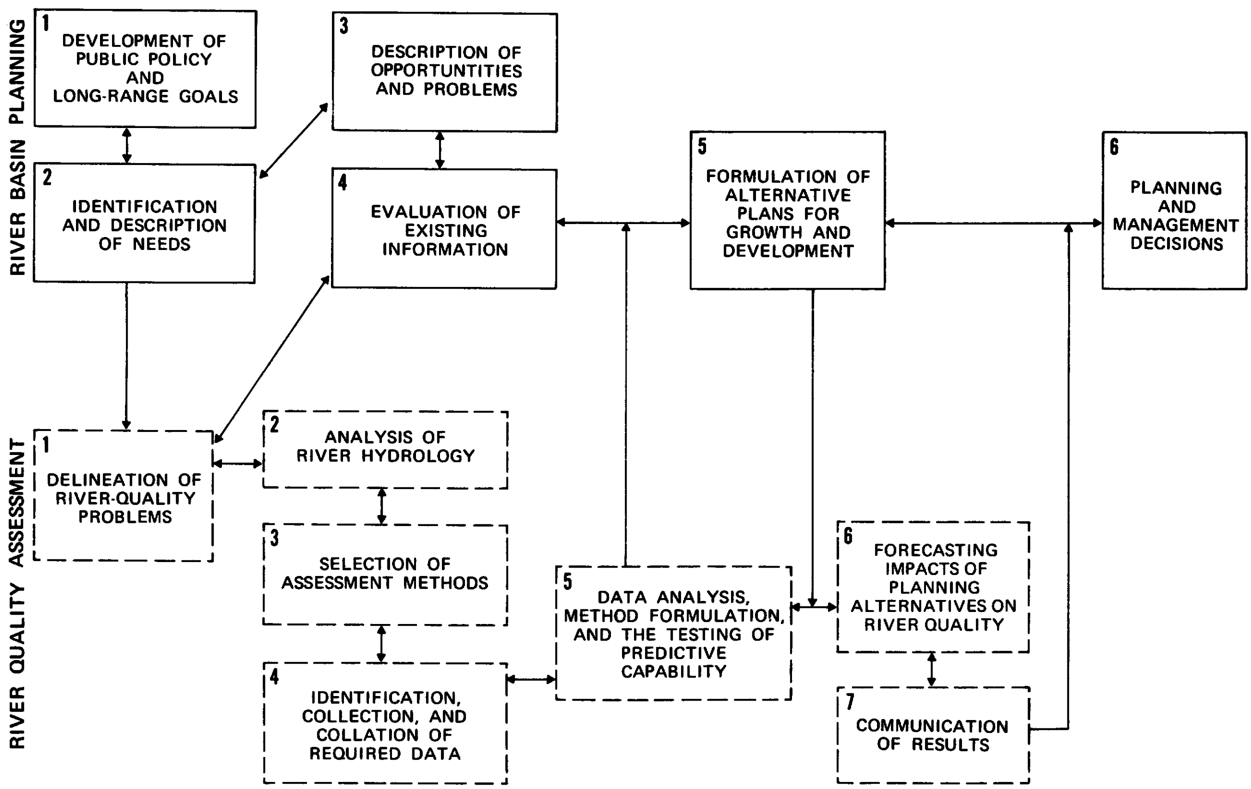

FIGURE 1.—The interrelation of river-quality assessment to river-basin planning.

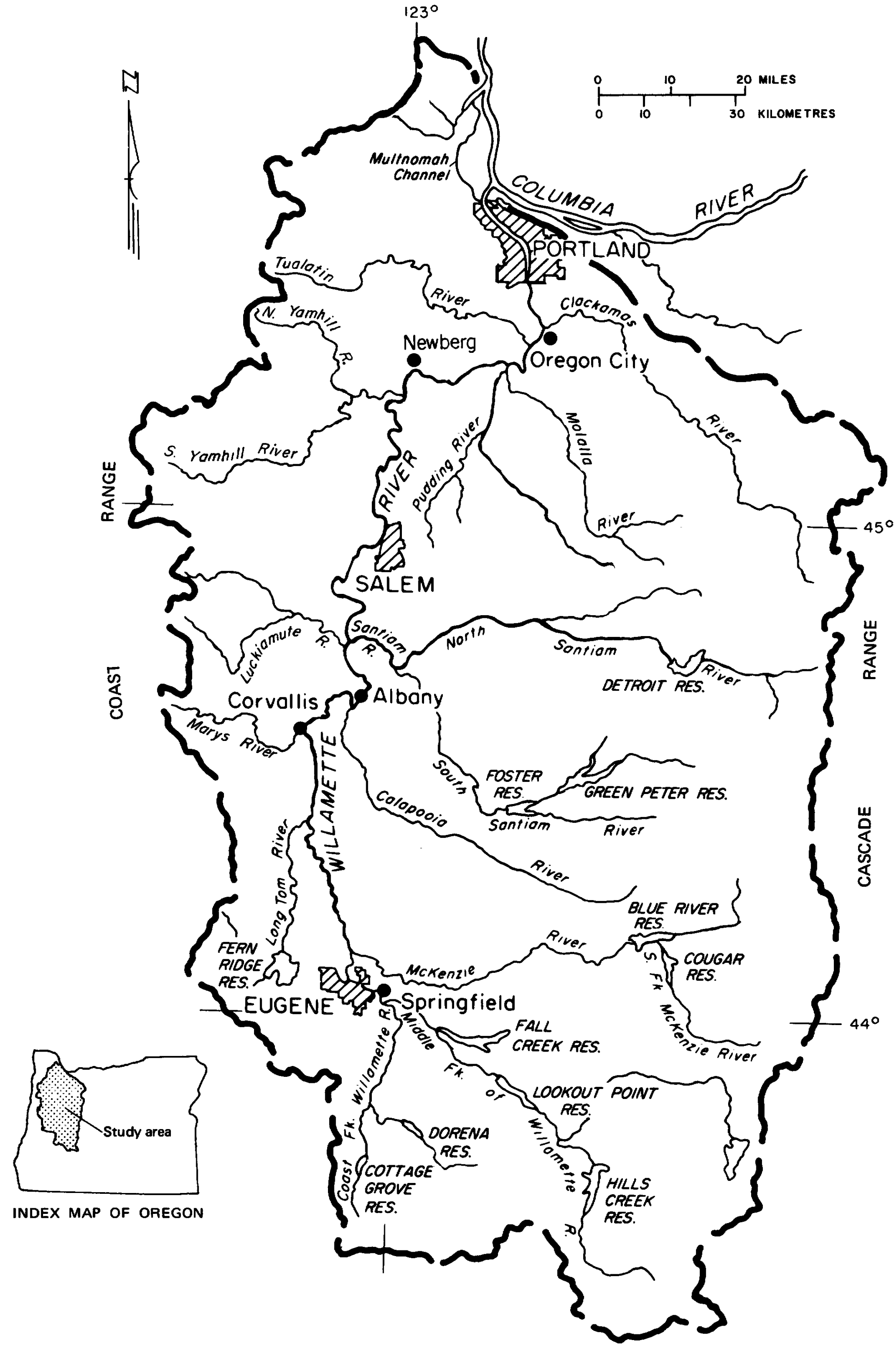

FIGURE 2.—Willamette River basin Oreg., emphasizing the main stem, principal tributaries, and major reservoirs.

economy based on timber, agriculture, industry, and recreation and contains extensive fish and wildlife habitats.

The basin is roughly rectangular, with a north-south length of about 150 mi (240 km) and an east-west width of 75 mi (120 km). Elevations vary from less than 10 ft (3 m) near the mouth of the Willamette River to 450 ft (140 m) on the valley floor near Eugene and to more than 10,000 ft (3,050 m) in the Cascade Range. Average annual precipitation in the basin is 63 in. (1,600 mm).

The slopes and foothills of the Cascade Range account for more than 60 percent of the basin area. About 62 percent of the basin is timber land, located largely in the tributary basins (Gleeson, 1972). Approximately 33 percent of the area is farmland, and the remaining 5 percent is urbanized and in other uses.

GEOLOGIC OVERVIEW

On the basis of physiography and geology, the Willamette River basin can be divided into three north-south provinces: The Cascade Range, the Coast Range, and the interlying Willamette Valley (Willamette Basin Task Force, Appendix A, 1969).

The volcanic rocks that compose the Cascade Range can be divided into two major groups. The older group consists of basalt and andesite together with volcanic debris. These rocks have been folded, faulted, and extensively altered. The younger rocks, which form the High Cascades, are derived from more recent basaltic and andesitic lava flows.

The mountains and foothills of the Coast Range are formed largely by volcanic rocks and by marine sedimentary rocks derived from them. The older volcanic rocks, consisting of basalt flows and volcanic debris, are interbedded with continental sedimentary rocks. The marine sedimentary rocks consist of sandstone, shale, and mudstone.

The Willamette Valley is an elongated alluvial lowland framed by resistant volcanic and sedimentary rocks. Much of the valley is covered by sandy to silty terrace deposits that settled from water ponded in a great glaciofluvial lake. Most of the materials in these deposits appear to have originated from upstream areas of the Columbia River basin (Glenn, 1965). The alluvial deposits that border existing rivers were derived largely from the surrounding mountains. These deposits consist of intermingled layers of clay, silt, sand, and gravel.

WILLAMETTE RIVER MORPHOLOGY

The main stem Willamette River is formed by the confluence of the Coast and Middle Forks near Eugene (fig. 3) and flows for 187 mi. (301 km) to the Columbia River. Over this distance the channel bed drops from an elevation of 435 ft. (133 m) to slightly below mean sea level. The main stem comprises three distinctive reaches whose physical characteristics govern the hydraulics of flow and therefore the patterns of deposition, channel scour, and sediment transport.

The Upstream Reach (fig. 3 and table 1), extending for 135 mi (217 km) from Eugene to above Newberg, is characterized by a meandering channel. The river is shallow and the bed is composed almost entirely of cobbles and gravel which, during summer, are covered with biological growth. During low-flow conditions, average stream velocity in the Upstream Reach is about 7 times that of either of the two downstream reaches (table 1). During floods, velocities are sufficiently high to transport large quantities of cobbles and gravel as bedload. Morphologically, this upstream section of the Willamette River is an "eroding" reach.

The Newberg Pool extends for 25.5 mi (41.0 km) from above Newberg to the Willamette Falls. Hydraulically, the deep, slow-moving Pool can be characterized as a large stilling basin behind a weir (Willamette Falls). As evidenced by the elevation profile (fig. 3), average low-flow velocity (table 1), and the presence of fine bottom sediments, the Pool is a depositional reach.

The Tidal Reach, covering the lower 26.5 mi (42.6 km) of the river, is affected by tides and, during spring and early summer, by backwater from the Columbia River (Velz, 1961). The Tidal Reach is extensively dredged to maintain a 40 ft (12 m) deep navigation channel from the mouth to about river mile (RM) 14. During the summer low-flow period, net downstream movement is slow, but tidal effects cause flow reversals twice daily and large changes in velocity. Low-flow hydraulics are most complex in the lower 10 mi (16 km) where, depending on hourly changes in tide- and river-stage conditions, Willamette River water may move downstream, or Columbia River water may move upstream. Owing to morphologi-

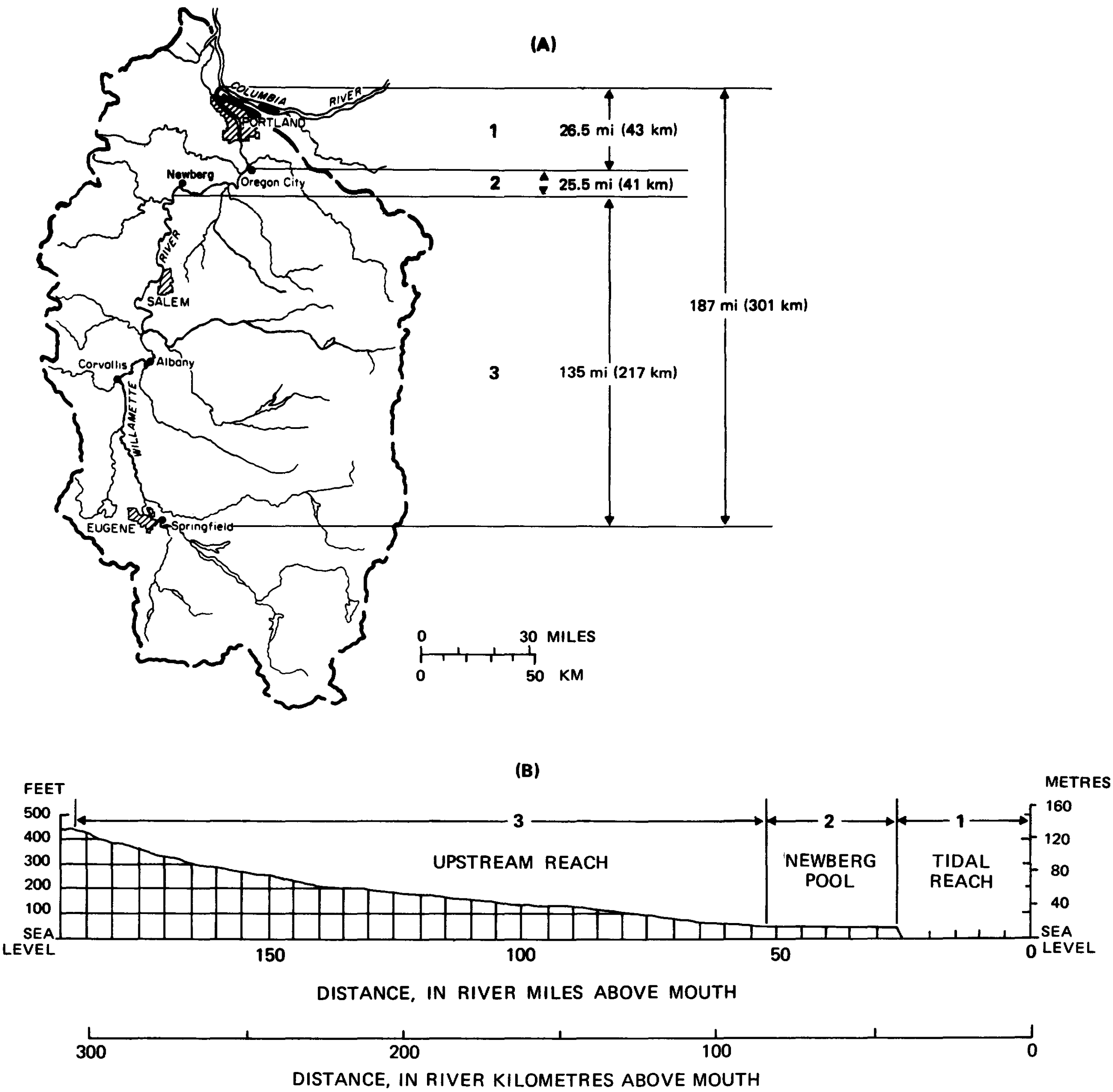

FIGURE 3.—Willamette River, Oreg. A, Distinctive hydrologic reaches. B, Elevation profile.

TABLE 1.—*Selected physical characteristics of the main stem Willamette River, Oreg.*
[Characteristics refer to summer low-flow conditions of 6×10^3 ft³/s at Salem]

Reach (see fig. 3)	Length (mi)	Approximate bed slope (ft/mi)	Bed material	Representative midchannel water depth (ft)	Average velocity (ft/s)	Approximate traveltime in reach (days)
Tidal Reach (1)	26.5	<0.1	Intermixed clay, sand, and gravel.	40	[1]0.16	10.0
Newberg Pool (2)	25.5	.12	Intermixed clay, sand, and gravel with some cobbles.	25	[1]0.40	3.9
Upstream Reach (3)	135	2.8	Mostly cobbles and gravel	7	[2]2.9	2.8

[1]Calculated by volume displacement method using channel cross-sectional data.
[2]Calculated from dye study by Geological Survey (Harris, 1968).

cal characteristics and the hydraulic conditions, the subreach between RM's 10 and 3 is the primary depositional area of the Willamette River system.

RESERVOIRS AND HISTORICAL STREAMFLOW PATTERNS

There are 11 major reservoirs in the Willamette River basin (see fig. 2) with a combined usable capacity of nearly 1.9 million acre-ft (2,300 hm^3) (see Chapter H). The reservoirs are designed for multipurpose use, but their primary legal function is the maintenance during summer of a minimum navigable depth in the Willamette River (Willamette Basin Task Force, Main Rept., 1969). The required minimum flow for navigation is 6,000 ft^3/s (170 m^3/s) at Salem. Other uses of the reservoirs and reservoir water include power generation, onsite recreation, flood protection, maintenance of adequate streamflow for anadromous fish propagation, irrigation, and flow augmentation for water-quality enhancement. The latter use is not explicitly planned but occurs as a result of summertime releases made for the other purposes.

Most of the flow in the Willamette occurs in the period November to March as a result of persistent winter rainstorms and spring snowmelt. Post-March snowmelt in the high Cascade Range often prolongs seasonal runoff into June or early July. These patterns of flow are illustrated by the hydrographs in figure 4. The 1944 hydrograph is typical of natural runoff patterns prior to large-scale reservoir regulation (considered to be pre-1953), whereas the 1964 and 1973 hydrographs reflect postregulation patterns. Three reservoirs began operation on tributaries in the Coast Range and Calapooya Mountains in the period between 1941 and 1949. However, it was not until operation of reservoirs on Cascade Range tributaries, beginning in water year 1953, that reservoirs had a significant impact on Willamette River flow.

Reservoir regulation has had a profound impact on low flows in the Willamette River (Chapters D and H). Marked increases have occurred in the 1-, 3-, 7-, 14-, and 30-day low flows during the post-1953 period. Reservoir regulation also has curtailed the length of the period of low flow, typically from about mid-July through mid-October before regulation, to about mid-July through mid-or late-August following regulation. This condition occurs because the reservoirs, as recently operated, release extra water in the early fall to enhance anadromous fish runs.

PROJECT FRAMEWORK

DURATION

The time required to conduct a useful assessment of river quality is a compromise between taking enough time to do a sound and comprehensive scientific study and so much time that results become irrelevant to the decision-making process. The compromise initially selected for the prototype Willamette Study was 2 years, beginning in January 1973. (See Rickert and others, 1975a and Chapter C.) The original concept was to use 6 months for planning and for organizing field and laboratory programs, 15 months for collecting and analyzing data and the writing of initial reports, and 6 months for completing the analysis of data and the final reports.

After the first 2 months, it became obvious that assessment of certain river-quality problems would require extending the data collection into the fall of the second year. The study duration was thus expanded to 2½ years.

In retrospect, 2½ years appears to be a reasonable period for intensive, practical assessment of river-quality problems. This duration provides time for (1) identification of specific river-quality problems, (2) project planning prior to initiation of fieldwork, (3) 1 full year of fieldwork, and (4) the opportunity to recheck specific problems in the field during the most critical time periods of the annual cycle. In many river basins (including the Willamette), the low-flow, high temperature season is the critical time period for most river-quality problems (for example, dissolved-oxygen depletion). For such basins a study duration of 2½ years, together with a January start, provides for two summer field seasons. Specific critical problems may require assessment over longer periods, but initial assessments of immediate problems need to be completed as quickly as possible in order to be of value to the resource-planning process. As noted in Chapter A, reappraisals can then be made under reduced time pressures, while full scale updates can be scheduled on a periodic basis.

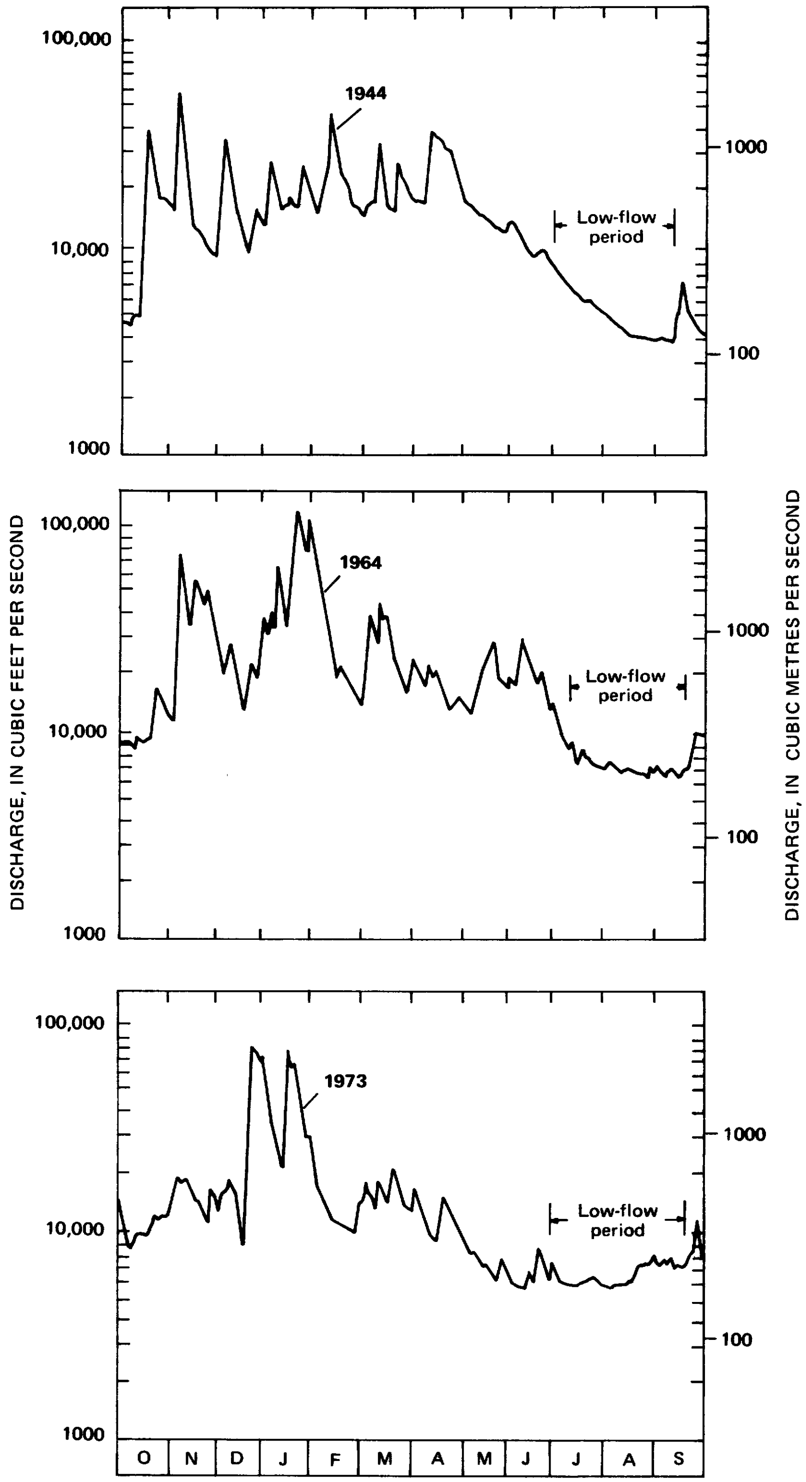

FIGURE 4.—Willamette River discharge at Salem, Oreg., 1944, 1964, and 1973 water years. Note the recurrent nature of the July, August, and September low-flow periods even after large-scale streamflow regulation began in 1953.

MANPOWER

The nature of river-quality problems requires an interdisciplinary, team-oriented approach. In the Willamette Study, the team was composed of scientists and of engineers experienced in river work and trained in the discipline categories of hydrology, sanitary chemistry, aquatic biology, mathematical modeling, and geology. The core team included four individuals having different training and professional backgrounds and five part-time aides. In addition, the project periodically used the talents of the Survey's research staffs and District offices, as well as the consultative, fieldwork, and laboratory services of scientists from several universities. Analytical work was done by the project team and by several Geological Survey laboratories.

PROJECT ELEMENTS

Specific work elements for the program were determined through discussions with State, interstate, and Federal agencies concerned with the management of river quality. The discussions proceeded over the first 4 months of the project to identify eight existing or potential river-quality problems (table 2). These problems were then evaluated using published and unpublished data from the Oregon Department of Environmental Quality (1970), the U.S. Geological Survey (1962–73, 1964–73), and the STORET system of the U.S. Environmental Protection Agency (Sayers, 1971). Next, in conjunction with the resource agencies, the problems were ranked in order of their relative importance to resource management (table 2).

Selection of project elements for this pilot assessment was completed by analyzing the priority list in terms of ability to produce useful information within the constraints of time, funding, and manpower. All three priority 1 problems were selected as project elements, whereas the three priority 3 problems were rejected. Both priority 2 items were considered for inclusion over a period of several months, but, finally, on the basis of available manpower, "algal-problem potential" was included and "riverbank esthetics" was rejected. The four rejected elements are discussed in Chapter C and suggestions are provided for several additional studies.

Once the project elements were identified, it was clear that additional hydrologic information was needed to adequately assess the impact of planning alternatives on "dissolved-oxygen depletion" and "algal-problem potential." The most critical needs were information on (1) future low-flow quantities and frequencies, and (2) the character of flow and velocities in the hydraulically complex lower 10 mi (16 km) of the river. These needs required the development of predictive mathematical models. The modeling approaches, data inputs, and results are described by Bennett (1975) and in Chapters E and H. No details of these modeling efforts are provided in this report, but brief mention is made of certain results.

The following sections of the report describe the assessment methodology and the results attained for the four project elements. The descriptions are intended to provide only a summary of the individual studies. The interested reader may wish to consult the individual chapters for technical details and documentation.

TABLE 2.—*Existing or potential river-quality problems of the Willamette River basin, Oreg.*

Problem	Relative importance[1]	Selected for present study
Nonpoint-source pollution	3	
Reservoir-release quality	3	
Dissolved-oxygen depletion	1	×
Algal-problem potential	2	×
Trace-metal occurrence	1	×
Sanitary quality	3	
Accelerated erosion	1	×
Riverbank esthetics	2	

[1] 1=greatest importance; 3=least importance.

DISSOLVED-OXYGEN DEPLETION

BACKGROUND

Historically, maintenance of high DO concentration has been the critical problem in the Willamette River. During summer low-flow periods, the DO concentration in Portland Harbor often was zero (Velz, 1961; Gleeson, 1972), and for years, low DO levels inhibited the fall migration of salmon from the Columbia River.

In recent years, summer DO levels have increased dramatically (Chapter I). The improvement has resulted from a reduction in the loading of point source biochemical oxygen demand (BOD), coupled with streamflow augmentation from storage reservoirs. However, the Oregon Department of Environmental Quality (DEQ) still considers the maintenance of high DO levels to be the factor of highest priority in planning the Willamette's future.

Today (1976), the Willamette is the largest river in the United States on which all point-source discharges receive secondary wastewater treatment. The Willamette thus offers a unique opportunity to document the impacts of both secondary treatment and flow augmentation on the quality of a major river.

STUDY METHOD—MATHEMATICAL MODELING

Mathematical modeling provides a potential to quantify the cause-effect relationships that give rise to DO problems. The potential exists because (1) a sound theoretical and empirical basis exists for writing the necessary equations, (2) the data required for calibrating and verifying a practical and reliable model can be collected, and (3) proven techniques are available for analyzing raw data to obtain model coefficients. Mathematical models are usually preferable to other methods of studying DO problems because they are capable of providing the most quantitative analysis of critical relationships. They, therefore, represent the best available approach for predicting the possible impacts on DO of alternatives for future river-basin development. The predictive ability is essential, because, at present (1976), DO is the most important characteristic for managing quality in the majority of the Nation's rivers.

In concept, mathematical modeling of DO provides a powerful tool for problem solving to resource planners and managers, pollution-control officers, and governmental decisionmakers. However, with notable exceptions, these groups have failed to accept DO models as practical planning tools and have viewed river-quality models with considerable mistrust. This failure to accept and trust models stems from the fact that some river-quality models have not been based on sufficient data nor effectively applied to real planning and management situations.

Because of past experiences, the Oregon DEQ was skeptical at the outset of the DO study that a mathematical model could be formulated for practical use. The project staff determined the reasons for skepticism and devised a framework for avoiding the potential pitfalls. The following summarizes the modeling framework from Chapter B:

1. Select the simplest mathematical configuration capable of providing useful planning and management information.
2. Model only the critical time period and river reaches of DO depletion.
3. Carefully calibrate the model against one set of data and later verify it against a second set of completely new data.
4. Conduct an intensive data-collection program to provide the needed data (see "Data Program").
5. Present all modeling results in an easy-to-understand format.

DATA PROGRAM

Review of existing data indicated that an appreciable DO deficit occurs in the Willamette only below RM 86 and during the yearly low-flow period of July through August. The DO data-collection program was thus developed to formulate a mathematical model for simulating conditions below RM 86 for the critical summer period.

The program was designed to provide reliable data on the major cause-effect relationships that affect DO depletion. Emphasis was placed on obtaining data for direct calculation of required loading parameters and model coefficients. This emphasis was made to avoid reliance on literature values, arbitrary guidelines, and the estimation of model coefficients by computerized curve fitting.

All loading data were determined by analysis of waste-water and tributary stream samples collected specifically for the study. No use was made of existing data, nor were any loadings estimated from production or population records. Because the municipal and industrial waste-waters received secondary treatment, ultimate BOD (BOD_{ult}) loadings could not be determined by applying a rule-of-thumb constant to 5-day BOD (BOD_5). Thus, all carbonaceous loadings were obtained by running 20-day BOD's (BOD_{20}) and using the resultant rate curves for calculation of ultimate demands. A nitrification inhibitor was used because most effluents and several tributaries contained appreciable concentrations of ammonia-nitrogen. The actual ammonia loadings were determined by direct analysis of aliquot samples.

Data were collected to permit calculation of the coefficients for deoxygenation, reaeration, and nitrification. At least 15 BOD_{20} rate curves were determined at each sampling station for calculation of river-deoxygenation coefficients. Detailed channel-geometry data were assembled so that reliable reaeration rates could be calculated for each subreach of the river. Similarly, synoptic, in-river data on ammonia decay and nitrate generation were collected to permit calculation of nitrification rates on a reach-by-reach basis.

Horizontal and vertical traverses for DO, temperature, and BOD were made to determine if samples from the centroid of flow were representative of the station cross sections. Only cross sections that reconnaissance data indicated were well mixed were sampled. As a result, BOD_{20} levels seldom varied significantly either horizontally or vertically within the cross section. However, vertical variations in DO contents were often observed owing to photosynthetic activity. Continuous-monitor records of DO and temperature were collected to estimate the impact of algal activity on river DO.

DISSOLVED-OXYGEN REGIMEN

DISSOLVED-OXYGEN PROFILES

Basinwide secondary treatment has had a profound impact on the major deoxygenation processes and consequently on the DO regimen of the Willamette River. During the summer low-flow period of 1974, average daily DO concentrations met State standards for all reaches of the river at flow conditions between 6,500 and 7,000 ft^3/s (184 and 198 m^3/s) and water temperatures between 22° and 25°C (Celsius).

Figure 5 compares the 1973 DO profile of the Willamette River to selected historical conditions for the summer low-flow period. In spite of the steady improvement in DO since 1944, the profiles do not reflect a simple, clearcut time trend. The reason is that circumstances, often undiscernable from the existing records, tend to obscure the short term trends. For example, the

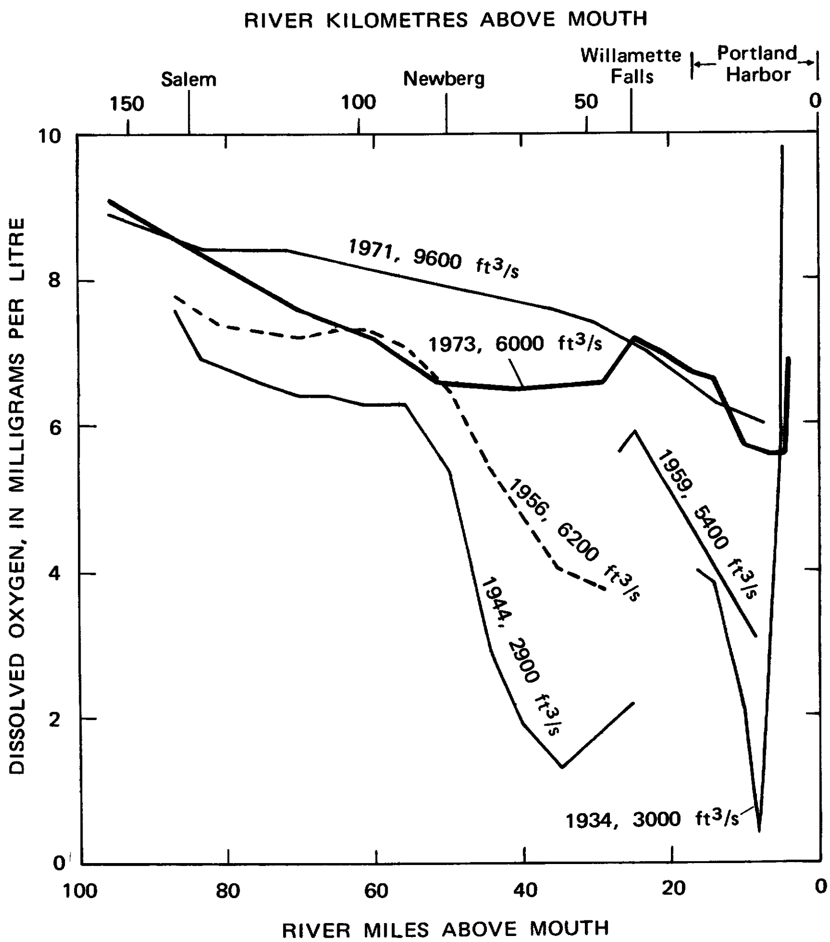

FIGURE 5.—Comparison of 1973 with historical DO profiles in the Willamette River for the summer low-flow period. (Historical data are adapted from Gleeson, 1972.)

1971 DO profile generally is higher than the 1973 profile despite the fact that certain secondary treatment plants were not in operation until 1972. This apparent anomaly can be explained by (1) higher summertime flows during 1971 and (2) the fact that during 1971, certain pulp and paper mills were on a waste management program whereby primary effluents were stored during summer and released to the river during the high flow conditions of fall, winter, and spring.

Figure 5 provides a comparison of the 1973 DO profile to profiles determined at similar flows during 1956 and 1959. In 1956, there was a DO-concentration "plateau" between Salem and Newberg, followed by a sharp decrease in DO through the Newberg Pool. These conditions were consistent with large loadings of BOD in the vicinity of Salem, a rapid traveltime between Salem and Newberg, and a large amount of carbonaceous deoxygenation in the slow-flowing Newberg Pool.

The 1959 data show an increase in DO concentration below Willamette Falls and a sharp decrease in DO through the Tidal Reach. These observations were consistent with known reaeration at the falls, inflow of cool water of high DO content from the Clackamas River, and the decay of carbonaceous wastes which entered the river just below the falls and throughout Portland Harbor.

The 1973 profile shows a rapid decrease of DO from RM 86 to Newberg, a DO "plateau" in the Newberg Pool, a DO increase over Willamette Falls, a gradual decline in DO between RM's 24 and 13, a sharp decrease in DO between RM's 13 and 5, and recovery of DO below RM 5. The DO decrease between RM 86 and Newberg contrasts with a "plateau" in 1956 and results from nitrification that did not occur at the earlier date. The 1973 DO "plateau" in the Newberg Pool indicates that carbonaceous deoxygenation is now occurring at a rate slow enough to be balanced by DO inputs from atmospheric reaeration. The DO decrease between RM's 24 and 13 is consistent with measured river loads of ultimate BOD, but the sharp decrease between RM's 13 and 5 cannot be accounted for by known sources of BOD. (See section entitled "Undetermined Oxygen Demand.") The recovery of DO below RM 5 results from the admixture of high-quality water from the Columbia River. The DO profile of the Willamette during July–August 1974 was essentially the same as that presented in figure 5 for 1973.

NITRIFICATION

During the summers of 1973 and 1974, nitrification was the dominant control on DO in the shallow, swift-flowing subreach between RM's 85 and 55. Examination of historical data indicates that this reach began to receive appreciable ammonia loading from a pulpmill in 1956. Dissolved-oxygen data from the 1950's and 1960's are sketchy, but suggest that nitrification did not become a significant oxygen sink until the advent of secondary treatment at pulp and paper mills. Secondary treatment incurred the use of ammonium hydroxide for neutralizing wastewaters prior to treatment and resulted in continuous discharge of effluents to the Willamette rather than the previously used program of summer lagooning and winter discharging.

Figure 6 shows the average instream concentrations of ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N) and nitrate nitrogen (NO_3-N) from RM 120 to 7 for August 12–14, 1974. The curves reflect a prominent ammonia source near RM 116 and rapid instream oxidation of ammonia to nitrite and nitrate downstream to RM 86. During the study period, the subreach below RM 86 received about 5,800 lb/d (2,630 kg/d) ammonia nitrogen from upstream sources, 16,200 lb/d (7,350 kg/d) from an ammonia-base pulp and paper mill at RM 85 and about 1,700 lb/d (770 kg/d) from a municipal sewage plant at RM 78. The instream data show a rapid conversion of the ammonia to nitrite and nitrate between RM's 85 and 55. The deep, relatively slow moving Newberg Pool begins at RM 52 and, although residual ammonia entered this reach, no further nitrification could be detected from nitrogen-species analysis.

The occurrence of nitrification in a shallow, surface-active reach and the contrasting absence in a deep, slow-moving reach is consistent with a recent hypothesis proposed by Tuffey, Hunter, and Matulewich (1974). According to the hypothesis, nitrification in shallow, swift-flowing reaches would occur by virtue of an attached, rather than a suspended community of nitrifying organisms. To test the hypothesis, enumerations were made of nitrifying bacteria in water samples and in biological slimes scraped from bottom

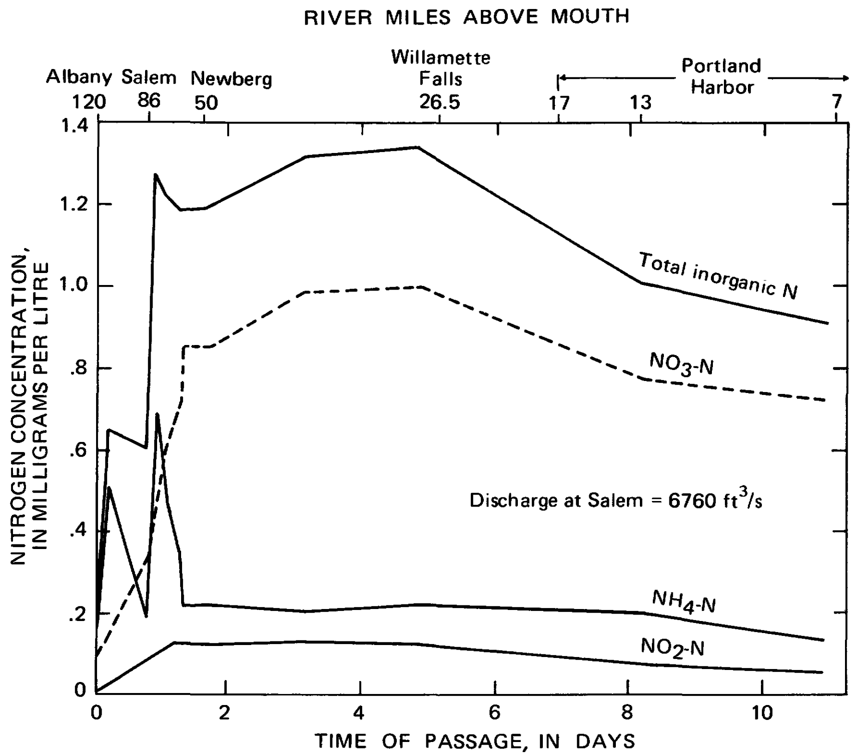

FIGURE 6.—Inorganic nitrogen concentrations in the Willamette River during mid-August 1974.

rocks. *Nitrosomonas* concentrations were <1 most probable number (MPN)/ml in all water samples. In slimes, *Nitrosomonas* concentrations were <1 MPN/mg above RM 86 and 1–4 MPN/mg in samples collected between RM's 85 and 55 (the active zone of nitrification). Shortly below RM 55, the deep Newberg Pool begins, and few bottom rocks are available for attachment of biological slimes. *Nitrobacter* enumerations were also made and in the zone of nitrification ranged from <1 to 4 MPN/ml in water samples and from 6–50 MPN/mg in slimes. The combined bacteriological data thus support the hypothesis that nitrification occurred in slimes attached to rocks rather than in flowing water. (See Chapter I for elaboration.)

Based on observed river concentrations of nitrate in the river (fig. 6), a rate of nitrification was calculated for the affected subreach. Assuming first-order decay, the rate, k_n ($\log_{10}$), was about 0.7/*d* (see Chapter I for discussion). Applying this rate to the measured loadings of ammonia indicates that, for the August 12–14 period, nitrification removed about 55,000 lb/d (25,000 kg/d) DO from the 30-mi (48-km) subreach. This satisfied demand was responsible for most of the decrease observed in DO concentration (fig. 5).

CARBONACEOUS DEOXYGENATION

Present-day BOD-loading patterns and rates of exertion contrast sharply with those observed during the mid-1950's.

BOD LOADING

During the dry-weather period of 1954, the estimated point-source loading of BOD_{ult} to the Willamette River was approximately 350,000 lb/d (160,000 kg/d). This total included chemical demands resulting from sulfite wastes, soluble and suspended carbonaceous demands from pulp and paper mills, and the carbonaceous demands of raw sewage and primary effluents.

In contrast, the point-source BOD_{ult} loading during August 1974 was about 92,000 lb/d (42,000 kg/d) (table 3). The decrease from 1954 resulted from secondary treatment of all carbonaceous wastes, chemical recovery of sulfite wastes, and the routing of sewage effluents from metropolitan Portland into the Columbia River instead of the Willamette.

TABLE 3.—*Dry-weather 1974 ultimate BOD loading, Willamette River, Oreg.*
[see Chapter I]

Source	Loading (lb/day)	Percent
Nonpoint	77,100	46
Point		
Municipal	37,600	22
Industrial	54,400	32
Total	169,100	100

Table 3 shows the distribution of BOD_{ult} loading between point and nonpoint (diffuse) sources for July–August 1974. Most of the estimated loading from diffuse sources represents natural background demand from essentially pristine streams (see Chapter I). Thus, during the summer low-flow period, only about one-half the observed BOD_{ult} loading to the Willamette is amenable to removal by future pollution-control programs assuming that such programs could provide total removal.

CONCENTRATIONS AND RATES

During the low-flow period of 1954, 5-day BOD's averaged about 2.5 mg/l at sites immediately below large waste-water outfalls, whereas in 1974 the concentration at the same sites was about 1.0 mg/l. This decrease resulted only partly from the noted reduction in waste water loading. The decrease also resulted from a treatment-caused change in the biochemical nature of waste-water materials, which in turn caused a decrease in the river rates of carbonaceous deoxygenation. (See Chapter I.) In 1954, the k_1 ($\log_{10}$) value for all river BOD samples was 0.1/d or greater (Velz, 1951). In contrast, measured k_1 values in 1974 were clustered around 0.04/d. This means that in 1954, a minimum of about 68 percent of BOD_{ult} was exerted in a river-water sample in 5 days, whereas in 1974 the comparative value was 37 percent (see Velz, 1970, for discussion of BOD exertion). This comparison underscores the need for determining k_1 values and BOD_{ult} (rather than BOD_5 alone) as a basis for accurately modeling DO under conditions of secondary treatment.

During both 1973 and 1974 the inriver concentrations of BOD_{ult} averaged about 2.5 mg/l.

DISSOLVED-OXYGEN MODELING

The model chosen for the study was the one developed and used for more than 30 years by C. J. Velz. The basic model (Velz, 1970) is applicable to conditions of steady (invariable), nonuniform (changing cross-sectional geometry), plug (nondispersive) flow. The computer program as formulated for the present study is called the WIRQAS (Willamette Intensive River Quality Assessment Study) Model.

The model was calibrated against 1974 streamflow and temperature conditions and verified against the slightly lower flow and higher temperature conditions of 1973. (See Chapter J for discussion.) For conditions representing 1974 summer low flow, the model indicates that an oxygen demand of 164,000 lb/d (74,000 kg/d) was satisfied between RM's 86 and 5. Of the total, about 22 percent resulted from background carbonaceous-oxygen demand, 28 percent from point-source carbonaceous demand, 34 percent from point-source ammonia, and 16 percent from an undetermined demand in Portland Harbor (see "Undetermined Oxygen Demand").

PLANNING IMPLICATIONS

As an aid to river-quality planning, the WIRQAS Model has been used to test management alternatives concerning (1) BOD loading, (2) ammonia loading, (3) low-flow augmentation, and (4) the effects of possible removal or reduction of the undetermined oxygen demand (Rickert and others, 1975b, and Chapter K). This section describes the major implications of tested alternatives by comparing measured DO profiles with profiles generated by the verified model. A fact the reader should bear in mind in examining the following illustrations (figs. 7–11) is that, for ease of presentation, the DO profiles are plotted as a function of river location. Thus the slopes of curves in specific subreaches do not represent the actual rates at which oxygen is added to or lost from the river. For example, the profiles in figures 7–11 suggest a rapid rate of oxygen depletion below Willamette Falls. Actually, the steepness of the curves is caused by the slow time-of-travel in the Tidal Reach (see table 1) rather than by an accelerated rate of oxygen depletion.

BOD LOADING

The effect of BOD loading on summertime DO is reflected in figure 7. The curve labeled 100 percent represents the average DO profile of the river at the flow, water temperatures, ammonia

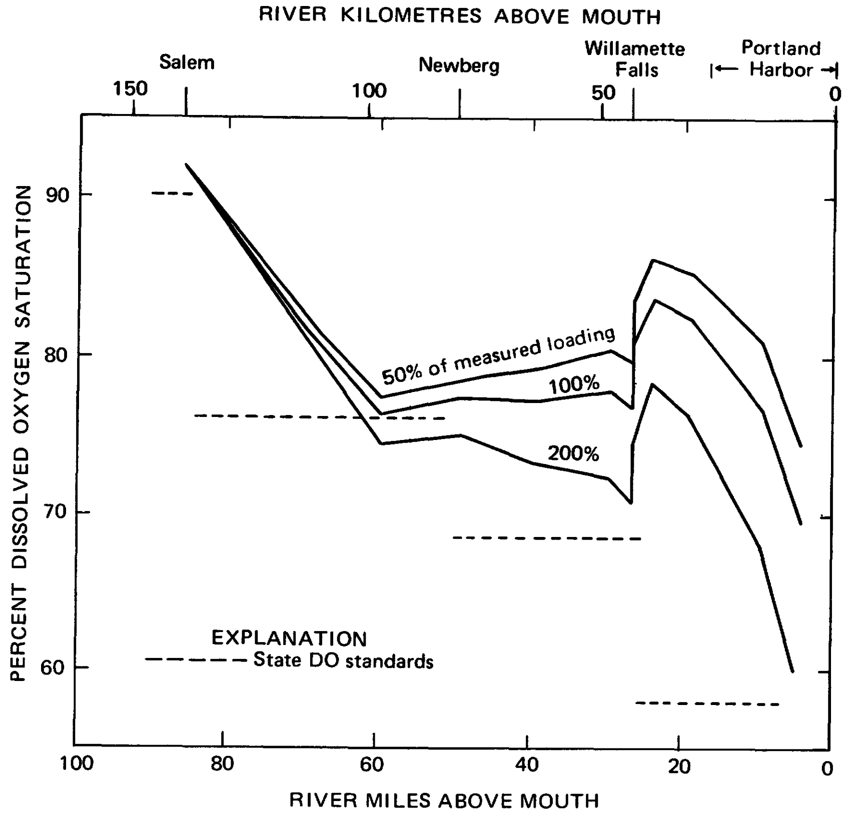

FIGURE 7.—Dissolved-oxygen profiles for selected percentages of the measured point-source BOD loading during mid-August 1974. Flow and ammonia loading held constant at observed levels.

loading, and BOD loading actually measured during the low-flow, steady-state period of mid-August 1974. The upper and lower curves represent the predicted DO profiles at 50 percent and 200 percent of the measured point-source BOD loading with all other variables held constant at observed levels. These curves are calculated on the basis that all point-source BOD receives secondary treatment and decays at rates of 0.06/d above RM 55 and 0.03/d below this point.

The upper curve in figure 7 indicates that only a slight improvement in DO can be obtained by a 50 percent decrease of BOD loading from each point source. The predicted increase in DO would be <5 percent of saturation at the bottom of the Newberg Pool (RM 28) and 5 percent at RM 5, the low DO point in the river.

In contrast, a doubling of BOD loading from each point source would depress DO by 5 percent of saturation at RM 28 and by 10 percent at RM 5. This decrease in DO would cause violation of the noted State DO standard in the subreach between RM's 62 and 50.

Figure 8 compares the DO profile observed in mid-August 1974 with the predicted profile assuming a BOD_5 standard of 10 mg/l for all municipal effluents. Such a standard, supposedly attainable by high-level secondary treatment, is being considered by Oregon. Application of the 10 mg/l standard to 1974 conditions would decrease municipal summertime loading of BOD_{ult} to the Willamette from 37,600 to 17,400 lb/d (17,100 to 7,900 kg/d). The largest individual decrease would be about 7,000 lb/d (3,000 kg/d) at Salem (RM 78). The modeling results (fig. 8) indicate that, over the investigated reaches, the reduced loading would have no effect on river DO. The lack of an effect stems from (1) the small reduction attainable in total loading of BOD_{ult} (about 12 percent; see table 3), (2) the low rates at which BOD_{ult} is exerted in the river, and (3) the locations within the basin of the largest municipal wastewater treatment plants (see Chapter I).

AMMONIA LOADING

Figure 9 illustrates the effect of ammonia loading

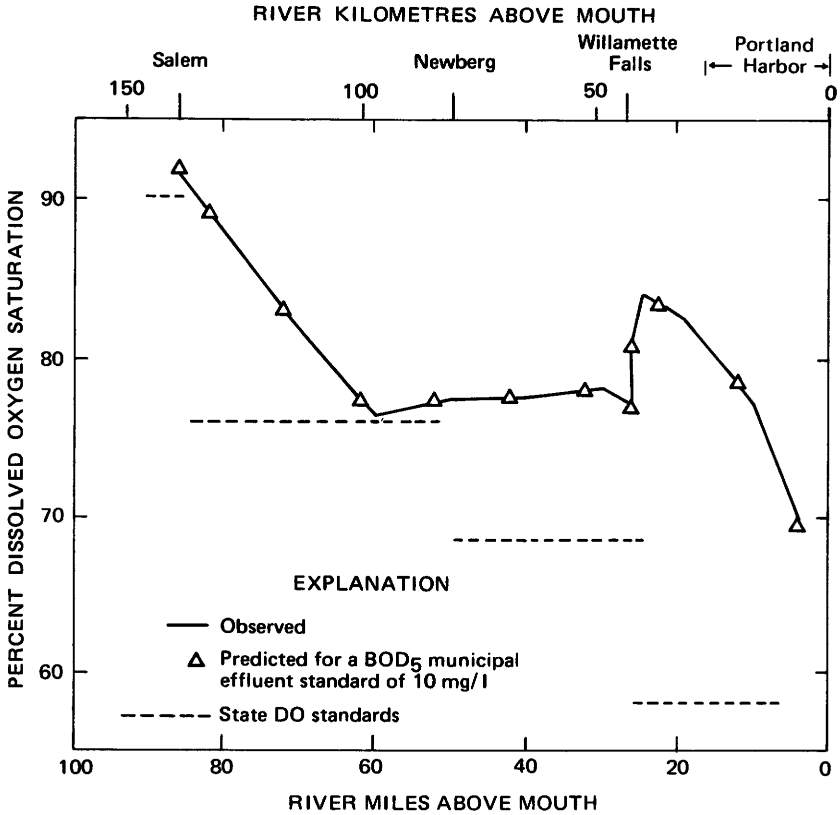

FIGURE 8.—Dissolved-oxygen profiles: observed mid-August 1974 and predicted for a BOD_5 municipal effluent standard of 10 mg/l. Flow and ammonia loading held constant at observed levels.

on summertime DO in the Willamette. Compared to the observed DO profile (the 100 percent curve), a 50 percent reduction in ammonia-nitrogen loading from each point source would increase the DO by 7 percent of saturation near the bottom of the Upstream Reach (RM 60), by 5 percent at RM 28, and by <5 percent at RM 5. In contrast, a doubling of ammonia-nitrogen loading in each point source would decrease the DO by 13 percent at RM 60, by 11 percent at RM 28, and by 7 percent at RM 5. These results illustrate two important points. First, ammonia loading has its greatest effect on DO in the active zone of nitrification between RM's 85 and 55. Thereafter, measurable nitrification ceases to occur and the upstream effects of the process are gradually diminished by atmospheric reaeration. Second, comparison of figures 7 and 9 indicates that point-source ammonia loading has a greater influence on Willamette River DO than point-source BOD loading. At the observed relative point-source loadings (43,000 lb/d, or 19,500 kg/d ammonia-nitrogen; 92,000 lb/d, or 42,000 kg/d BOD_{ult}), this occurs primarily as a result of (1) the greater oxygen demand per unit weight of ammonia as compared to the organic matter in secondary effluents and (2) the much greater rate at which ammonia is oxidized (k_1 = 0.03 to 0.06/d; k_n = 0.7/d) between RM's 85 and 55.

The upper curve in figure 9 shows the impact of applying a standard of 10 mg/l ammonia-nitrogen to all municipal and industrial effluents.

Most of the ammonia that enters the Willamette below RM 86 is discharged from a large pulp and paper mill at RM 85 (see "Nitrification"). Control of ammonia from this one source would greatly reduce the impact of nitrification on the DO regimen of the river.

LOW-FLOW AUGMENTATION

The effect of flow augmentation on DO is illustrated in figure 10. The observed flow at Salem during mid-August 1974 was 6,760 ft^3/s (191 m^3/s). For comparison, computed DO profiles are presented for Salem flows of 9,000, 5,000, and

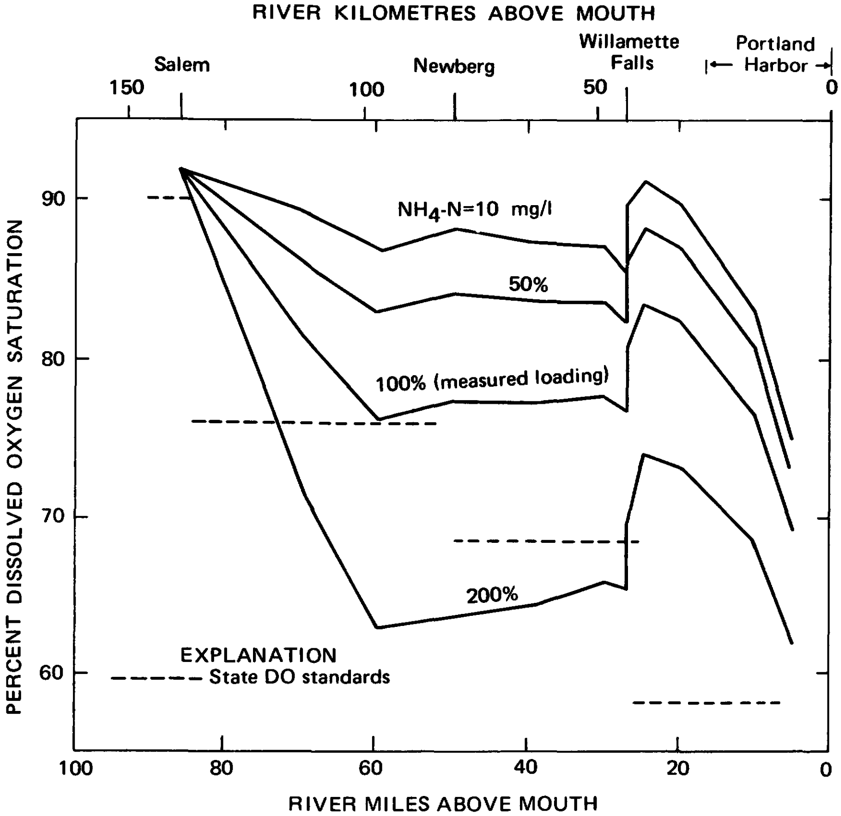

FIGURE 9.—Dissolved-oxygen profiles for a hypothetical effluent standard of 10 mg/l ammonia-nitrogen and for selected percentages of the measured point-source ammonia loading during mid-August 1974. Flow and BOD loading held constant at observed levels.

3,260 ft^3/s (255, 142, and 92 m^3/s). The latter value is near the lowest minimum monthly flow ever recorded for July under natural (nonaugmented) conditions (Velz, 1951). Predictions from a deterministic model (Chapter H) indicate this flow would have occurred during July of the unusually dry year of 1973.

The impact of flow augmentation is marked. At a flow of 3,260 ft^3/s (92 m^3/s), the 1974 BOD and ammonia-nitrogen loadings would cause violation of State DO standards by a wide margin at most locations. The predicted DO saturation levels at 3,260 ft^3/s (92 m^3/s) are nearly 30 percent less than the observed values (6,760 ft^3/s, or 191 m^3/s) at RM's 60, 28, and 5.

At a flow of 5,000 ft^3/s (142 m^3/s), the State DO standard would have been violated between RM's 67 and 50 and just have been met in the Newberg Pool and in the lower end of Portland Harbor.

In evaluating increased flow augmentation it should be recognized that improvements in quality are less dramatic as the DO profile is raised toward the level of saturation. Thus, augmentation of flow to 9,000 ft^3/s (255 m^3/s) would cause only a relatively small improvement in percent DO saturation. In fact, for conditions observed during August 1974, it appears that augmentation to discharges above 7,000 ft^3/s (198 m^3/s) would provide little incremental increase in DO. Nevertheless, under future conditions, augmented flows in excess of 7,000 ft^3/s (198 m^3/s) (if feasible) might be a desirable alternative to expensive, energy-consuming, advanced waste-treatment processes.

Figure 11 illustrates the combined effects of nitrification and flow augmentation. Curve B is the average DO profile observed during the steady, low-flow period of July-August 1973. Curve D is the predicted DO profile at a flow of 3,260 ft^3/s (92 m^3/s) and the observed ammonia loading. In comparing curves B and D, note that without augmentation, the State DO standards

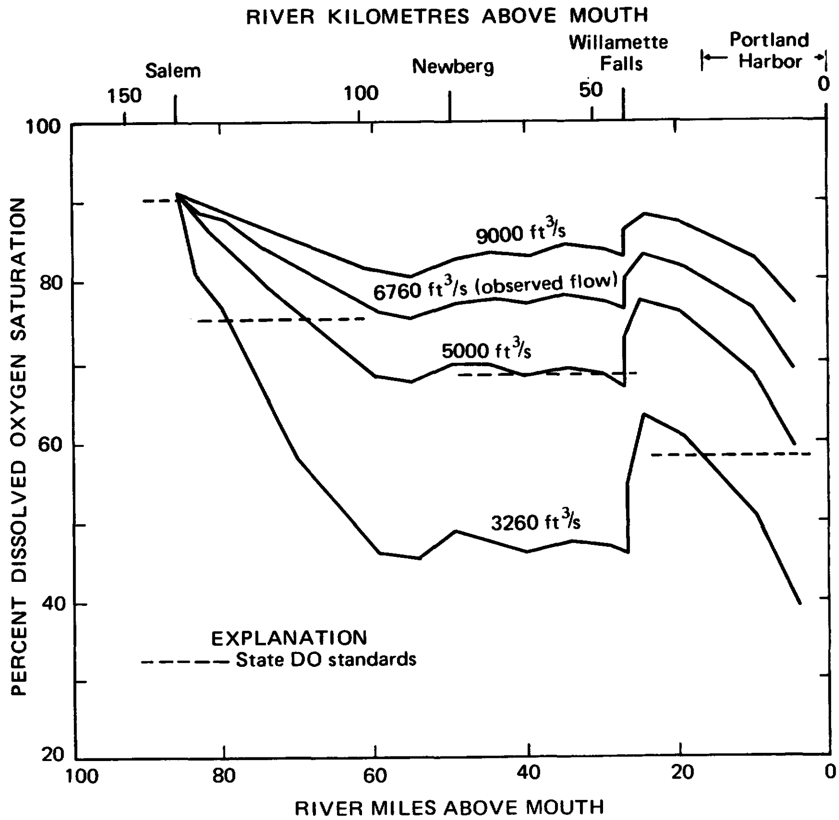

FIGURE 10.—Dissolved-oxygen profiles for selected flows with BOD and ammonia loadings held constant at levels measured during mid-August 1974. Observed flow was about 6,760 ft³/s.

would have been violated at most points in the river. Curves A and C represent predicted DO profiles at the same two flows, but with ammonia-nitrogen loading reduced to 10 mg/l in all point-source discharges. With such an effluent limitation, the DO profile predicted at 6,000 ft^3/s (170 m^3/s) is considerably above the observed profile (curve B) throughout most of the river. However, curve C portrays the most important finding for 1973 conditions. Even with complete secondary treatment and a reasonable limitation on ammonia loading, low-flow augmentation would be necessary to achieve DO standards in the Newberg Pool and in the Tidal Reach.

Figures 7 to 11 indicate the value of the WIRQAS model in evaluating planning alternatives. The calculations illustrated in these figures were based on the channel morphology, the sources of pollution, and the sources of flow augmentation that occurred during 1973 and 1974. However, the WIRQAS model can be readily adapted to evaluate a wide variety of new situations, including changes in the spatial distribution of inputs and in channel morphology. The predicted DO profiles in this report represent a small part of an extensive series which has been developed as an aid to planners and decision-makers.

UNDETERMINED OXYGEN DEMAND

During 1970, benthal respirometer studies (John Sainsbury, written commun., 1970) of the lower Willamette River documented a benthal-oxygen demand of 27,000 to 54,000 lb/d (12,000 to 24,000 kg/d) in the subreach between RM's 13 and 7. The river at that time still received some raw sewage in the form of combined sewer overflows and a moderate loading of fibers and other settleable solids from pulp and paper mills. Because these sources of solids were largely controlled by 1972, it was anticipated that the benthal demand would be greatly reduced by 1974. However, dur-

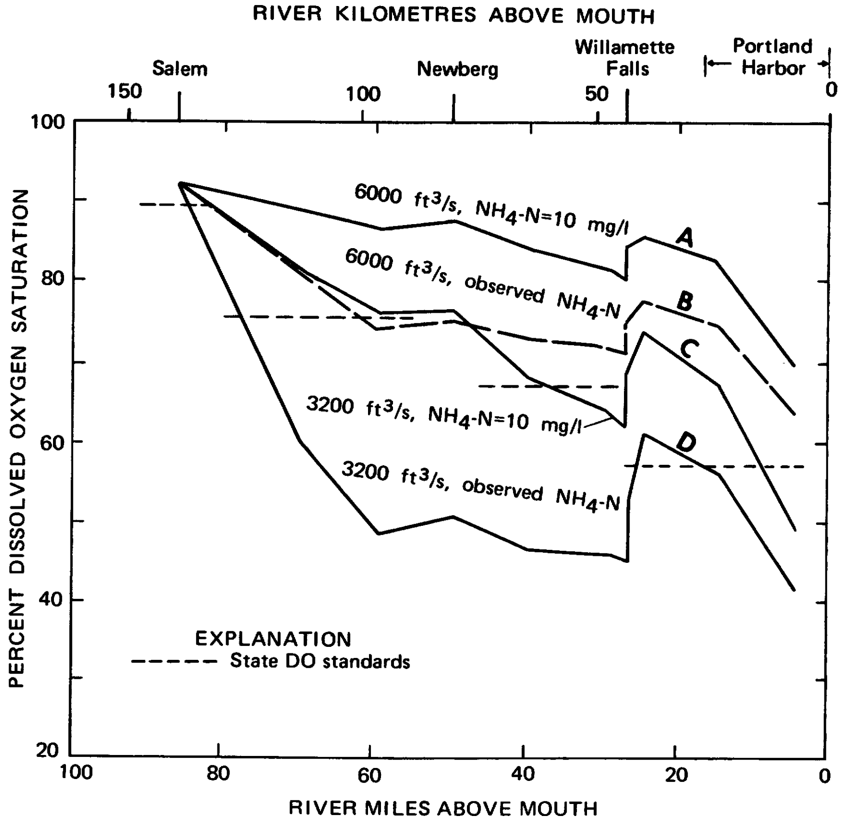

FIGURE 11.—Dissolved-oxygen profiles for selected conditions of flow and ammonia loading. BOD loading held constant at levels observed during July-August 1973. Curves A, C, and D are predicted; Curve B is observed.

ing preliminary calibration of the WIRQAS model, predicted DO concentrations between RM's 13 and 5 were higher than those measured in the river, whereas predicted BOD_{ult} concentrations were considerably lower. Refined modeling tests suggested an undetermined oxygen demand of about 27,000 lb/d (12,000 kg/d) in this subreach.

Field investigations (Chapter I) suggest that the demand is both suspended and benthal in origin, but the exact causes are unknown. Possible factors that may either cause or affect the oxygen demand include:

1. Unknown sources of raw sewage.
2. Combined-sewer overflows.
3. Urban storm runoff.
4. Bilge water and refuse from ships.
5. A net oxygen loss caused by algal respiration exceeding algal production owing to limited light penetration of the water column.
6. A turbid, high-oxygen demanding, estuarine-like "null zone" resulting from tidally influenced hydraulic conditions.
7. Sedimentation and decomposition of natural organics such as leaves and algae.

These possibilities are presently the focus of further study in the hope that all or at least part of the demand can be related to controllable sources. If so, management control of such sources would provide a means for improving summertime DO by up to 8 percent of saturation at RM 5.

SUMMARY AND CONCLUSIONS

Future achievement of DO standards in the Willamette River will require continued low-flow augmentation in addition to pollution control. Minimum flows of 6,000 ft^3/s (170 m^3/s) (Salem gage) are presently (1976) needed to meet the State standards at existing BOD and ammonia loadings and with occurrence of the unidentified oxygen demand in Portland Harbor. As basin development continues, it is likely that summertime flows above 6,000 ft^3/s (170 m^3/s) will be needed even with increased treatment removal of oxygen-depleting materials.

Point-source loading of ammonia is the major cause of oxygen depletion below RM 86. Because most of the ammonia comes from one source, reduction of ammonia loading offers a relatively simple alternative for achieving a large improvement in summertime DO.

Removal or partial reduction of the oxygen demand in Portland Harbor would improve the summer DO concentrations between RM's 10 and 5. However, the feasibility of reducing the demand is yet to be determined.

BOD loading from municipal waste-water treatment plants presently exerts a relatively small impact on DO. Increased efficiency of BOD removal at the largest municipal plants and at selected industrial plants might be desirable in the future. The benefits to be gained from this alternative would best be determined after ammonia loadings have been reduced to reasonable levels and the possibility of controlling the undetermined demand in Portland Harbor has been fully assessed.

POTENTIAL FOR ALGAL PROBLEMS

BACKGROUND

In 1972, the Willamette River achieved the status of being the largest river in the United States on which all known waste-water sources (municipal and industrial) receive secondary treatment. Although this action sharply decreased the waste loading of carbon to the river, the loading of nitrogen and phosphorus remained high because these nutrients are inefficiently removed by secondary treatment processes. As a result, summertime concentrations of carbon in the Willamette are fairly low, but the concentrations of nitrogen and phosphorus are high.

Despite the high nitrogen and phosphorus concentrations, excessive growths of algae have not been observed. The reason might be any one of several, including trace-metal limitations, unfavorable water temperatures, high summertime turbidities, or short water-detention times. On the other hand, the environment in the Willamette River could possibly be approaching a condition in which large, problem-causing growths of algae might begin to occur. Recent work in the Upper Potomac Estuary suggests that the initiation of secondary treatment may cause ecological shifts in receiving waters and actually stimulate the growth of nuisance blue-green algae (Jaworski and others, 1972).

Concern about the potential for algal problems in the Willamette led to a search for a suitable assessment method. An applied eutrophication model would have been ideal. At present, however, the complex eutrophication process is so poorly understood that it is virtually impossible to develop applied models capable of quantitative predictions (McGauhey, 1974).

Instead of attempting to formulate a predictive mathematical model, a qualitative descriptive study was designed to provide insight into the potential for nuisance algal growth. As applied in the algal study, descriptive assessment embodied problem definition, devising of hypotheses, collection and analysis of data, and exclusion of disproven hypotheses. For some specific problems, the cycle was repeated several times to refine the remaining possibilities. The final results are qualitative, because they provide no numerical predictions, but rather a general knowledge of the ways in which environmental and cultural factors combine to control river-quality phenomena.

The working hypotheses for this algal study were:

1. Nuisance algal growths are prevented by low water temperatures.
2. Nuisance algal growths are prevented by high summertime turbidities.
3. Algal growth is limited by a scarcity of certain trace elements.
4. Nuisance algal growths will develop provided the loading of major nutrients to the Willamette remains constant or increases, and loading ratios remain in the present proportion. This, in turn, is based on the hypothesis that certain undesirable species of algae (mostly blue greens and certain greens) compete better than desirable species (most diatoms and green algae) under a condition of low carbon concentrations and high nitrogen and phosphorus concentrations.
5. Nuisance algal growths are prevented by short detention times of water in the Willamette.

Using these hypotheses, available data on hydrology (fig. 3 and table 1) were analyzed to determine which reaches of the river have the greatest potential for algal problems. Conditions of high temperature and slow-moving, slowly mixing water would seem to be most favorable to the nuisance forms of green and blue-green algae. Thus, should nuisance algal growths develop in the river, they would probably occur in the Tidal Reach and the Newberg Pool.

Reconnaissance and intensive type studies were conducted to define environmental conditions and the nature of algal populations in the lower two reaches of the Willamette (see Chapters C and G). Existing data were used to provide an historical comparison.

ALGAL NUTRIENTS

NITROGEN AND PHOSPHORUS LOADINGS

During the low-flow period of 1974, point sources contributed about 80 percent of the orthophosphorus and 70 percent of the inorganic nitrogen (ammonia, nitrite, and nitrate) which entered the Willamette River (table 4).

For orthophosphorus, municipal effluents contributed 66 percent and industrial effluents 14 percent of the point-source loading (Chapter G). In contrast, industrial discharges accounted for 55 percent and sewage treatment plants for 14 percent of the point-source nitrogen. An undefined but localized source contributed 24 percent of the nitrogen between RM's 120 and 114 (vicinity of Albany, Oreg.). This source was in addition to the estimated input from Fourth Lake and was also evident in data collected between 1972 and 1975 by the Oregon DEQ. The resultant nitrogen loading has been categorized as unknown (table 4) because sufficient data were not collected to verify the source and the points of entry into the river. However, available information suggested that this nitrogen did not derive from normal land runoff and hence was a potentially controllable source.

"Controllable" sources thus contributed about 90 percent of the inorganic nitrogen and 80 percent of the orthophosphorus which entered the Willamette during the peak period of algal productivity. Moreover, a comparison between mathematically flow-routed inputs and measured river loads indicated that bottom sediments did not contribute to the summertime inriver loads of dissolved nitrogen and phosphorus.

The high percentage of phosphorus from point-source discharges compares closely with the reported values of 87 percent for the Potomac River basin and 73 percent for the Hudson River basin (Jaworski and Hetling, 1970). However, the estimated 90 percent point-source loading of nitrogen exceeds by a wide margin the comparative values of 63 percent for the Potomac and 51 percent for the Hudson. This difference results primarily from a relatively large industrial loading of ammonia in the Willamette River basin, together with the large unknown (but probably industrially related) source of nitrogen in the vicinity of Albany.

TABLE 4.—*Estimated, dry-weather 1974 nutrient loadings, Willamette River, Oreg.*[1]

Source	Orthophosphate as phosphorus		Ammonia + nitrite + nitrate as nitrogen	
	lb/d	Percent	lb/d	Percent
Land runoff	860	20	3,250	7
Municipal effluents	2,850	66	6,950	14
Industrial effluents	580	14	27,530	55
Unknown[2]	----	----	12,000	24
Total	4,290	100	49,730	100

[1]Data from Chapter G.
[2]See text for explanation.

OBSERVED CONCENTRATIONS OF NITROGEN, PHOSPHORUS, AND SILICA

During the 1973 and 1974 field seasons, the lowest determined concentration of orthophosphate-phosphorus was 0.035 mg/l and the highest was 0.092 mg/l. Most concentrations fell between 0.05 and 0.08 mg/l (fig. 12), a narrow range that is consistent with the limited range of streamflows under which most of the samples were collected (see Chapter G). Moreover, not only were the concentrations relatively stable, but they were at all times well above the concentrations of phosphorus observed in some highly productive natural waters (Schindler, 1971).

The concentrations of ammonia plus nitrate nitrogen (range of 0.28–2.90 mg/l) were considerably more variable than the phosphorus concentrations (fig. 12), but were always quite high relative to theoretical algal requirements. The scales in figure 12 are adjusted so that nitrogen (N) and phosphorus (P) concentrations appear equal when the two are present in a molar ratio of 16N:1P (approximate ratio in algal cells) (Stumm and Morgan, 1970).

The concentrations of dissolved reactive silica ranged from about 4 to 10 mg/l and, thus, were at

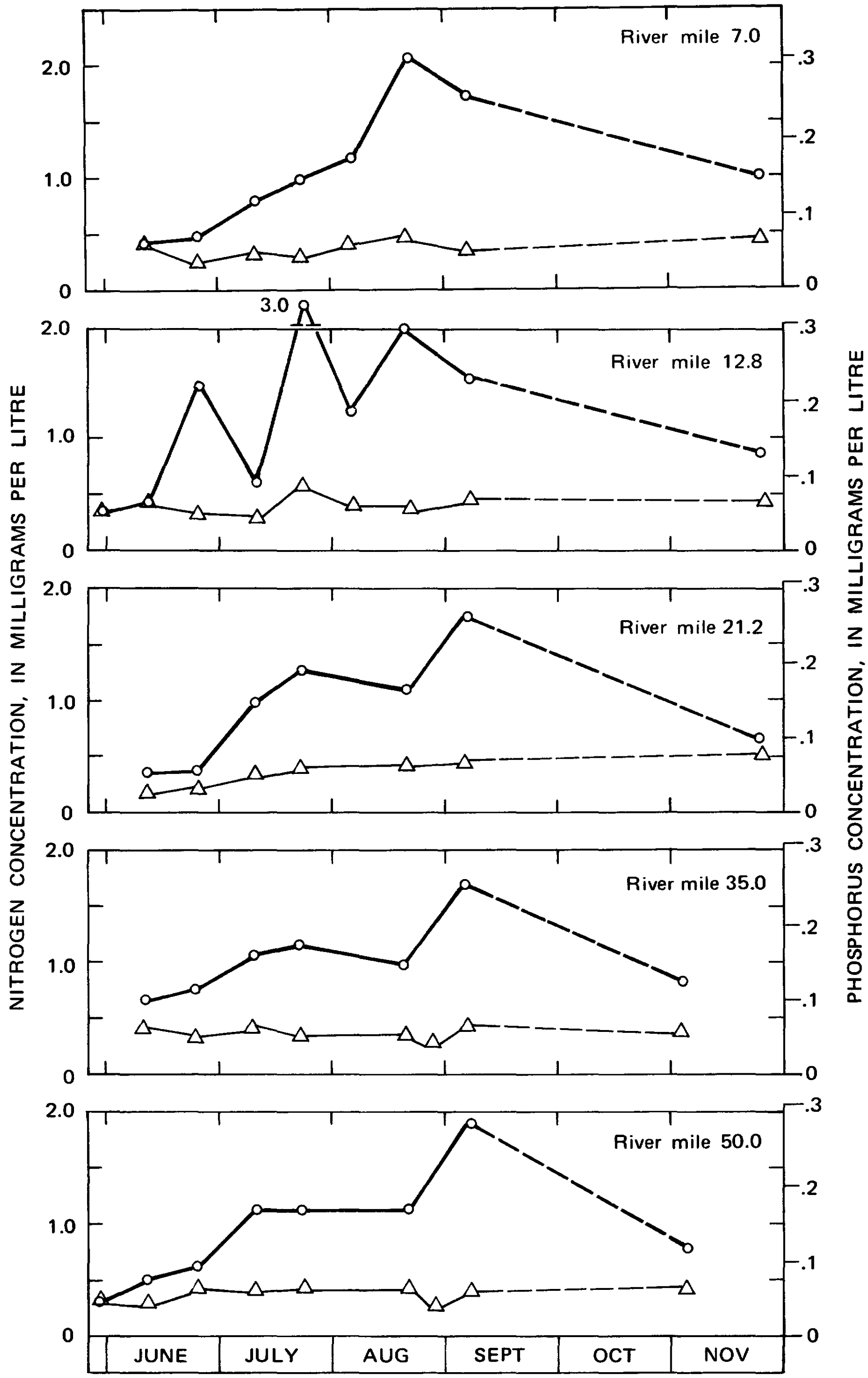

FIGURE 12.—Time and spatial variations of selected major nutrient concentrations in the Willamette River, June-November 1974; O, ammonia plus nitrate as nitrogen; Δ,orthophosphate as phosphorus.

all times above those required for diatom growth (Kilham, 1971). The data showed no evidence of a decrease in silica concentration from upstream to downstream locations. Additional samples collected between RM's 183 and 50 showed similar results. Thus, there was no apparent downstream depletion of dissolved silica in spite of the presence of suspended diatoms throughout the river and extensive beds of periphytic diatoms above RM 52.

ALGAL POPULATIONS

Diatoms dominated the suspended-algae populations at all sites during both 1973 and 1974. (See Chapter G for details.) The most common diatom genera were *Melosira, Stephanodiscus, Cymbella, Achnanthes, Nitzschia,* and *Fragilaria.* Some blue-green algae and a variety of colonial green algae appeared but were less abundant than the diatoms.

Densities of diatoms were rather high, with individual species present in abundances of 10^2 to 10^3 cells/ml. During both years, the diatom populations were remarkably stable. The same species persisted, and there were no major changes in the total abundance of cells with location (sampling station).

The common species of diatoms observed in the Willamette River can be characterized as cosmopolitan and eutrophic. No species appeared that would indicate highly polluted conditions, although some of the common diatoms are moderately tolerant of organic enrichment (Palmer, 1969). Although short filaments of *Anabaena* were observed in some samples, no "blooms" of blue-green algae or other algal types occurred during the study. Collectively, the composition of all suspended algae suggest that the lower two reaches of the Willamette were nutrient enriched, but not grossly polluted.

The aggregate nature of diatoms in the lower Willamette indicates that the population resulted from both inriver growth of suspended forms (planktonic) and the exportation of cells from above RM 52, where most of the algae grow attached to river bottom rocks (periphytic).

Figures 13 and 14 compare the relative abundances during 1963 (U.S. Public Health Service, 1964) and 1974 of diatoms, green algae, and blue-green algae in the lower Willamette River. Differences in methodology between the two studies could well account for the observed higher abundance of green algae during 1963 (Williams, 1964, 1972). However, the point of major importance is that the suspended algal population in the lower river was dominated by diatoms in 1963, just as it was during 1973 and 1974. This observation is significant, because the lower Willamette was polluted with sewage and pulp-mill wastes in 1963 (Velz, 1961; Gleeson, 1972) but now is relatively free of such organic pollution (Rickert and others, 1975b; Chapter I). Unfortunately, no 1963 data are available on nitrogen and phosphorus concentrations to provide a comparison of nutrient availability.

Figure 15 shows the relative abundance of diatoms and blue-green algae in net plankton

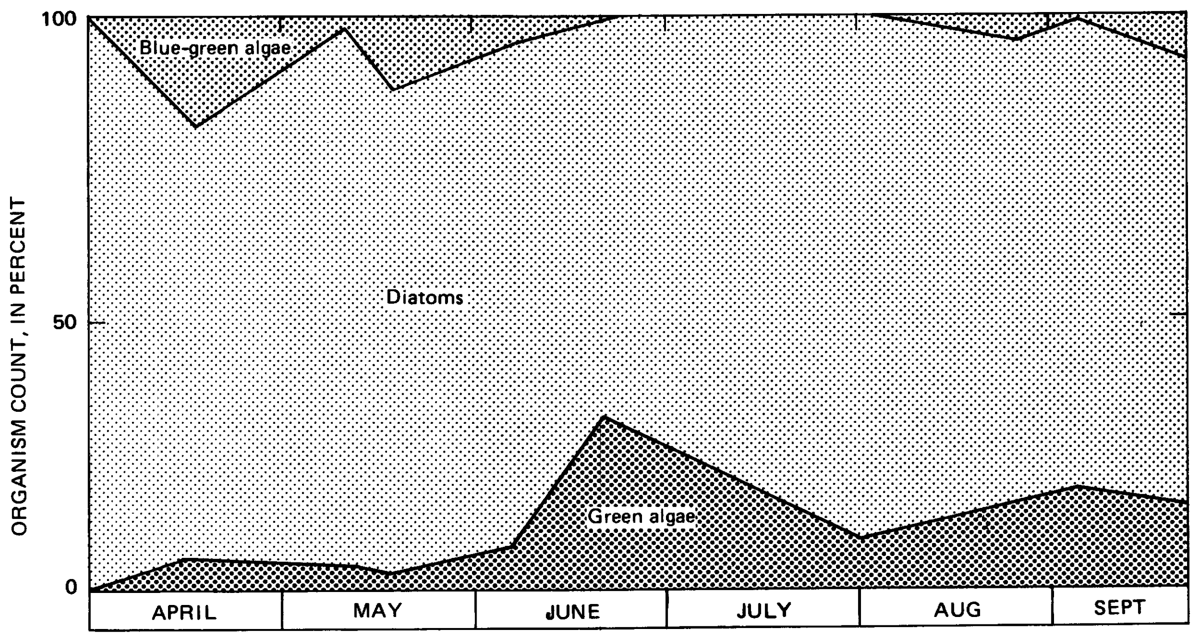

FIGURE 13.—Time variation of algal types in the Willamette River, at mile 8.1, April-September 1963 (U.S. Public Health Service, 1964).

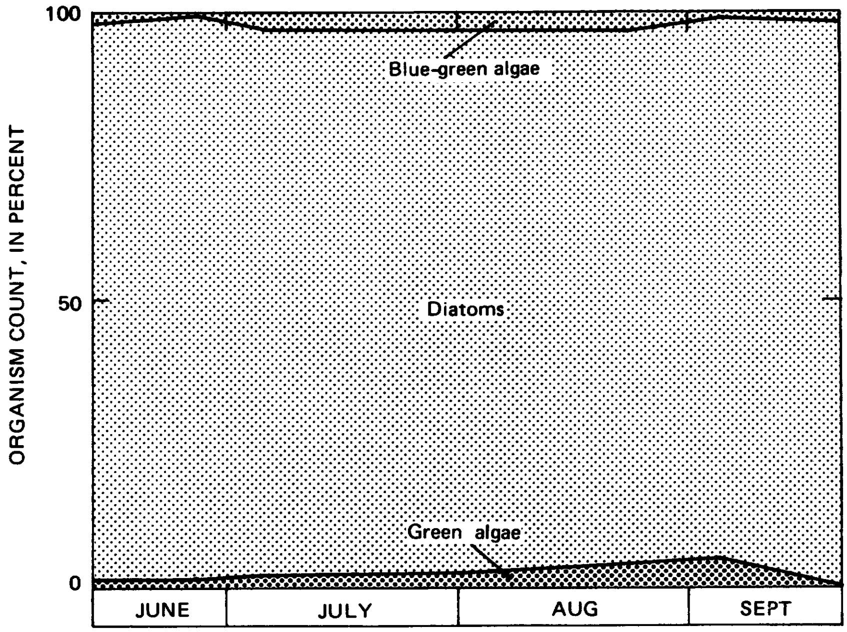

FIGURE 14.—Time variation of algal types in the Willamette River, at mile 7.0, June-September 1974.

from the Tualatin River (see fig. 2). The illustrated data (Carter, 1975) indicate that the eutrophic but not heavily polluted reach at Farmington was dominated by blue-green algae during July-August 1973. During this period, streamflow in the Tualatin was low, at about 10 ft^3/s (0.3 m^3/s). The Tualatin enters the Willamette at RM 28.6, and this tributary inflow may account for the low counts of *Anabaena* sometimes observed in the Tidal Reach.

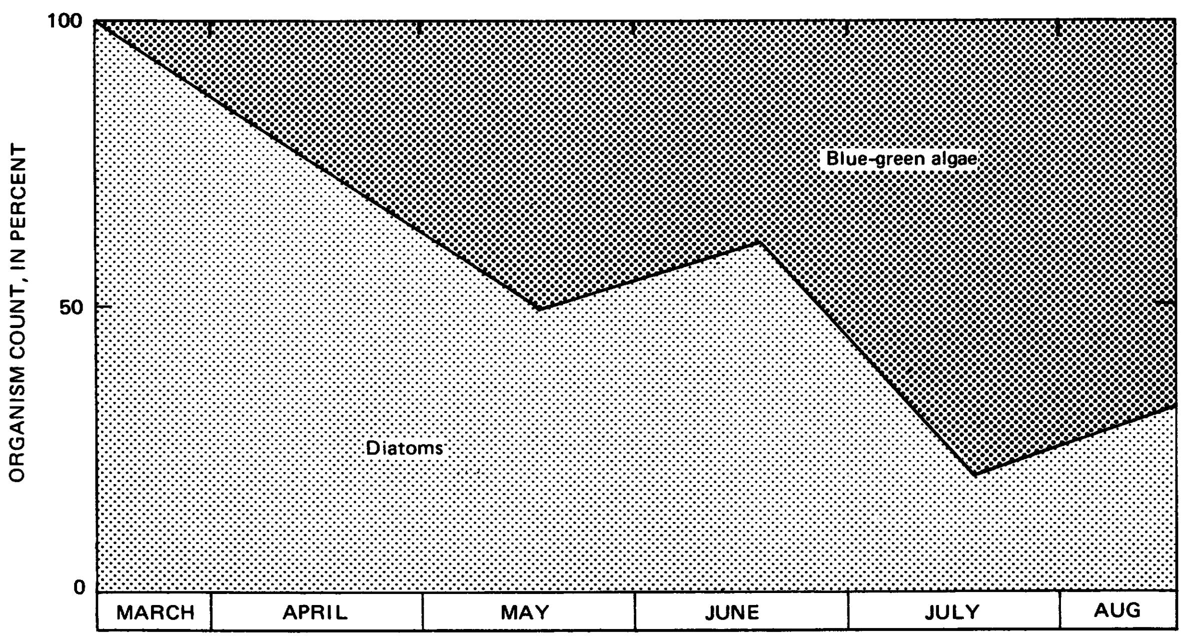

FIGURE 15.—Relative abundance of diatoms and blue-green algae in net plankton of the Tualatin River at Farmington, Oreg., March-August 1973 (Carter, 1975).

PRIMARY PRODUCTIVITY

Figure 16 shows two examples of the vertical distribution of gross productivity at RM 7.0. From such plots, total gross productivity was calculated for several sampling dates. The results ranged in magnitude from 1.6 to 4.4 $(gO_2/m^2)/d$ (grams DO per square metre per day) and, in comparison to data from other rivers, (see Chapter G, table 3) indicate that primary productivity in the lower Willamette was low to moderate. The data verify, however, that the suspended algae in the lower Willamette were metabolically active rather than dead cells transported from the periphytic beds above RM 52.

The vertical distributions in figure 16 show that gross productivity decreased rapidly with depth, a result consistent with the turbid nature of the water. (See "Light Limitation.")

EXAMINATION OF THE WORKING HYPOTHESES

The following discussions examine the five previously listed working hypotheses to determine which best explain observed algal conditions in the lower Willamette River.

LOW-TEMPERATURE LIMITATION

Water temperatures in the Willamette River and in all tributaries reach a maximum during the July-August low-flow period. For the lower Willamette River, records compiled by the Willamette Basin Task Force (Appendix B, 1969) indicate the average water temperature during July ranges from about 20°C at RM 50 to about 22°C at RM 7.0.

During 1974, water temperature at RM 7.0 was about 10°C in mid-May and increased to only 13°C by mid-June. From this date, the temperature increased rather steadily to a maximum of about 24°C in early August. The temperature stayed about 20°C through the remainder of August and early September and then decreased steadily through the remainder of September.

The recorded temperatures in the lower Willamette River are lower than those observed in many lakes and rivers that experience nuisance algal growths. Cairns (1956) noted that diatoms generally are favored at temperatures below 25°C, green algae between 30 to 35°C, and blue-green algae above 35°C. Hutchinson (1967) concluded that blue-green algae may dominate in mid-to-late-summer because they out-compete other forms by growing faster at low inorganic nutrient levels and at high temperatures. However, in the Willamette River basin, blooms of *Anabaena* (a nuisance blue-green alga) occur under the quiescent conditions in certain headwater reservoirs at water temperatures below 18°C.

In spite of this occurrence, the moderate summer temperatures in the lower reaches of the Willamette could be one factor that helps maintain suspended algal growth in its present desirable state.

LIGHT LIMITATION

The water in the lower Willamette River was relatively turbid during the study periods in 1973 and 1974. Extinction coefficients, calculated from the measurement of relative light at the 10-ft (3-m) depth, were between 1.4 m^{-1} and 2.0 m^{-1}. Coefficients caluclated for the 3-ft (1-m) depth

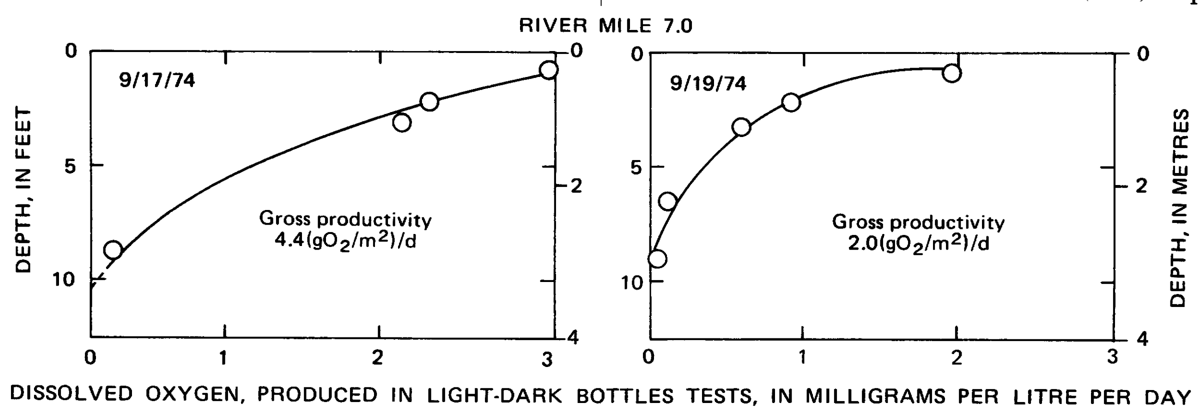

FIGURE 16.—Vertical distribution of primary gross productivities in the Willamette River, at mile 7.0, for selected times during summer 1974. Gross productivities for the euphotic zones (reported as $(gO_2/m^2)/d$) were calculated according to Slack, Averitt, Greeson, and Lipscomb, 1973.

were somewhat higher owing to selective wavelength absorption.

The euphotic zone of a water body is the thickness of the surface layer that receives sufficient light to permit algal photosynthesis to equal or exceed algal respiration. This thickness is approximately equal to the depth to which 1 percent of the surface light penetrates. The determined range of extinction coefficients implies a euphotic-zone thickness between 7.5 to 11.5 ft (2.3 to 3.5 m) along the course of the Willamette River. In contrast, the representative midchannel water depth is 40 ft (12 m) in the Tidal Reach and 25 ft (8 m) in the Newberg Pool (table 1). Generally, in these reaches, both the water and suspended matter is completely mixed to the bottom (unstratified); consequently, only part of the suspended algae is capable of photosynthesis at any moment, whereas algae and all other organisms are respiring throughout the entire water column.

The above information, when combined with the production data (see "Primary Productivity") and other evidence (See Chapter G for elaboration), indicates that low light availability restricts the rate of primary productivity in the Tidal Reach and the Newberg Pool. It seems that there is insufficient light throughout the water column for suspended algae to grow rapidly in these reaches.

From a management standpoint, there are two important questions concerning light limitation: (1) what are the natures and sources of the materials causing the high light extinction and (2) if turbidity were decreased, would the increased light availabilities result in greater primary productivities and possibly cause undesirable shifts in algal populations? Unfortunately, at present, there is insufficient information to answer either question. Until such time that definite answers are available, it may be prudent to assume that measures aimed at decreasing summertime turbidities (if this is indeed possible) might cause undesirable changes in algal-growth dynamics.

TRACE-NUTRIENT LIMITATION

Bioassay tests were conducted to determine if addition of selected nutrients would stimulate the growth of Willamette River algae under controlled conditions. The tests were conducted on three occasions, and one set of results is shown in figure 17. In no case did the productivity of treated samples exceed that in controls by a significant amount. The overall results indicate that nutrient availabilities in the lower Willamette River were not limiting to algal productivity nor to possible development of nuisance algal conditions. These results are consistent with the many possible sources of trace elements and with the presence of numerous metals in the river-bottom sediments. (See "Trace-Metal Occurrence.")

MAJOR-NUTRIENT LIMITATION

CARBON

The Willamette is a low alkalinity (15–25 mg/l as $CaCO_3$) river (U.S. Geological Survey, 1974), so the possibility of a carbon limitation on algal production needs to be considered. In assessing this topic, there are two relevant questions: (1) Are carbon concentrations possibly limiting to gross production of phytoplankton and (2) how does the distribution of carbon among the inorganic forms affect the qualitative nature of the phytoplankton?

The first question can be assessed by comparing the ratios of total carbonate carbon to inorganic nitrogen to orthophosphorus in Willamette River water to reported ratios of carbon:nitrogen:phosphorus (C:N:P) in algal protoplasm. During July and August 1974, the C:N:P ratios at RM 7.0 in the Willamette varied from 185:21:1 to 285:60:1. In contrast, the commonly quoted ratio of these elements in algae is 106:16:1 (Stumm and Morgan, 1970), and a ratio reported as typical for blue-green algae is 40:7:1 (James and Lee, 1974).

Comparison of the two sets of ratios shows that, on a relative basis, carbon in the Willamette was more abundant than the phosphorus needed for algal growth and equal to or more abundant than the required nitrogen. These findings suggest that carbon was not limiting to algal production in the lower Willamette River.

The second question can be assessed by examining diel records of pH values. During July and August of 1973 and 1974, continuous 3-day pH traces were obtained at RM's 7.0 (depths of 3 and 20 ft, or 1 and 6 m) and 12.8 (depths of 3 ft, or 1 m). During each of six measurement periods the maximum daily variation in pH was from 6.8 to 7.1.

The stability of pH near neutrality indicates that free carbon dioxide (CO_2) was not depleted by

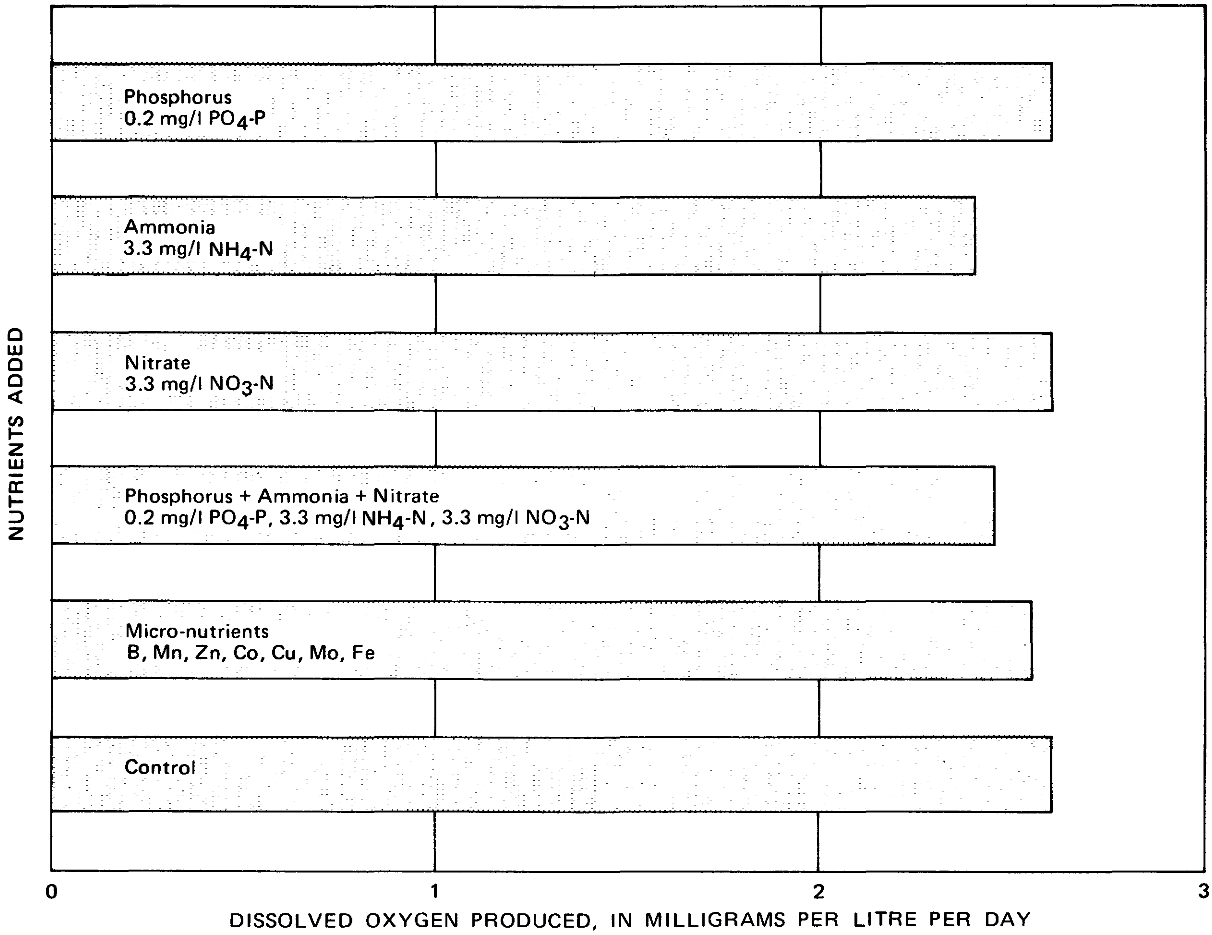

FIGURE 17.—Effect of nutrient additions on algal productivity of Willamette River samples, mile 7.0, July 24, 1973.

algal production to the point where extensive bicarbonate carbon was utilized. Such a condition is favorable to maintenance of diatom and green-algae populations. In contrast, blue-green algae tend to dominate under conditions of high pH, because their advantageous uptake kinetics allow them to compete better for bicarbonate CO_2 once free CO_2 is depleted (King, 1970; Shapiro, 1973). In the lower Willamette River, there apparently was a maintenance of sufficient free CO_2 to prevent conditions where blue-green algae would have competitive advantage over diatoms and green algae.

NITROGEN AND PHOSPHORUS

The concentrations of nitrogen and phosphorus in the lower Willamette River are higher than those reported as sufficient to cause nuisance algal blooms in lakes (Sawyer, 1954; Schindler, 1971), but lower than concentrations observed in certain rivers and estuaries that have nuisance algal problems (Shane and others, 1971; Jaworski and others, 1972; Clark and others, 1973).

The observed nitrogen and phosphorus concentrations seem sufficient to support higher levels of primary production than those measured in the river. This deduction is supported by the nutrient enrichment tests (see fig. 17) which indicated that neither nitrogen nor phosphorus was limiting to algal productivity at RM's 7.0 and 12.8.

Comparison of N:P ratios in Willamette River water (fig. 12) to the commonly reported ratio for algal tissue (16:1) indicates that nitrogen was relatively more abundant than phosphorus by a wide margin during 1974. Thus, if algal production were greatly increased and nutrient loading remained constant, phosphorus (not nitrogen or carbon) would probably become the limiting major nutrient. However, the 1973 and 1974 concentrations of phosphorus were far from being depleted to the point where limitation of productivity was even a remote possibility.

DETENTION-TIME LIMITATION

OBSERVED AND REPORTED RELATIONSHIPS

As in the Willamette, the suspended-algae populations of most rivers in the United States (Williams, 1964; 1972) and throughout the world (Hynes, 1970) are dominated by diatoms. Exceptions to the general pattern of diatom dominance do occur, however, and are usually observed in parts of river systems having long detention times (slow rates of water exchange). As described in Chapter G, detention time has been noted by several authors as the dominant factor in algal productivity and succession in certain rivers, estuaries, lakes and reservoirs.

As previously noted (see "Reservoirs and Historical Streamflow Patterns"), summer low flows in the Willamette River are augmented by reservoir releases to maintain a minimum of 6,000 ft^3/s (170 m^3/s) at Salem. At this discharge, water-detention times are small, with volumetric displacement times of 3.9 days for the Newberg Pool and 7.5 days for the Tidal Reach down to RM 5.0 (point of mixing with the Columbia River). The water at this discharge is confined within well-defined banks (very few sloughs and side channels) and is totally mixed to depth. Thus, in the lower Willamette, the total detention time of water during the period having the slowest flow velocities and the highest water temperatures is about 11 days.

In contrast to the Willamette, low-flow detention time in the 35-mi (56-km) Upper Potomac Estuary, where algal problems occur, is reported as 50 days (Walker, 1971). Thus, under low-flow conditions, detention time in the freshwater reach of the Potomac Estuary is four to five times greater than that observed in the Willamette River between RM's 52 and 5.

Based on the results and on comparisons with other rivers, we believe that short detention time is the primary reason productivity is low in the Willamette and diatoms dominate in spite of the high availability of nitrogen and phosphorus. However, based on published results (Fogg, 1965), the 11-day, low-flow detention time seems long enough to permit the reproduction of planktonic blue-green algae. Thus, the absence of nuisance blooms in the Willamette apparently results from the influence of detention time on other factors which control algal growth. The following section examines several relationships which could be prominent in the Willamette and in many other rivers.

ROLE OF DETENTION TIME AND LIGHT PENETRATION IN CONTROLLING BIOMASS AND THE NATURE OF ALGAE

Figure 18 schematically portrays the relationship of algal biomass and dominant algal types to water-detention time and light penetration. The schematic is based on observations made in waters of the Willamette system but is presented as a conceptual model to be considered for all river basins.

The schematic was devised to generalize the locations and stream-current conditions under which nuisance algal growths are likely to occur. Nuisance algal conditions include problems of esthetics, DO depletion, and increased water-treatment costs. In this context, the occurrence of nuisance conditions depends on the type and amount of biomass (weight of algal cells per unit volume of water) that can develop and accumulate in the water.

In the diagram, water-detention time increases toward the right and biomass toward the top. The figure body is divided into three hydraulic-ecological habitats. The habitat at the left is representative of fast-moving shallow rivers in which the photosynthetic zone extends to the bottom. Under such conditions, periphytic diatoms are typically the dominant algal type and both primary production and biomass are high.

The habitat at the center of the schematic is typical of moderate-velocity rivers in which average depth is high relative to the penetration of light. This habitat characteristically occurs downstream from the regime at the left of the figure and is commonly the condition found over long reaches of most large rivers. In such waters, the dominant algae are planktonic diatoms. Biomass is relatively low because of lower productivity and the dispersion and transport of cells by the current. This hydraulic-ecological habitat can also occur in tidal rivers (such as the Willamette Tidal Reach) where net downstream velocities are low but the waters are well mixed owing to tidally induced currents.

The hydraulic-ecological habitat at the right of figure 18 is representative of sluggish and stand-

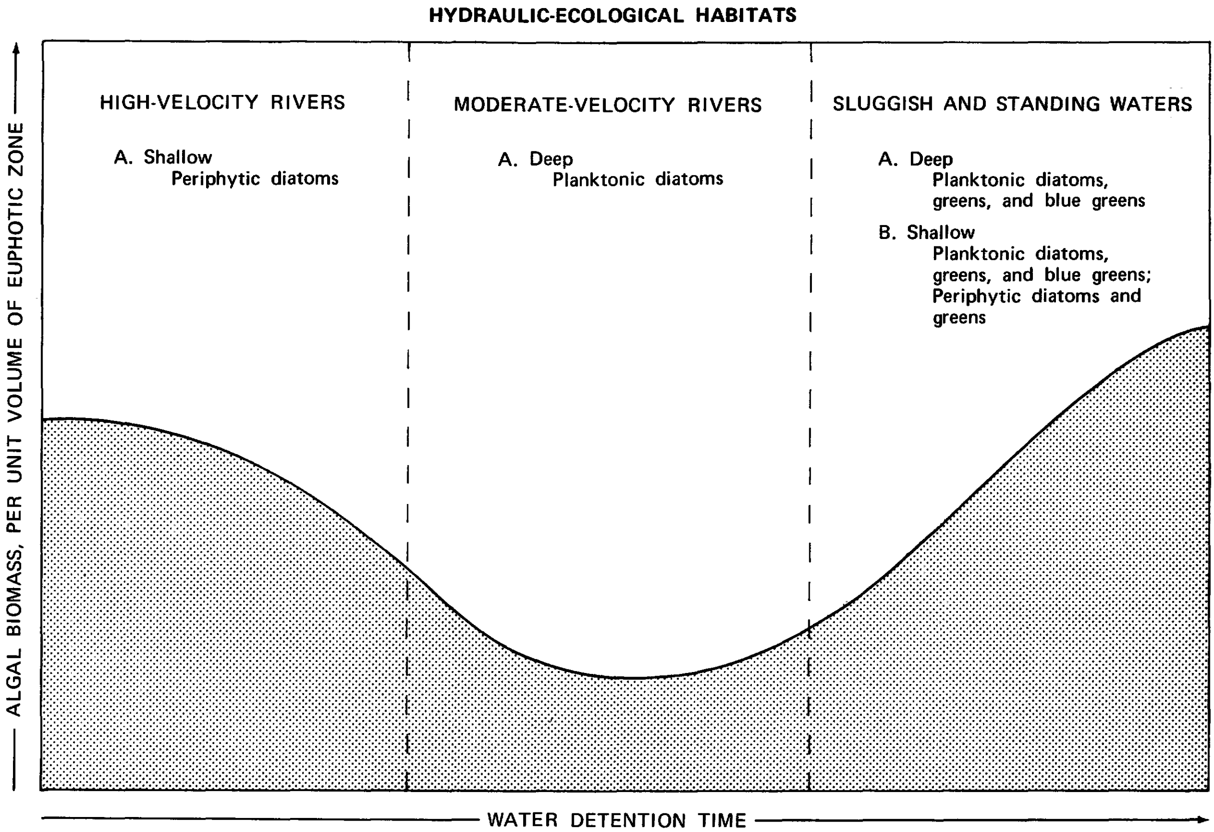

FIGURE 18.—Conceptual diagram relating algal biomass and dominant algal types to water detention time and light penetration. Shallow implies that the euphotic zone extends to the bottom; deep implies the euphotic zone does not reach the bottom.

ing waters such as pooled rivers, lakes, reservoirs, and poorly mixed estuaries. In such waters, environmental conditions can be diverse and, depending on depth, the dominant algal types may range from planktonic diatoms, greens, and blue-greens to periphytic diatoms and filamentous greens. In the euphotic zone of this habitat, productivity tends to be high, and biomass accumulation can be great. This combination often leads to the development of nuisance algal conditions. The deep waters of this hydraulic regime are commonly poorly mixed or stratified. It is at the surface of these waters that planktonic blue-green blooms must commonly occur, sometimes as the result of a seasonal succession beginning with diatoms and green algae.

With figure 18 for perspective, we can hypothesize why significant growth of blue-green algae does not occur in the Willamette nor in most large free-flowing rivers (as represented by the middle regime).

The exact relationship between water-detention time, biomass, and the qualitative nature of algae depends on a large number of factors. Included among these are nutrient availability, water temperature, light penetration, and perhaps simply the requirement of some algae for a period of adjustment to new environmental conditions. However, the crux of the conceptual model (fig. 18) is that in free-flowing rivers detention time largely controls these factors in a manner that prevents the onset of conditions conducive to the growth of planktonic blue-green algae.

Perhaps most importantly, flowing water provides a constant chemical influx that prevents depletion of major nutrients to concentrations at which blue-green algae would enjoy a competitive advantage. In addition, most flowing waters remain unstratified (except estuaries), and temperatures do not reach the same levels that would occur in stratified standing water under identical climatic conditions. Moreover, because flowing water carries suspended sediment, rivers are usually more turbid and permit less light penetration than standing water. Also, in flowing water, turbulent mixing negates the buoyancy advantage that blue-green algae enjoy in standing water because of their unique possession of gas vacuoles (Walsby, 1970).

All these factors may be important in various combinations and degrees in different rivers. In the Willamette River, the most important factor is probably the maintenance of a balance in nutrient concentrations by flow and mixing, but low light availability resulting from turbidity also plays a role.

SUMMARY AND CONCLUSIONS

The key to keeping algal growth in the Willamette River at its present balance appears to be control of those factors that maximize summertime flow and thus minimize time-of-passage. Such control would require maintenance of present levels of flow augmentation and avoidance of large increases in summertime diversions. The high observed concentrations of nitrogen and phosphorus result primarily from point-source loading but, under the present physical conditions, do not stimulate algal succession leading to nuisance growths. It appears that treatment to remove nitrogen and phosphorus from point sources is not needed to control algal growth provided summer low flows are maintained in the range of 6,000 to 7,000 ft^3/s (170 to 198 m^3/s). However, algal problems might develop if flow were greatly reduced and the point-source nitrogen and phosphorus loadings remained at the 1974 levels.

The results of this study indicate that arbitrary standards for permissible nitrogen and phosphorus concentrations in rivers may bear little relationship to primary productivity and to algal-growth dynamics. This means that the need for advanced waste-treatment removal of phosphorus and nitrogen must be assessed on a river-by-river or reach-by-reach basis. The environmental benefits that will result from different pollution-control measures can only be determined by conducting sound river-quality assessments that are keyed to local conditions.

TRACE-METAL OCCURRENCE

BACKGROUND

Many materials discharged into river systems can be toxic to aquatic organisms if present in critical concentrations. These materials include numerous trace metals and manmade organic compounds such as insecticides, polychlorinated biphenyls (PCB's), herbicides, and certain industrial organics. Even though such materials are usually discharged to rivers at subtoxic levels, many are capable of being concentrated at successive steps in aquatic food chains in a process called "biological magnification."

Review of industrial-discharge permits for the Willamette River basin indicates that there is very little possibility of toxic industrial organics entering the Willamette River. Furthermore, over the last 10 years, hard pesticides (such as DDT) have not been used in the basin for disease-vector control nor for widespread plant-pest control. In contrast, there are several industrial sources of trace metals in addition to the metals that enter the river in urban runoff. Thus, if a toxicity problem occurred, it would probably result from the accumulation of trace metals.

Prior to this study, few data existed for the Willamette River system on the content of trace metals in the water, sediment, and food chains. Data were so sparse as to preclude even a preliminary assessment of whether metal concentrations were low, moderate, or critically high. To partly fill this void, a reconnaissance study was designed to determine the concentration and distribution of trace metals in river-bottom sediments. The objectives of this reconnaissance were to provide not only baseline information for future comparison, but also an alert on possible accumulation of metals.

POSSIBLE SOURCES OF TRACE METALS

Besides natural geological background, the possible sources of trace metals in the Willamette River basin include industrial activities, urban runoff, municipal waste-water discharges, and old mining areas. Table 5 was compiled from unpublished records of the Oregon DEQ to show the river-mile location on the Willamette of most known or potential sources of metals. The table also indicates the discharge locations of tributaries.

In the Portland metropolitan area, the land corridor along the Willamette is used for many industrial and shipping activities which represent potential sources of metals (table 5). In addition, the city of Portland is served by a combined sewerage system that during intense rainfall

TABLE 5.—*Possible sources of trace metals in the Willamette River system*[1]

Location[2]	Industries and industrial waste-water effluents	Municipal, secondary waste-water effluents[3]	Tributaries and urban runoff
0–6.0			Intrusion of Columbia River sediments.
Columbia Slough (1.2).	Calcium carbide and related products.		
2.5–12.0	Shipping terminals.		
3.0–8.0	Oil tank farms.		
3.3			Multnomah Channel.
7.0	Agricultural organic chemicals (Cr, Cu, Pb, Ni, Zn).		
7–17			Combined sewer overflows from Portland (Pb and others).
7.4	Chlorine and related products (Cr, Zn).		
Swan Island Channel (8.1).	Drydocks and ship repairs.		
11.0	Cement plant.		
13.7	Ship salvage yards.		
17.0–27.5			Urban storm drainage from Portland metropolitan area (Pb and others).
18.4		Milwaukie—1.9 Mgal/d (Cr, Ni, and Zn from plating wastes).	
20.1		Oak Lodge—1.8 Mgal/d	
20.3		Tyron Creek—3.7 Mgal/d	
24.1		West Linn—0.7 Mgal/d	
25.2		Oregon City—2.8 Mgal/d	
27.6	Ground-wood pulp and paper mill—13.5 Mgal/d (Zn).		
27.8		West Linn—0.5 Mgal/d.	
28.0	Ground-wood and magnesium sulfite pulp and paper mill—12.9 Mgal/d (Zn).		
28.5			Tualatin River.
33.0		Canby—0.3 Mgal/d	
35.6			Molalla River.
48–51			Urban storm drainage from Newberg (Pb and others).
49.2	Ground-wood and magnesium sulfite pulp and paper mill—11.7 Mgal/d (Zn).		
50.3		Newberg—0.7 Mgal/d	
54.8			Yamhill River.
78.2		Salem—22 Mgal/d	
80.5–87.0			Urban storm drainage from Salem (Pb and others).
84.2			Boise Cascade Slough.
85.2	Ammonium sulfite pulp and paper mill.		
107.7			Luckiamute River.
108.0			Santiam River.
Fourth Lake (117.0).	Metal extraction and processing, Kraft pulp and paper mill, resin plant, wood flour mill, oil tank farm (Zr, Hf, Ta, Nb, V, W, Mo, and others).		
117.9		Albany—5 Mgal/d	
118–120			Urban storm drainage from Albany (Pb and others).
119.6			Calapooya River.
130–134			Urban storm drainage from Corvallis (Pb and others).
130.8		Corvallis—6 Mgal/d	
132.0			Marys River.
132.2	Hardboard mill.		
147.5	Kraft pulp and paper mill.		
148.0			Long Tom River.
174–187			Urban storm drainage from Eugene-Springfield (Pb and others)
174.9			McKenzie River.
178.6		Eugene—13 Mgal/d	
184.3		Springfield—5 Mgal/d	
187.0			Confluence of Coast Fork and Middle Fork.

[1]Specific metals associated with specific sources are identified in brackets by their chemical symbols.
[2]River-mile location or river-mile interval unless specifically named.
[3]Approximate flows for summers of 1973 and 1974.

overflows into the Willamette carrying metals from raw sewage, various industries, and street runoff. (Dry-weather flow is diverted via the municipal treatment plant to the Columbia River.) Moreover, between RM's 17 and 25.6, street runoff periodically enters the Willamette through a separate storm-drainage system, and farther upstream, storm drainage and municipal secondary effluents represent additional trace-metal sources in other urban areas.

Pulp and paper production is a major industry of the Willamette River basin. For many years zinc hydrosulfite has been used as a brightening agent in the ground-wood pulping process at three large mills (table 5). The three plants and their 1973 zinc loadings to the Willamette were Publishers Paper Co. at Newberg (RM 49.2), 71 tons (64 t) (Zenon Rozycki, oral commun., 1975); Publishers Paper at Oregon City (RM 28.0), 89 tons (81 t); and Crown Zellerbach Corp. at West Linn (RM 27.6), 75 tons (68 t) (Herman Amberg, oral commun., 1975). In compliance with orders of the Oregon DEQ, Publishers switched to a nonzinc brightening agent at both plants in spring 1975, and Crown Zellerbach will switch by July 1977.

There are seven mineralized areas (fig. 19) in the Willamette River basin (Oregon Department of Geology and Mineral Industries, 1951; Willamette Basin Task Force, Appendix A, 1969) which at one time or another were commercially mined. Mercury was once mined from the Black Butte area on the Coast Fork above Cottage Grove Reservoir, and from the Oak Grove Fork area in the headwaters of the Clackamas River.

The five other areas were mined at various times for copper, gold, lead, silver, and zinc. The five areas and their drainage tributaries are (see fig. 19):

1. North Santiam district; tributary to the Santiam River.
2. Quartzville district; tributary to the Santiam River.
3. Blue River district; tributary to the McKenzie River.
4. Fall Creek district; tributary to the Middle Fork Willamette.
5. Bohemia district; tributary to the Coast Fork Willamette.

No natural deposits of cadmium or chromium are known to exist in the Willamette River basin. No commercially exploitable source of arsenic exists, but high concentrations of this metal occur in the ground water of Lane County at the southern end of the basin (Goldblatt and others, 1963).

Fourth Lake, near Albany, is worthy of special mention. The Lake, which is actually a slough, receives drainage from 11 industries, including the metal-extraction and processing operations at Teledyne-Wah Chang. Wah Chang extracts zirconium and hafnium from imported ores and produces various alloys from these metals and from tantalum and niobium, which are purchased in purified form (Tom Nelson, Teledyne-Wah Chang, oral and written communs., 1975). The imported ores also contain scandium, yttrium, lanthanum, and ytterbium. Additional metals used in production of alloys include molybdenum, tungsten, tin, chromium, and nickel. At one time, Wah Chang also used silver in the production of a special tungsten alloy.

From the information in table 5 and figure 19, it can be seen that the potential sources of trace metals to the Willamette River are generally known. To determine the effects of these sources, it was necessary to develop an approach for the collection and preparation of samples.

SAMPLING APPROACHES AND RATIONALES

For purposes of this study, bottom sediments were considered the most desirable sampling medium. Because trace metals associate strongly with particulate materials, bottom sediments can act as metal accumulators during periods of low velocities when the riverbed is not being scoured. During such periods, the riverbed is a depository for incoming sediments, and these, as well as the sediment already in place, can serve as scavengers of dissolved metals from the passing water. Bottom sediments collected during a stable low-flow condition thus provide the opportunity to obtain information on the presence and distribution of metals over an extended period of time. Such information can be used to delineate areas of anomolously high concentrations and possible sources.

Sampling sites were selected to provide (1) general coverage of the entire main stem of the Willamette and (2) specific coverage of locations below potential trace-metal sources (table 5).

The objective of field sampling was to obtain sufficient fine-grained material from each site for the laboratory analyses. In the Tidal Reach, satis-

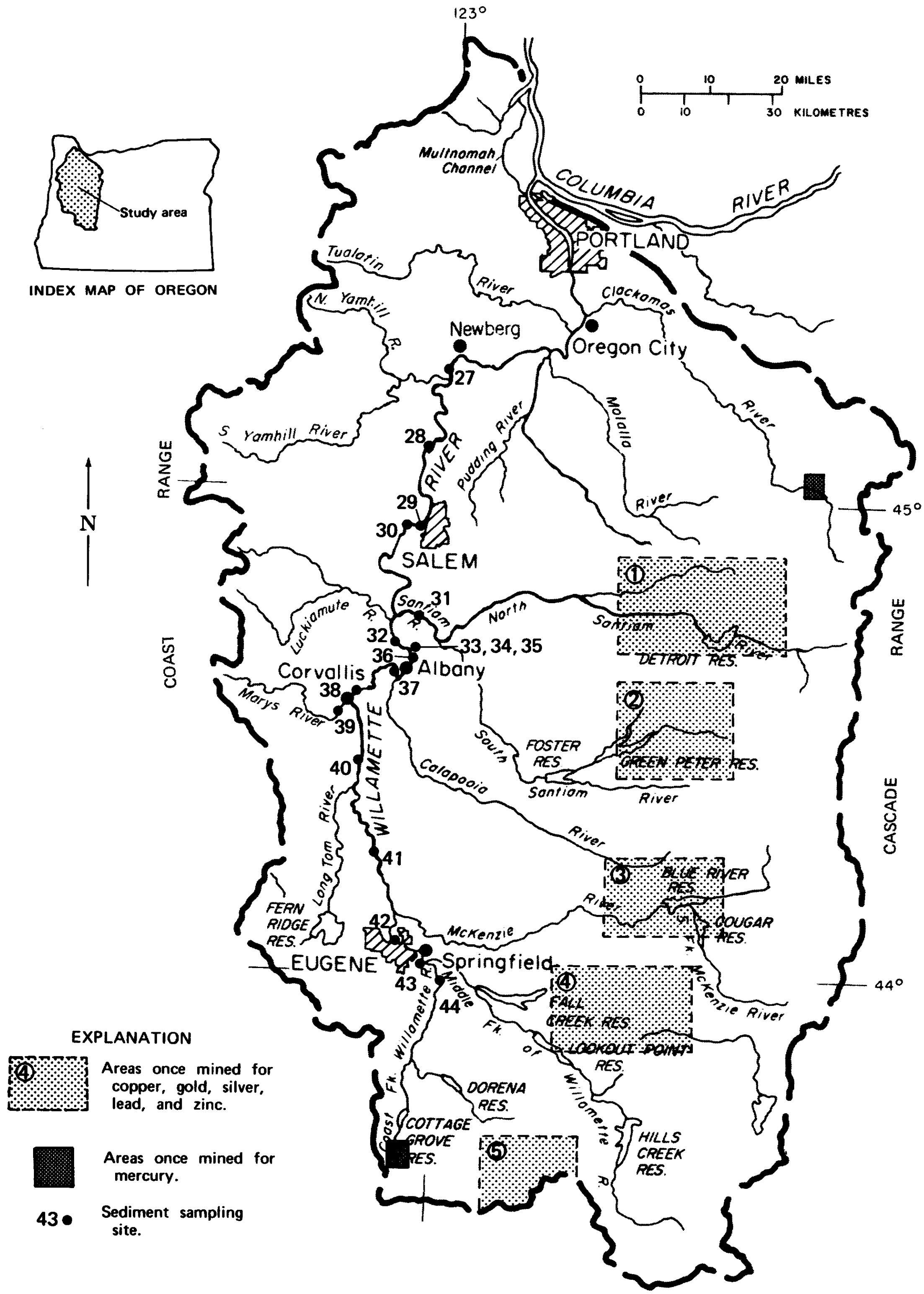

FIGURE 19.—Willamette River basin, Oreg., showing sediment sampling sites in the Upstream Reach and historical mining areas.

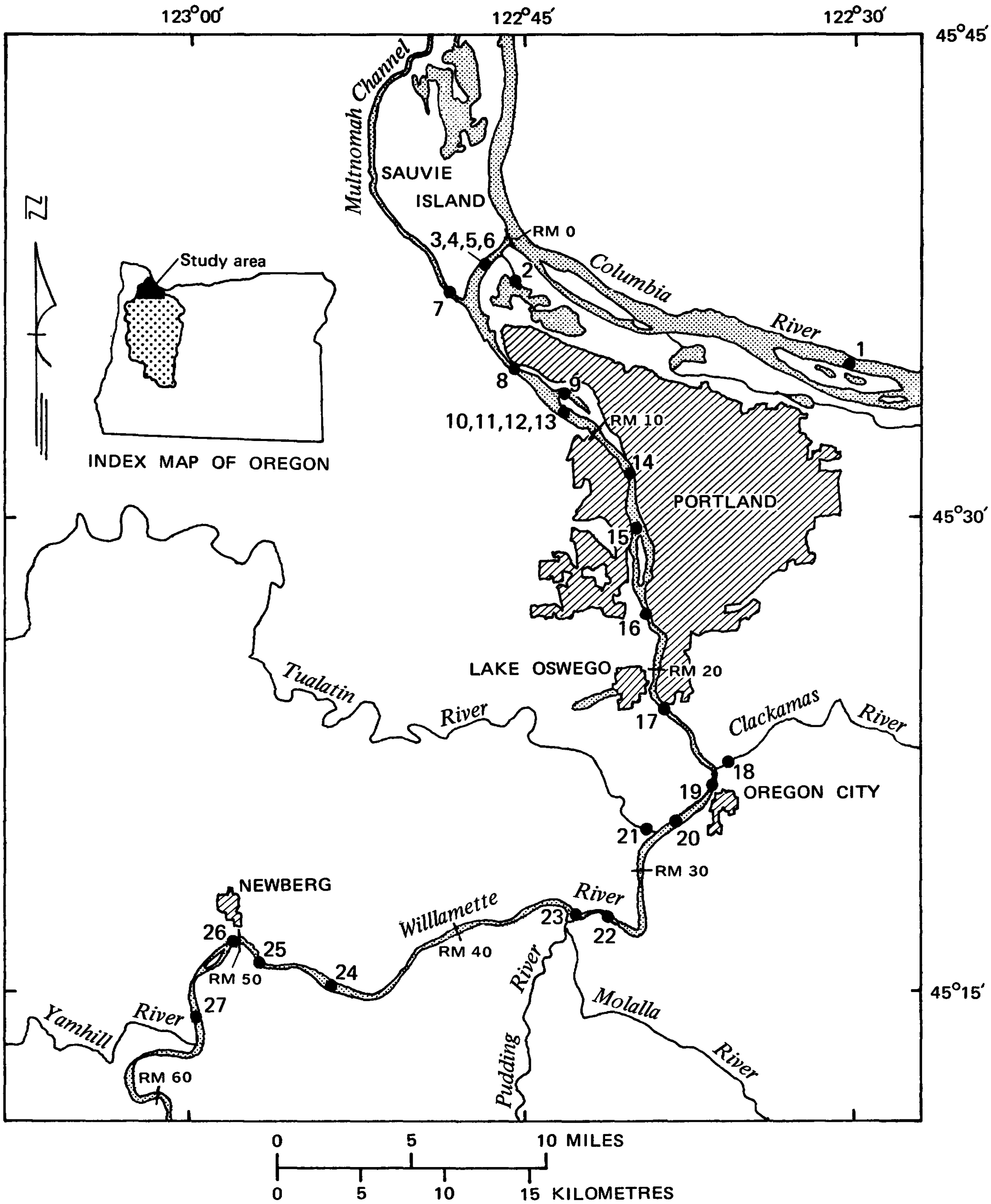

FIGURE 20.—Sediment sampling sites in the Tidal Reach and Newberg Pool.

factory samples were obtained with a Petersen dredge by compositing two or more bites at the visual center of flow. The center of flow was used in preference to the center of the cross section because, in many subreaches, the channel and most of the flow is near one bank. At each location, the specific sampling site was determined by combining information provided by aerial photographs (U.S. Army Corps of Engineers, 1973) with information attained by visually estimating the discharge at various points in the cross section.

In many upstream subreaches, the riverbed is almost completely covered with gravel. In these locations, the sampling approach consisted of searching with an Ekman dredge for small areas of fine-grained sediments. Thus, the samples are unrepresentative of the channel-bed materials. This sampling approach simply uses the fine materials in bottom sediments as a natural trace-metal concentrator to determine the relative occurrence of trace metals in each subreach.

Bottom-sediment samples were collected from 44 sites (figs. 19 and 20) in late September 1973 after a period of more than 4 months of steady low flow. Thirty-one samples were taken from the Willamette River and 13 from tributaries, sloughs, and other adjacent waters.

Geographically, 19 of the sites were associated with the 26.5 mi (42.6 km) Tidal Reach (see fig. 3 and table 1), 7 with the 25.5 mi (41.0 km) Newberg Pool, and 18 with the 135 mi (217 km) Upstream Reach. The sampling density was designed to be greatest in the Tidal Reach because this section of the river is the most highly urbanized and, as previously noted, the subreach between RM's 10 and 3 is the primary depositional area of the Willamette River system.

LABORATORY PROCEDURES AND RATIONALES

PHYSICAL PROCEDURES

Laboratory procedures are described in considerable detail in Chapter F. However, a brief synopsis of the procedures is needed here to provide a basis for presenting and discussing the results.

Prior to analysis of samples for metals, the 44 samples were size fractionated. First, the samples were sieved through a 2-mm sieve to exclude gravel-sized materials. Then, part of the <2-mm materials of each sample was analyzed to determine the percentages of sand, silt, and clay. Finally, another part of each sample was size fractionated at 20 μm to obtain subsamples of very fine sediments.

One reason for obtaining <20-μm fractions was to minimize variations in metal concentrations that normally arise from sample-to-sample differences in the proportion of fine-grained materials. Data presented in Chapter F show that this objective was attained and that the metal concentrations in the <20-μm fractions thus provided a sensitive comparative basis for detecting trace-metal pollution.

A second reason for fractionating the samples was that the <20-μm materials are roughly comparable in grain size to claystones and shales, and also to the fine-grained fractions of soils. Fractionation at 20 μm thus provided a basis for comparing the trace-metal results to existing geochemical data.

ANALYSIS OF METALS

Fifty elements were investigated using a six-step semiquantitative emission-spectrographic method developed for geochemical exploration (Myers and others, 1961). Because the analyses were semiquantitative, the emission-spectrographic method was used primarily for the scanning of trace-metal occurrence. The intent of its use was to determine if any of the wide array of investigated metals was present in anomalously high concentrations. Only the <20-μm fractions of samples were analyzed by this method.

Atomic-absorption spectrophotometry was used to determine more quantitatively the concentrations of cadmium, chromium, copper, lead, mercury, silver, and zinc, and colorimetry was used for arsenic. These eight metals were specifically selected for intensive analysis because they are widespread byproducts of man's activities and are potentially toxic to aquatic organisms. The wet-chemical methods used to determine the metals were developed for geochemical prospecting (Ward and others, 1963, and 1969). These methods are less sensitive than others presently available but are adequate for a reconnaissance. Both whole samples (<2 mm) and the prepared <20-μm fractions were analyzed for the eight metals.

RESULTS

Results obtained by the wet-chemical methods are presented in table 6 for both the <2-mm and <20-μm materials. For easier inspection, the <20-μm results are geographically summarized as averages and ranges in table 7.

The emission spectrographic data agreed with the results reported in table 6. In addition, the data showed that the less common trace metals were present in anomalously high concentrations

TABLE 6.—*Concentrations of trace metals in bottom sediments from the Willamette River and adjacent waters*[1]

[Concentrations[2] in parts per million]

Sample number	Site[3]	<2-mm materials[4]								<20-μm materials							
		As	Cd	Cr	Cu	Pb	Hg	Ag	Zn	As	Cd	Cr	Cu	Pb	Hg	Ag	Zn
1	Columbia River	10	1	65	5	5	0.15	<0.5	75	20	4.5	60	95	70	0.90	1.5	460
2	Columbia Slough	10	1	80	10	5	.17	< .5	140	20	2	60	35	35	.11	.5	270
3	1.5	10	.5	85	10	20	.10	< .5	195	10	2.5	80	40	40	.13	.5	340
4	1.5	<10	.5	90	10	20	.27	< .5	210	10	2	50	40	40	.09	.5	350
5	1.5	<10	.5	100	15	10	.09	< .5	215	10	1	70	45	40	.10	.5	340
6	1.5	20	1	90	15	10	.08	< .5	215	20	2	60	40	35	.03	.5	340
7	Multnomah Channel	20	.5	55	5	5	.08	< .5	150	20	1.5	60	35	35	.07	.5	370
8	6.0	10	.5	55	5	10	.14	< .5	145	20	1	60	45	40	.14	.5	310
9	Swan Island Channel	20	1	70	25	35	.11	< .5	215	20	1	50	60	35	.12	.5	315
10	8.5	10	.5	80	15	10	.11	< .5	185	10	1	50	40	25	.03	.5	260
11	8.5	10	.5	75	15	30	.08	< .5	225	10	1	50	40	35	.03	.5	315
12	8.5	10	1	65	10	20	.13	< .5	205	10	1	50	35	40	.22	.5	335
13	8.5	10	.5	70	15	20	.20	< .5	180	10	.5	60	40	35	.31	.5	260
14	11.7	10	.5	55	5	5	.10	< .5	155	10	1	50	50	90	.34	1	445
15	13.7	10	1	65	10	15	.10	< .5	175	10	1	60	50	40	.18	1	395
16	17.0	10	.5	70	10	20	.19	< .5	225	10	1	50	45	25	.05	1	470
17	21.1	10	.5	60	10	10	.16	< .5	215	20	.5	60	55	40	.20	1	1215
18	Clackamas River	10	.5	90	5	5	.07	< .5	70	10	1	60	30	20	.19	.5	135
19	25.6	10	.5	65	5	10	.08	< .5	180	20	.5	50	70	80	.16	.5	475
20	27.9	10	.5	70	5	5	.08	< .5	140	10	1	50	35	20	.11	.5	295
21	Tualatin River	10	1	65	5	15	.17	< .5	85	10	1.5	60	40	70	.31	.5	245
22	34.1	10	.5	75	10	10	.26	< .5	155	10	1	50	35	20	.26	.5	215
23	34.9	10	.5	70	5	5	.15	< .5	110	20	.5	60	35	20	.16	.5	210
24	45.8	10	.5	65	10	10	.13	< .5	130	10	.5	50	35	20	.27	.5	175
25	48.6	10	.5	75	10	10	.16	< .5	120	10	.5	50	35	30	.24	1	185
26	50.2	<10	1	65	15	20	.12	< .5	130	10	.5	50	35	35	.05	1	145
27	54.0	10	.5	80	15	15	.25	< .5	125	10	.5	50	35	30	.26	1	140
28	69.0	10	1	70	5	5	.14	< .5	85	10	.5	50	35	20	.29	.5	130
29	Boise Cascade Slough	10	1	65	10	60	.14	< .5	145	10	1	50	35	80	.08	.5	165
30	86.7	10	.5	60	10	5	.08	< .5	80	10	.5	60	40	40	.09	.5	140
31	Santiam River	10	.5	60	5	5	.14	< .5	80	10	.5	40	35	25	.05	.5	125
32	112.6	10	.5	80	5	5	.08	< .5	80	10	1	60	30	10	.09	.5	135
33	Head-Fourth Lake	40	1	95	30	65	.12	< .5	190	10	1	80	95	80	.12	4.5	185
34	Middle-Fourth Lake	60	1	75	30	100	.80	< .5	185	10	.5	80	95	120	.09	3	185
35	Fourth Lake near confluence	<10	.5	80	15	15	.16	< .5	110	10	.5	50	45	25	.02	1	130
36	117.0	10	.5	75	10	5	.20	< .5	110	10	1	50	35	20	.38	.5	145
37	120.0	10	.5	70	5	10	.08	< .5	90	20	1	50	30	15	.31	.5	130
38	130.1	10	.5	85	10	5	.12	< .5	95	10	1	50	30	15	.25	.5	115
39	Marys River	10	.5	135	10	5	.18	< .5	100	10	.5	100	55	15	.10	.5	130
40	141.3	10	.5	75	5	5	.08	< .5	100	10	1	50	35	35	.29	.5	160
41	161.2	10	.5	80	5	10	.26	< .5	85	10	1	60	30	45	.13	.5	175
42	178.1	10	.5	65	5	5	.04	< .5	60	10	1	50	30	25	.30	.5	145
43	185.3	10	.5	65	5	10	.11	< .5	80	20	1	50	40	70	.17	.5	120
44	Coast Fork	10	.5	75	15	35	.08	< .5	140	20	.5	50	40	40	.10	.5	120

[1]Samples collected September 18–29, 1973. All analyses by atomic absorption spectrophotometry and colorimetry.
[2]Concentrations are in units of milligrams of metal per kilogram dry sediment which equals parts per million by weight (ppm).
[3]Numbers refer to river-mile locations.
[4]The <2-mm materials include the <20-μm fraction.

in only a few samples. The emission spectrographic data are presented in the appendix of Chapter F and are referred to briefly in the following discussions.

DISTINCTION BETWEEN NATURAL BACKGROUND AND POLLUTION

If trace metals in Willamette sediments represented only natural or unpolluted conditions, the concentrations might be expected to follow either a normal or a log-normal distribution (Levison, 1974). Furthermore, because the fine bottom sediments are derived primarily from the weathering of two chemically related rock types (andesite and basalt), the natural concentrations of the metals might be expected to be distributed as one statistical population.

To test these assumptions and to distinguish polluted from unpolluted conditions, the concentrations of chromium, copper, lead, mercury and zinc in the <20-μm materials were plotted on probability papers according to the method described by Velz (1970, p. 522–542). Plots were not prepared for arsenic, cadmium, nor silver because the determined concentrations were uniformly low (see table 6). In preparing the plots, the Columbia River sample was excluded, providing a total of 43 data points (concentrations) for each metal.

Examination of the completed plots showed that the metal concentrations more closely conformed to a normal rather than a log-normal distribution. Normal-probability plots were thus used as the basis of the interpretive approach, and the most interesting results were obtained for zinc, lead, and copper.

TABLE 7.—*Geographic distribution of trace-metal concentrations in the <20-μm materials of bottom sediments from the Willamette River and adjacent waters*[1]

[Concentrations in parts per million]

Metals	All Willamette River basin samples (4)[2]	Main stem Willamette River: Main stem, river miles 0–187 (31)[2]	Main stem Willamette River: Tidal Reach, river miles 0–26.5 (14)[2]	Main stem Willamette River: Newberg Pool, river miles 26.5–52 (6)[2]	Main stem Willamette River: Upstream Reach, river miles 52–187 (11)[2]	Tributaries[3]	Off river sloughs and channels[4]	Fourth Lake[5]	Columbia River[6]
Arsenic:									
Range	10–20	10–20	10–20	10–20	10–20	10–20	10–20	------	------
Average	13	12	13	12	12	12	18	10	20
Cadmium:									
Range	0.5–2.5	0.5–2.5	0.5–2.5	0.5–1.0	0.5–1.0	0.5–1.0	1.0–2.0	0.5–1.0	------
Average	1.0	1.0	1.2	0.7	0.9	0.8	1.4	0.7	4.5
Chromium:									
Range	40–100	50–80	50–80	50–60	50–60	40–100	50–60	50–80	------
Average	57	55	57	52	53	62	55	70	60
Copper:									
Range	30–95	30–70	35–70	------	30–40	30–55	35–60	45–95	------
Average	42	39	45	35	34	40	41	78	95
Lead:									
Range	10–120	10–90	25–90	20–35	10–70	15–70	35–80	25–120	------
Average	38	35	43	24	30	34	46	75	70
Mercury:									
Range	0.02–0.38	0.03–0.38	0.03–0.34	0.05–0.27	0.09–0.38	0.05–0.31	0.07–0.12	0.02–0.12	------
Average	0.16	0.18	0.14	0.18	0.23	0.15	0.10	0.10	0.90
Silver:									
Range	0.5–4.5	0.5–1.0	0.5–1.0	0.5–1.0	0.5–1.0	------	------	1.0–4.5	------
Average	0.8	0.6	0.6	0.7	0.5	0.5	0.5	2.8	1.5
Zinc:									
Range	115–1295	115–1295	260–1295	145–295	115–175	120–245	165–370	130–185	------
Average	249	269	419	204	140	151	280	167	460

[1]Individual values reported in table 6.
[2]Number of samples.
[3]Samples 19, 21, 31, 39, and 44.
[4]Samples 2, 7, 9, and 29.
[5]Samples 33, 34, and 35.
[6]Sample 1.

ZINC

The normal-probability plot of zinc concentrations (<20 μm) defines a two-stage curve with a sharp break at 145 ppm (fig. 21a). The lower segment of the curve represents 15 samples and the upper segment 27 samples; the value of 1,215 ppm at RM 21.1 (table 6) stands by itself far off the upper end of the scale.

From foreknowledge of the potential sources of zinc pollution (see table 5), it was expected that samples collected downstream from the pulp mill at RM 49.2 would show higher concentrations than those taken from farther upstream. This is confirmed by figure 21A, because all the 15 samples represented by the lower segment were collected above RM 50. The concentrations of these samples were replotted in figure 21B, and a well-defined normal distribution was formed, as evidenced by the straight-line fit.

Spatially, the increased levels of zinc in the Newberg Pool and the Tidal Reach correspond to the locations of the three ground-wood pulp mills (compare tables 5 and 6). The especially high concentrations between RM's 25.6 and 11.7 were below the outfalls of the two mills located between RM's 27 to 28.

The combined knowledge of zinc sources and concentrations indicates that the lower segment in figure 21A represents natural background conditions, whereas the upper segment represents polluted conditions. The spatial distribution of concentrations precludes the possibility that the two-stage curve results from areal differences in geochemistry.

LEAD

Lead concentrations (in <20-μm materials), like those of zinc, define a two-stage curve when plotted on normal probability paper (fig. 22A). The lower curve includes concentrations from 10 to 40 ppm and the upper curve concentrations from 45 to 120 ppm. As with zinc, the levels included on the upper segment seem to represent pollution.

In contrast to zinc, the enriched lead concentrations occurred at discrete locations (table 6), rather than in a large downriver zone. Most of the lead-enriched sites were in urban areas, suggesting that the pollution resulted largely from storm

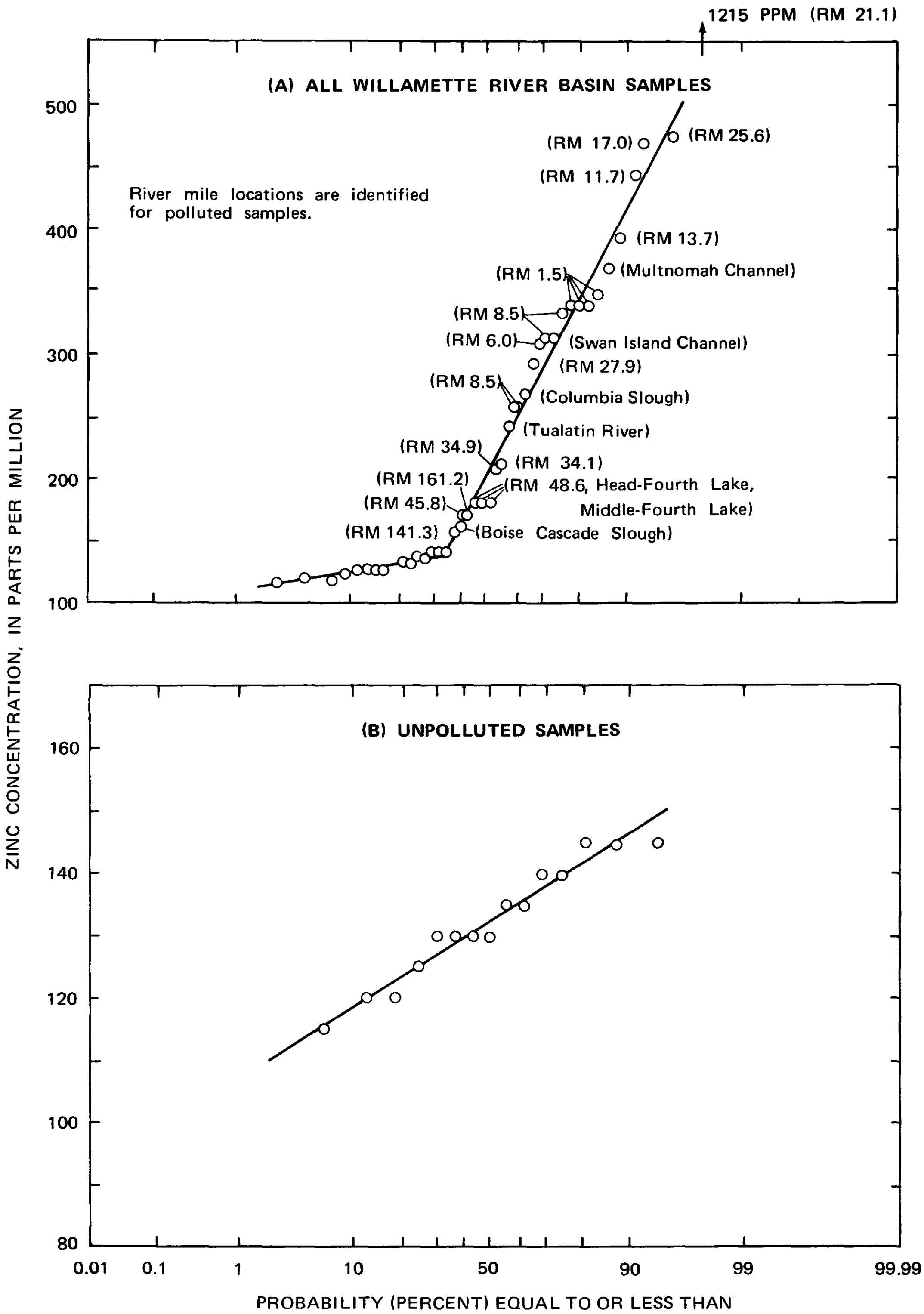

FIGURE 21.—Normal-probability plots of zinc concentrations in less than 20-μm materials.

drainage off streets and roads (see table 5). The high-concentration site at RM 185.3 was within the storm drainage zone of the Eugene-Springfield area, and the sample at RM 161.2 was

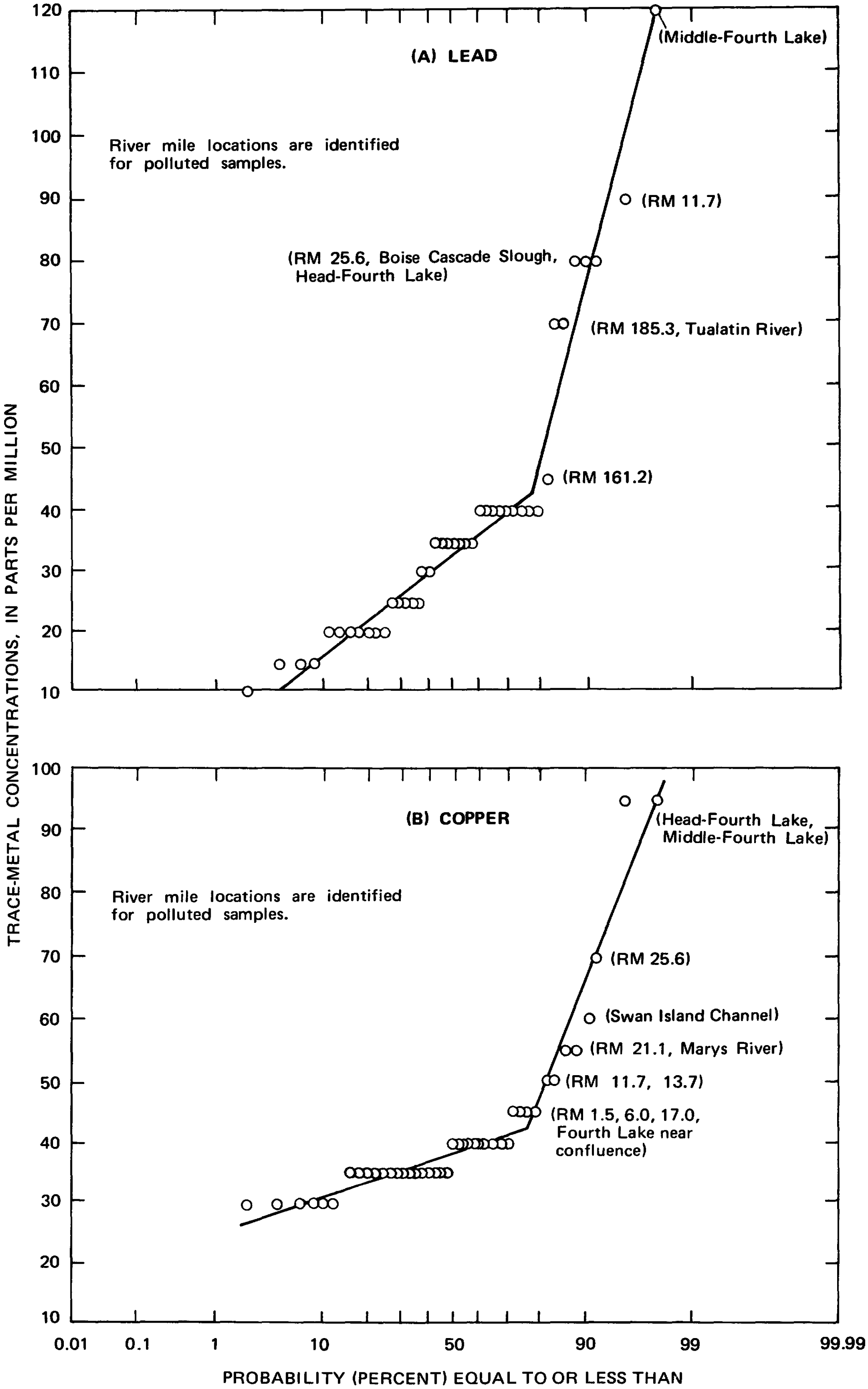

FIGURE 22.—Normal-probability plots of lead and copper concentrations in less than 20-μm materials.

collected near the highway bridge at Harrisburg. In the Tidal Reach, the samples at both RM's 25.6 and 11.7 were collected just below bridges which cross the Willamette.

Other lead-enriched samples were collected from Fourth Lake, Boise Cascade Slough, and the Tualatin River. Boise Cascade Slough receives garbage dump leachate which may account for the elevated lead concentration. Also, the elevated lead content of the Tualatin River sample is consistent with the high degree of urban development in the basin.

Comparison of data in table 6 with possible pollution sources noted in table 5 indicates that all lead concentrations >25 ppm are from sites that receive either urban runoff or storm drainage from roads. Thus, although the probability plot suggests that lead concentrations from 10 to 40 ppm are from one population, the comparison suggests that concentrations >25 ppm might constitute pollution. Moreover, as described in Chapter F, such a delineation is more consistent with lead concentrations in Willamette River basin soils.

Geographically, if we use the 25-ppm value as a breakpoint, zones of lead enrichment occur around Newberg (samples 25 to 27) and in the Tidal Reach (all Tidal Reach samples except RM 17.0). As noted in table 5, the Tidal Reach receives street runoff below RM 27.5, either in the form of urban storm drainage or combined sewer overflows. Samples 25 and 26 from near Newberg were collected from a subreach which receives urban runoff. In addition to the two zones, lead enrichment would be designated at RM 86.7 (sample 30), which is adjacent to a highway, and at RM 141.3 (sample 40), which is just below the village of Peoria.

The 25-ppm breakpoint seems to be reasonable because all samples designated as enriched (≥30 ppm) were collected from sites which received urban drainage. In contrast, nearly all samples designated as unpolluted (lead concentrations ≤25 ppm) were collected from locations which were away from the direct influence of urban drainage.

COPPER

The plot of copper concentrations on normal probability paper is best fitted by a two-stage curve (fig. 22B). The geographic locations of samples on the upper curve are suggestive of pollution. The locations include Fourth Lake (3 samples), the Marys River, a zone between RM's 11.7 and 25.6 (samples 14, 15, 16, 17, and 19 in table 6), and Swan Island Channel plus the immediate downstream site (RM 6.0). The Marys River sample also contained relatively high concentrations of chromium, cobalt, nickel, and vanadium (see Chapter F). The high copper concentrations between RM's 11.7 and 25.6 coincide with the zone of high zinc concentrations (fig. 21A), and with elevated levels of lead (fig. 22A). The cause of the elevated copper concentrations in this zone is unknown, but possible sources (table 5) include municipal secondary effluents in addition to the urban drainage and the pulp and paper mill effluents.

FOURTH LAKE

The sediments from sites 33 and 34 in Fourth Lake were oily, black, odorous, and composed entirely of clay and silt-sized materials. In contrast, sample 35, collected near the confluence of Fourth Lake with the Willamette, showed indications of mixing with coarse river sediments. In reporting the trace-metal data (table 8), the concentrations at sites 33 and 34 are averaged, and the values at site 35 listed separately. For comparison, table 8 also lists the average and model concentrations of each metal in the other Willamette River basin samples.

Table 8 indicates that the Fourth Lake samples were polluted by a large number of metals. Of the total list of enriched metals, the following 12 can be associated with processes at Teledyne-Wah Chang (see section "Possible Sources of Trace Metals"): chromium, hafnium, lanthanum, molybdenum, nickel, niobium, scandium, silver, tin, ytterbium, yttrium and zirconium.

Arsenic, copper, lead, mercury, and zinc were also enriched, but the sources of these metals are unknown. The arsenic and mercury enrichments occurred only in the <2-mm materials.

Although Fourth Lake was heavily polluted, the sample (32) collected just downstream at RM 112.6 (table 6) showed no enrichment of any of the listed metals. Moreover, none of the special metals discharged by Teledyne-Wah Chang were determined at enriched levels in any downstream sample. Thus, it appears that metals discharged into Fourth Lake precipitate and stay within the slough, at least under low-flow conditions. If the metals do flush from the slough at high flows, they must (1) flush entirely from the basin, (2) be diluted to background levels, (3) be annually buried at depths greater than those sampled in the study (improbable), or (4) be affected by some

TABLE 8.—*Concentrations, in parts per million, of trace metals in Fourth Lake*

Atomic absorption spectrophotometry and colorimetry

Metal	Average of samples 33 and 34	Sample 35	Average for other Willamette River basin samples[1]
	<2–mm materials		
Arsenic	50	<10	12
Cadmium	1.0	.5	.6
Chromium	85	80	74
Copper	30	15	10
Lead	83	15	16
Mercury	.46[2]	.16	.15
Silver	<.5	<.5	<.5
Zinc	188	110	142
	<20–μm materials		
Arsenic	10	10	13
Cadmium	.8	.5	1.0
Chromium	80	60	57
Copper	95	45	42
Lead	100	25	38
Mercury	.10	.02	.16
Silver	3.8	1.0	.8
Zinc	185	130	249

Emission spectroscopy

Metal	Range of samples 33 and 34	Sample 35	Modal value for other Willamette River basin samples
	<20–μm materials		
Hafnium	500–700	150	<100
Lanthanum	50	<50	<50
Molybdenum	7–10	3	<3
Nickel	50	50	30
Niobium	200	70	<10
Scandium	50–70	50	30
Tin	150–200	20	<10
Ytterbium	20–50	15	3
Yttrium	200–300	70	30
Zirconium	15,000–20,000	7,000	200

[1]Forty samples (excluding Columbia River sample).
[2]This value is dominated by the concentration of 0.80 ppm in sample 34.

combination of these possibilities. Further work is needed to determine if Fourth Lake is actually a year-around sink of incoming metals and, if so, whether the capacity for storage is still very large or possibly nearing its limit.

SUMMARY AND CONCLUSIONS

Trace-metal concentrations determined in this study indicated a clean environment with the exception of a moderate enrichment of zinc, slight enrichment of copper and lead, and pollution by several metals in Fourth Lake.

The zinc enrichment resulted primarily from use of zinc hydrosulfite as a brightening agent in three ground-wood pulp and paper mills. As a result of orders from the Oregon DEQ, the mills will cease using zinc hydrosulfite by July 1977. The lead enrichment appeared to be tied directly to urban drainage, but no specific source was identified for copper. Fourth Lake, an industrial slough, showed enrichment of 15 elements including uncommon metals such as zirconium, hafnium, yttrium, ytterbium, and tin. However, none of these metals was present in enriched concentrations at any downstream site.

The study results suggest that no metals were present in the Willamette River at concentrations which might represent an immediate ecological threat. However, from a resource management standpoint, further studies are needed to determine (1) how zinc concentrations in the Tidal Reach respond to the ban on zinc hydrosulfite, (2) the amount of lead entering the river in urban drainage and combined sewer overflows, and (3) the ultimate fate of metals discharged to Fourth Lake. Answers to these questions still will not define the relationship of trace-metal concentrations in Willamette sediments to possible long-range potentials for toxic effects. It is hoped that basic knowledge of aquatic ecosystems will advance rapidly in the near future so studies can be initiated in the Willamette and in other United States rivers to assess this critical relationship.

IMPACT OF LAND-USE ACTIVITY ON EROSION AND DEPOSITION

BACKGROUND

The Willamette River at high flow is sediment laden, and man's activities, such as logging, construction, and agriculture, are primarily responsible (Willamette Basin Task Force, Appendix G, 1969). The economic costs include dredging (especially Portland Harbor) for navigation, increased costs of water treatment, and the loss of spawning and feeding areas for fish. In addition, man's activities in the basin sometimes trigger large-scale land deformations such as gullies, landslides, and streambank failures. Such deformations often ruin the land for further intended use and result in large costs for clean-up and restoration. The deformations also release additional quantities of sediment to tributary streams and thus eventually to the mainstem of the river.

Projections for the Willamette River basin indicate a great increase in population and industry over the next 50 years. Large acreages of land now in forest and agricultural use will be urbanized. In addition, vast areas of forest land will be logged for Oregon's pulp and paper industries. The potential impacts of these activities on land and river quality have not been appraised.

The quality of a river is largely determined by the interaction between climate, basin-terrain characteristics, and land-use activity. At present, the controlling interrelationships are poorly defined because of (1) inadequate recognition of the linkages between land-use activity and river quality and (2) until recently, lack of a suitable basis for synoptic terrain analysis of entire river basins.

In the Willamette River basin, an integrated assessment is urgently needed of how different land uses affect the quality of water resources. The first requirement of such an assessment is a method for delineating the erosional impacts associated with different land-use activities on different types of terrain.

ASSESSMENT APPROACH

A new procedure was applied in the Willamette River basin to define the relationships between terrain properties, land-use activities, and erosional problems. The procedure was based on interpretive mapping and derived from approaches used to delineate erosional problems in the San Francisco Bay area (Brown and Jackson, 1973 and 1974).

The premises of the procedure were: (1) climate and terrain properties determine the potential erodibility of land in its natural state, (2) land-use activities represent cultural disruptions of terrain surfaces, and (3) different combinations of terrain properties and land-use activities result in different types and severities of erosional-depositional problems. The procedure was used to first produce an erosional-depositional province map and then to prepare an erosional-impact matrix for direct use by basin planners. Details of the procedure are given in Chapter L, and its subsequent application to the Willamette River basin is described in a report presently being prepared under the direction of J. D. Meyers (referenced here as a written communication because it has not been approved for publication).

As a basis for developing the map and matrix, an up-to-date photomosaic base was needed at a scale suitable for recognition of natural and altered surface-cover conditions. The scale selected for the regional scope objectives of this study was 1:130,000 (see Chapters C and L). The mosaic was prepared from high altitude photographs taken by the U.S. National Aeronautics and Space Administration (NASA) during July 1973.

DEVELOPMENT OF THE EROSIONAL-DEPOSITIONAL PROVINCE MAP

COLLATION OF CRITICAL TERRAIN FACTORS

A small section of the basinwide erosional-depositional province map is shown in figure 23. The first step in producing the map was to select carefully and then integrate the physical factors that exert the greatest control on terrain-surface stability. This work was based on the province concept as formulated by Brown and Jackson (1973 and 1974).

THE PROVINCE CONCEPT

As noted in the "Geologic Overview," the Willamette River basin can be divided into three north-south physiographic units: the Cascade Range, the Coast Range, and the Willamette Valley. These units can be considered as large erosional-depositional provinces, with the Coast Range on the western side and the Cascade Range to the east being dominated by erosional processes, and the centrally located Willamette Valley dominated by depositional processes.

For our purposes, these regional physiographic divisions were further subdivided for better definition of erosional cause-effect phenomena and for application to environmental planning. The delineation process was based on development of criteria for identifying distinctive erosional and despositional provinces.

PROVINCE CRITERIA

The criteria for delineating erosional-depositional provinces were based on the de-

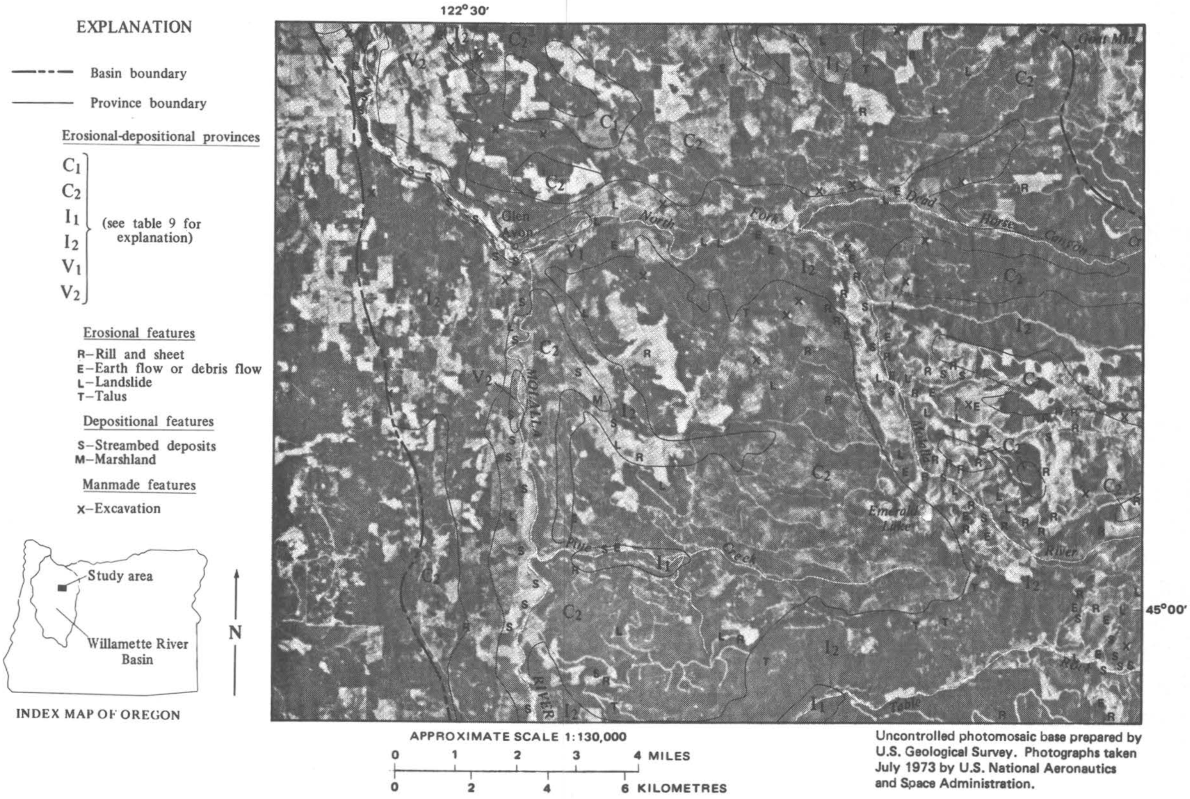

FIGURE 23.—Erosional-depositional provinces in part of the Molalla River subbasin, Oreg.

velopment of hypotheses concerning the controlling influence of different physical factors on terrain-surface stability. The investigated factors were vegetation, precipitation and runoff, soils, geology, and slope.

The hypotheses for evaluating these factors were tempered by four overriding considerations: (1) the primary objective of the study as a regional overview of the major processes and problems of the sediment system, rather than as a comprehensive geomorphic investigation suited for site-specific interpretations, (2) the need for a simple, practical product that is understandable by planners and compatible with the 1:130,000-scale photomosaic base, (3) the large variability in quality, quantity, and scale of existing earth-resource data and maps, and (4) the extensive background of observations, publications, and knowledge concerning the functions, relationships, and relative importance of the major factors affecting the sediment system.

In concert, these four considerations dictated that the hypotheses be (1) general and not overly concerned with minor terrain anomalies and special, localized conditions, (2) suited to the identification of a small number of erosional and depositional mapping units (not more than ten) so as to minimize confusion and clutter on the photomosaic base, (3) compatible with the quality, quantity, and resolution of available earth-resource information, and (4) consistent with accepted scientific fact and reason.

Each of the developed hypotheses is briefly stated below. (Detailed descriptions are provided in Chapter L with regard to rationale, substantiation, qualifications, and possible refinements.)

Vegetation.—The extensive surface cover and soil-holding characteristics afforded by natural vegetation allow only minimal erosion. Only when vegetation is removed by man's land-use activities can severe erosional problems develop.

Precipitation and runoff.—As to their regional impact on the sediment system, the precipitation and runoff regimes can be considered generally constant throughout the Willamette River basin.

Soils.—Insofar as susceptibility to erosion is concerned, the soils of the Willamette River basin are considered generally homogeneous. The exception is the highly erodible soils developed on the geologically defined lacustrine and loessial Upland Silt Deposits (see below).

Geology.—For purposes of this study, the valley floor of the Willamette River basin was considered an area dominated by depositional processes and was classified into two basic categories: the Valley Floodplain Alluvium and the Valley Terrace Alluvium. The upland area of the Willamette basin consisting of the valley buttes, foothills, and mountains of the Coast and Cascade Ranges is dominated by erosional processes and was classified into three basic categories according to the susceptibility of the rock units to fluvial erosion and mass wasting. The three categories are: The Upland Silt Deposits, which locally mantle the buttes and foothills of the northern part of the valley; the Incompetent, or weakly coherent, Bedrock units, which are prone to slope failure; and the Competent, or strongly coherent, Bedrock units, which make up the higher ridges and steep peaks of the mountain areas.

Slope.—A slope of 12 percent demarks the approximate boundary between upland terrain, that is predominantly erosional, and lowland terrain, that is predominantly depositional. This criterion was used to distinguish two erosional provinces in each of the three upland geologic categories.

Thus, on the basis of the stated hypotheses, geology and slope were determined to be the critical criteria for defining erosional-depositional provinces. These two factors were used to identify the six erosional and two depositional provinces defined in table 9.

PROVINCE DELINEATION

From the defined criteria for geology and slope, the six erosional and two depositional provinces (table 9) were delineated throughout the Willamette River basin. As an example, figure 23 includes the two depositional provinces (V_1 and V_2) and four of the six erosional provinces (I_1, I_2, C_1, and C_2).

The eight provinces were delineated using the overlay approach. First, generalized geologic and soils maps of the basin were optically enlarged and scale matched to the photomosaic base (Vickers and others, 1976). Floodplain and terrace alluvium units were then outlined to identify the two depositional provinces. Next, the Upland Silts and the Incompetent and Competent Bedrock groups were outlined. Finally, a scale matched slope map was used to separate the Silt, Incompetent, and Competent units into <12 and >12 percent slope groups.

Throughout the overlay procedure, aerial photographs and 1:24,000- and 1:62,500-scale topographic maps were used to make adjustments to province boundary lines. This was necessary because slope and geological information was generalized from maps of various scales that did not strictly conform with the semicontrolled 1:130,000 photomosaic base. For this reason, the erosional-depositional provinces in figure 23 (and on the basinwide map) are regional in nature.

TABLE 9.—*Erosional—depositional provinces delineated in the Willamette River basin, Oreg.*

Map symbol	Geologic group	Slope (percent)
	Erosional provinces [1]	
	Upland Silt Deposits:	
S_1	Sloping uplands	<12
S_2	Steep uplands	>12
	Incompetent Bedrock:	
I_1	Sloping uplands	<12
I_2	Steep uplands	>12
	Competent Bedrock:	
C_1	Sloping uplands	<12
C_2	Steep uplands	>12
	Depositional provinces	
	Valley Alluvium:	
V_1	Floodplains	<3
V_2	Terraces	>12

[1]Erodibility increase from unit C_2 through S_1.

MAPPING OF EROSIONAL-DEPOSITIONAL FEATURES

The second step in producing the map was the delineation of existing erosional-depositional features. The continual erosion, transport, and deposition of sediment in the basin is manifested most dramatically by formation of features such as gullies, landslides, and streambed deposits. The location, density, and size of such features provides visual verification of the interaction of critical terrain factors with land-use activities. Figure 23 shows the location of active erosional and depositional features in part of the Molalla River basin (subbasin of the Willamette) as identified from false-color, infrared (IR) aerial photographs. In the map of the entire basin, three categories and 10 individual features are identified (table 10). These features are described by Meyers and others (written commun., 1976), and the technique by which the features were located and verified is presented in Chapter L.

DEVELOPMENT OF THE EROSIONAL-IMPACT MATRIX

The completed erosional-depositional province map with accompanying erosional and depositional features (see fig. 23) provides a basic tool for examining the basinwide condition of the sediment system. However, the map's utility for environmental planning was augmented through development of an erosional-impact matrix (table 11.) The matrix provides a systematic basis for making predictive estimates of the relative impact, in terms of erosion, of human activity on different types of terrain (provinces). The horizontal axis is composed of weighting factors for slope and geology, and the vertical axis of weighting factors of selected land-use activities. The body of the matrix is composed of erosional-impact ratings, ranging from $<10^{-3}$ to $>10^{3}$, resulting from the product of the three sets of weighting factors.

The rationale for developing the three erosional weighting factors and the subsequent erosional impact ratings is based on (1) the concept of order-of-magnitude differences in annual average sediment yield due to land use–terrain interaction (Judson, 1968) and (2) the universal soil loss equation (see Musgrave, 1947, and Chow, 1964).

LAND USE EROSIONAL FACTORS

Land-use activities in the basin were identified from field-checked interpretation of stereomagnified, false-color IR aerial photographs. Five major categories and 20 individual land-use activities (see table 11) were chosen on the basis of their prevalence and socioeconomic importance in the basin. For purposes of illustration, the activities comprising the categories of agriculture and forestry-logging are described in table 12 along with their associated erosional factors.

The erosional factors were assigned to each land-use activity on the basis of approximate order-of-magnitude differences in sediment-yield potential (Meyers and others, written commun., 1976). The factors were derived from a review of pertinent quantitative studies (including some made in other river basins) and roughly represent order-of-magnitude rates for average sediment yields expressed in tons/acre/yr. As a basis for transferring the quantitative data from studies made outside the basin, it was necessary to compensate for differences in climate and soil type. Thus, in developing the sediment-yield estimates, the Willamette River basin was characterized as having a temperate marine west coast climate with annual precipitation of 35 to 80 in. (890 to 2,030 mm) and a "standard" clay loam soil that is permeable and moderately erodible.

TABLE 10.—*Erosional-depositional features mapped in the Willamette River basin, Oreg.*

Feature	Mapping symbol
Erosional:	
Sheet and rill erosion	R
Gully erosion	G
Landslide	L
Earth flow or debris flow	E
Talus	T
Streambank failure	B
Depositional:	
Streambed deposit	S
Marshland	M
Manmade:	
Excavation	X
Artificial fill	F

SLOPE AND GEOLOGIC EROSIONAL FACTORS

The factors for slope and geology were derived in a similar manner to those for land use. In this case, the empirical judgments were based on (1) a review of available sediment yield data for the Willamette River basin; (2) observations of erosional phenomena by the U.S. Soil Conservation Service (Oregon State Water Resources Board, 1969); and (3) photointerpretation of stereomagnified color IR photography to determine the occurrence and magnitude of different erosional features on different slope and geologic settings. For compatibility with the land use-erosional factors, order-of-magnitude numbers were assigned to each slope and geologic category included in the matrix (table 11).

APPLICATION TO PLANNING

In conjunction with the erosional-depositional province map, the completed matrix provides a means for making tentative estimates of

TABLE 11.—*Matrix for estimating interactive erosional impact of land-use activities with terrain properties of geology and slope, Willamette River basin, Oreg.*

	Slope (percent)	0–3	3–7	7–12			12–20			20–60			>60	
	Slope-erosional factor	10^{-2}	10^{-1}	10^{0}			10^{1}			10^{2}			10^{3}	
	Geologic group[1]	V_1/V_2	V_2/I_1	C_1	V_2/I_1	S_1	C_2	I_2	S_2	C_2	I_2	S_2	C_2	I_2
	Geologic-erosional factor	10^{0}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{-1}	10^{0}	10^{1}	10^{-1}	10^{0}	10^{1}	10^{-1}	10^{0}
	Product[2]	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Land-Use Activity	Land use-erosional factor[3]	Erosional impact rating[4]												
Mature forest	10^{-3}	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	10^{-3}	10^{-2}	10^{-3}	10^{-2}	10^{-1}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}
Managed silviculture or nursery	10^{-3}	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	10^{-3}	10^{-2}	10^{-3}	10^{-2}	10^{-1}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}
Forest regrowth or mixed woods and shrubs	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-1}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}
Helicopter or ballon logging	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-1}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}
Metropolitan (developed)	10^{-2}	$<10^{-3}$	10^{-3}	10^{-3}	10^{-2}	10^{-1}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}
Orchard with groundcover	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Pasture or grassland (light grazing)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Semirural (developed with light farming)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Paved roads (well maintained)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Cable logging	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Powerlines (dirt maintenance road)	10^{-1}	10^{-3}	10^{-2}	10^{-2}	10^{-1}	10^{0}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}
Cropland (row crops)	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Orchard without groundcover	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Pasture or grassland (heavy grazing)	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Gravel roads	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Tractor logging	10^{0}	10^{-2}	10^{-1}	10^{-1}	10^{0}	10^{1}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}
Fallow agricultural land	10^{1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}	$>10^{3}$	10^{3}	$>10^{3}$
Light construction and excavation	10^{1}	10^{-1}	10^{0}	10^{0}	10^{1}	10^{2}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}	$>10^{3}$	10^{3}	$>10^{3}$
Temporary dirt roads (poorly maintained)	10^{2}	10^{0}	10^{1}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}	$>10^{3}$	10^{3}	$>10^{3}$	$>10^{3}$	$>10^{3}$	$>10^{3}$
Heavy construction and excavation	10^{2}	10^{0}	10^{1}	10^{1}	10^{2}	10^{3}	10^{2}	10^{3}	$>10^{3}$	10^{3}	$>10^{3}$	$>10^{3}$	$>10^{3}$	$>10^{3}$

[1]See table 9.
[2]Product of slope- and geologic-erosional factors.
[3]See table 12 for an example.
[4]Ratings are the product of land use-, slope-, and geologic-erosional factors.

Ratings of 10^{-2} or less reflect low erosional impact.

Ratings from 10^{-1} to 10^{1} reflect moderate erosional impact.

Ratings of 10^{2} or greater reflect major erosional impact.

TABLE 12.—*Relative erosional factors associated with agricultural and forestry-logging activities, Willamette River basin, Oreg.*

Land-use activity	Land use-erosional factor	Remarks	References utilized in deriving land use-erosional factor
Agriculture:			
Fallow (bare soil)	10^1	Fluvial erosion is cause of most sediment yield from agricultural areas, except on steeper lands (>12 percent) used for orchards and pasture where mass wasting may also be significant in areas of incompetent rock and unstable soils.	Ursic and Dendy (1965); Wolman (1967).
Cropland (row crops)	10^0		
Orchard, without groundcover crop	10^0		
Orchard, with groundcover crop	10^{-1}		
Pasture or grasslands (heavy grazing)	10^0		
Pasture or grasslands (light grazing)	10^{-1}		
Forestry and logging:		Logging activities remove vegetation, disturb soils, artifically steepen slopes, and cause compaction in areas worked by tractors. Where logs are skidded, soil is laid bare, compacted, and channels formed for rapid runoff. Roads are the most disruptive of all logging practices, particularly in areas of incompetent rock and unstable soils. (Note that: the approximate sediment yields for logging are significantly lower than for construction. This apparent anomaly is due to our assumption, for comparative purposes, of a standard 7–12 percent slope.) Most logging activities occur on slopes between 20 to 60 percent and consequently cause greater sediment yields per unit area than indicated here (J.D. Meyers and others, written commun., 1976).	Ursic and Dendy (1965); Dyrness (1967); Fredricksen (1970) Megahan and Kidd (1972); Kid and Kochenderfer (1973)
Ten-year old regrowth or mixed woods and shrubs (old logging roads partially overgrown)	10^{-2}		
Mature forest (no roads)	10^{-3}		
Managed silva-culture, mature nursery	10^{-3}		
Tractor logging (10–20 lineal mi/mi² of logging roads)	10^0		
Cable logging (1–4 lineal mi/mi² of logging roads)	10^{-1}		
Helicopter or balloon logging (1 lineal mi/mi² of logging roads)	10^{-2}		

the erosional impact of human activities on various lands in the basin. The following sequence of steps provides a guide for using the map and matrix:

(1) Locate the parcel of land for which a particular land-use activity, or set of activities, has been proposed.

(2) Identify the province in which the proposed activity would occur and examine the prevailing patterns of land-use activities and erosional features. The existence, or absence, of erosional features and their type will indicate to some degree the possible magnitude of erosional impact in terms of land deformation that would be generated by the proposed change in land-use activity.

(3) Note the prevailing geologic and slope conditions for the area in question by cross referencing (a) the province (for example, I_2) within which the parcel of land is enclosed with (b) the geologic and slope criteria shown in table 11.

(4) Enter the matrix body under the specified combination of slope, geology, and land-use activity. Note the appropriate erosional-impact number or range of numbers. An impact rated below 10^{-1} indicates minimal potential for erosion. Impacts in the 10^{-1} to 10^1 range indicate that moderate to high erosion could be generated and hence that management and/or conservation practices may be required. Impact ratings of $>10^2$ indicate that high to extraordinary erosional impacts are likely to be generated and that the proposed land-use activity should be questioned.

The erosional-impact ratings in table 11 were developed as guidelines for regional planning purposes. High impact ratings do not necessarily mean that a proposed land-use cannot be reasonably undertaken provided stringent conservation and engineering practices are applied. Final judgments as to land-use suitability, particularly for lands receiving ratings above 10^1, should be based on detailed site investigations.

SUMMARY AND CONCLUSIONS

We believe that the map and matrix developed in this study provide the kind of framework needed to develop regional programs for quantitatively defining the effects of land management on river quality. The map is regional in scale and shows where erosional and depositional problems are most prevalent. Using the map, data programs can be spatially designed to better define the cause-effect relationships of land and river processes. The matrix provides the necessary collaborative information for selecting baseline and other comparative areas. Once the spatial framework of a data program is defined, the analysis of climate and streamflow records can be used to determine the optimum timing and frequency of sampling.

Thus, the erosion-potential map and matrix are useful tools for (1) immediate land-use planning and (2) the design of data and research programs. For both purposes, the tools are flexible, because through interpretation of aerial photography, they can be regularly updated to provide information under rapidly changing conditions.

FURTHER STUDIES

The Willamette assessment is the first of three prototype studies being conducted by the Geological Survey. The effects of urbanization on water quality are being analyzed in the Chattahoochee River basin in Georgia, and the potential environmental problems of energy development are being assessed in the Yampa River basin in Colorado-Wyoming. In both studies, information will be developed for assessing specific basin problems. However, as in the present study emphasis will be placed on developing flexible methodologies and data programs that can be used throughout the country.

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