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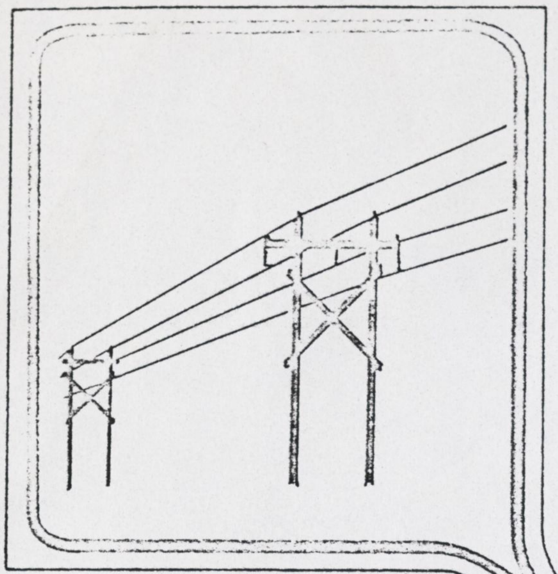
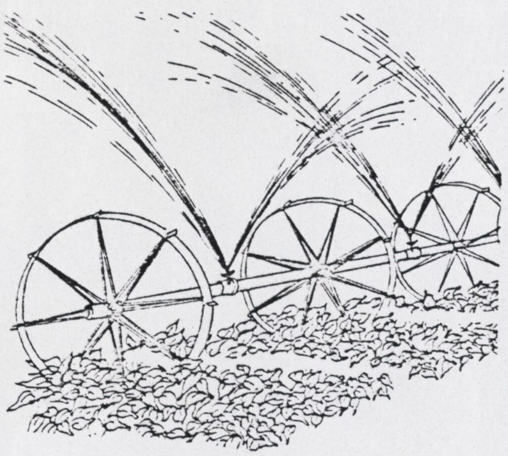


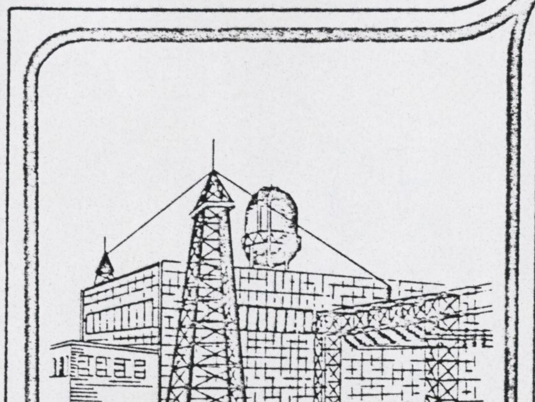
METHODOLOGIES FOR THE DETERMINATION OF STREAM RESOURCE FLOW REQUIREMENTS: AN ASSESSMENT

Edited

by

C. B. Stalnaker
and
J. L. Arnette





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Western Water Allocation

by
Utah State University
Logan, Utah
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FOREWORD

The need for improved methodologies for determining instream flow requirements has long been recognized by individuals and agencies responsible for evaluating proposed water resource development projects. During recent years, this need has become more widely apparent due to our efforts toward energy self-sufficiency. Investigations indicate that the inability to quantify the flow of water that must remain in streams to maintain their dependent natural systems prevents the determination of water availability for non-stream uses. Because these determinations are critical for future water resource planning, it is imperative that improved methodologies are developed as soon as possible.

The Office of Biological Services was established in FY '75 within the Fish and Wildlife Service to provide an ecological capability essential for furnishing decisionmakers with information regarding the environmental aspects of proposed resource development activities. Western Water Allocation, as a major project in the Biological Services' Program, is involved with water use effects on fish, wildlife, and other environmental values. One thrust of the Project includes the development of methodologies and other tools for evaluating the impact of altered streamflow characteristics on ecological systems.

A study and workshop conducted at Utah State University was an initial effort of the Western Water Allocation Project to determine the state-of-the-art of instream flow methodologies. As this report indicates, the adequacy of the methodologies available for determining instream flow requirements varies considerably among uses. Although additional investigation seems to be called for in several areas, this report represents the most comprehensive compilation of methodologies available at this time. It is being released in its present form to provide field workers and planners with an immediate interdisciplinary reference source, and to stimulate a continuing flow of ideas and dialogue. We anticipate that this state-of-the-art report will be updated in the near future to incorporate any new or omitted aspects. Therefore, your comments concerning the present document and suggestions for a revised edition would be greatly appreciated.

Robert P. Hayden,
Project Leader
Western Water Allocation

PREFACE

A developed discipline generally has a considerable fund of codified knowledge at its disposal. When several disciplines confront the same problem, the information base is increased, but is no longer systematic and, as a result, not widely available. In addition, all disciplines have valuable information that exists in forgotten files, as unrelated data and techniques or only in the minds of the practitioners. This is the current status of methodologies for assessing the numerous requirements for instream flows.

Although a number of technical reports dealing with instream flow methodology development and use have been written during the past few years, most described either a single approach in detail or several in a cursory fashion. There has been no single document or series of documents that has compiled and described existing instream flow assessment methodologies. Recognizing this gap in the state of the art and knowledge, the U.S. Fish and Wildlife Service contracted Utah State University to document and evaluate instream flow methodology development in the areas of fisheries, wildlife, water quality, recreation and aesthetics. The following report is the result of this study.

The area of instream flow assessment is rapidly becoming multi-disciplinary in its concerns and problem solutions and will soon require an intense collaborative effort. Workers involved in this collaboration will be immediately confronted with interdisciplinary difficulties that few, because of specialized training, will be prepared to solve. It is the intent and hope of the authors that this document will be a step towards bridging this potentially significant gap.

There is a growing concern among scientists dealing with instream flow problems that work in this area should directly contribute to the solution of practical problems as they arise, or prevent them from ever occurring. Where the material has allowed, and this varies among sections, the authors have emphasized the practicability and feasibility of methodologies and have attempted to indicate those that are not, or cannot be, readily applicable.

It was originally intended that this work provide a complete compilation of methodologies, emphasizing the approaches of agencies, institutions and individuals actually involved in or practicing streamflow management in its various forms. Some of the sections are relatively complete or they provide the basis for additional development. However, certain sections do not describe all appropriate or available methodologies, but emphasize fundamental concepts or particular approaches. Section 2 provides a general overview of hydrologic and hydraulic concepts as they relate to instream flow assessment. The authors of Section 3 present mathematical modeling and nomograph analysis as the primary methods for determining the relationships between water quality and instream flow. Sections 6 and 7 consider the interactions between recreation, aesthetics and instream flow from a sociological and social psychological view, emphasizing attitude scaling techniques. The latter two sections do not evaluate, in any depth, flow assessment methodologies used by landscape architects, outdoor recreationists and resource management agencies. These various orientations may, in the future, prove to be the most appropriate, particularly the modeling approach. However, readers of these sections, especially those from other disciplines, must be aware that the state of the art as it presently exists is not completely represented.

The U.S. Fish and Wildlife Service sponsored an Instream Flow Workshop that was held at Utah State University, Logan, Utah on September 17-19, 1975. The workshop was conducted to evaluate the quality, accuracy and level of comprehensiveness of the second draft of the present document. To accomplish this ambitious objective, the participants (in most cases acknowledged practitioners of various forms of streamflow assessment) gathered in workgroups based on their specialty. To further the document evaluation, various specialty workgroups met and discussed interdisciplinary considerations. This workshop provided considerable individual and collaborative input that certainly raised the quality of the final document.

A work of this magnitude, carried out over a short period of time, requires the cooperation of many people—so many in fact, that it is not possible to acknowledge each of them by name. However inadequate, a "blanket" thank you must suffice for all of those individuals whose contributions provide the "foundation" of this document. Appreciation is extended to all workshop participants, especially the work group chairmen and documentarians, whose efforts provided much toward what success this document may achieve. A special note of appreciation must go to all of the "unsung heroes" of this project: The Utah State University, Conference and Institute Division for organizing the workshop; the USU secretarial staff for typing all of the drafts; and the USU Printing Services for typesetting the final document. This entire project would have never come about without the sponsorship, funding and continued interest of the U.S. Fish and Wildlife Service, especially Robert P. Hayden, Project Leader, Western Water Allocation Project.

C. B. Stalnaker
J. L. Arnette

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INTRODUCTION

C. B. STALNAKER

Aquatic stream systems are declining in quality and extent at a rapid rate in direct proportion to man's development of water resources for domestic, industrial, and irrigation uses and may decline at more rapid rates under proposed energy development programs. Existing and proposed water resource development projects in the western United States will ultimately result in the removal of substantial portions of stream flows during all or specified portions of the year.

Fundamentally, water resource development entails the modification of a natural hydrologic system to meet man's needs. Regardless of the modifications made to certain parts of the system, the equilibrium of the system is changed and other components or elements are affected. Consequently, one of the main questions raised in connection with any water development scheme is: What will be the effect on existing stream systems use?

Changes which may be expected as the result of altering water flow within a stream are complex. This complexity is due, in part, to the great number of interactions which may occur both within the stream environment and external to it.

Often, the claim is made that surplus water can be removed for out-of-channel uses without dramatically affecting the aquatic system. This raises another important question: How much water must remain for the maintenance of viable aquatic ecosystems (water quality, fish, and wildlife) as well as the qualities for aesthetics and recreational use by man?

These relationships, economic and social as well as physical and biological, are so intimate as to require that planning of water development be accomplished on a systems basis. In the application of systems analysis to water resources planning, the first step is to define the system to be analyzed. In water planning, this means the identification of objectives along with associated boundary conditions or constraints. These are then transformed into optimal plans for development. In general, water resources planning is a technique of public investment decision making. Consequently, there has been an upsurge of interest and concern in recent years in water allocation and instream requirements for maintaining the integrity of the aquatic-riparian ecosystem.

The interrelationships among elements of the hydrologic system, though varied and complex, are relatively simple in comparison with the social, legal, economic and institutional interdependencies involved. This report does not attempt to address the problem of balancing the trade-offs between instream and out-of-stream uses of water. Rather, it attempts to summarize and evaluate techniques and methodological approaches to establishing instream flow requirements for fish (and other aquatic life), wildlife, water quality, estuarine inflows, recreation, and aesthetics.

Conflicting requirements among the seven considerations will not be directly discussed in this document. The assumption is made that more equitable and rational decisions can be made relative to conflicting instream use only after the extent of the conflict is established. By adequately assessing the effects of a range of conditions (in this case, different flows) upon each instream use, the possible conflicts may be readily identified and minimized. These interrelationships and the effects of changes in streamflows are shown conceptually in Figure 1. The steps required and factors which must receive consideration in the establishment of instream flow requirements have been summarized by Crutchfield et al. (1973), as shown in Figure 2.

There are a number of Federal Acts which relate to instream uses. Of particular importance are the Fish and Wildlife Coordination Act of 1958 (PL 85-624) and amendments; the Federal Water Project Recreation Act of 1965 (PL 89-72); the Wild and Scenic Rivers Act of 1968 (PL 90-542); the National Environmental Policy Act of 1969 (PL 91-190); the Rivers and Harbors Act of 1970 (PL 91-611); the Federal Water Pollution Control Act and Amendments of 1972 (PL 92-500); and the Endangered Species Act of 1973 (PL 93-205). This legislation has resulted in much more rigorous demands for data gathering, analysis and assessment of fish, wildlife, water quality, and recreation needs in relation to water resources planning.

Further, the Water Resources Planning Act of 1965 (PL 89-80) established the Water Resources Council to coordinate water use planning studies carried out by Federal agencies in cooperation

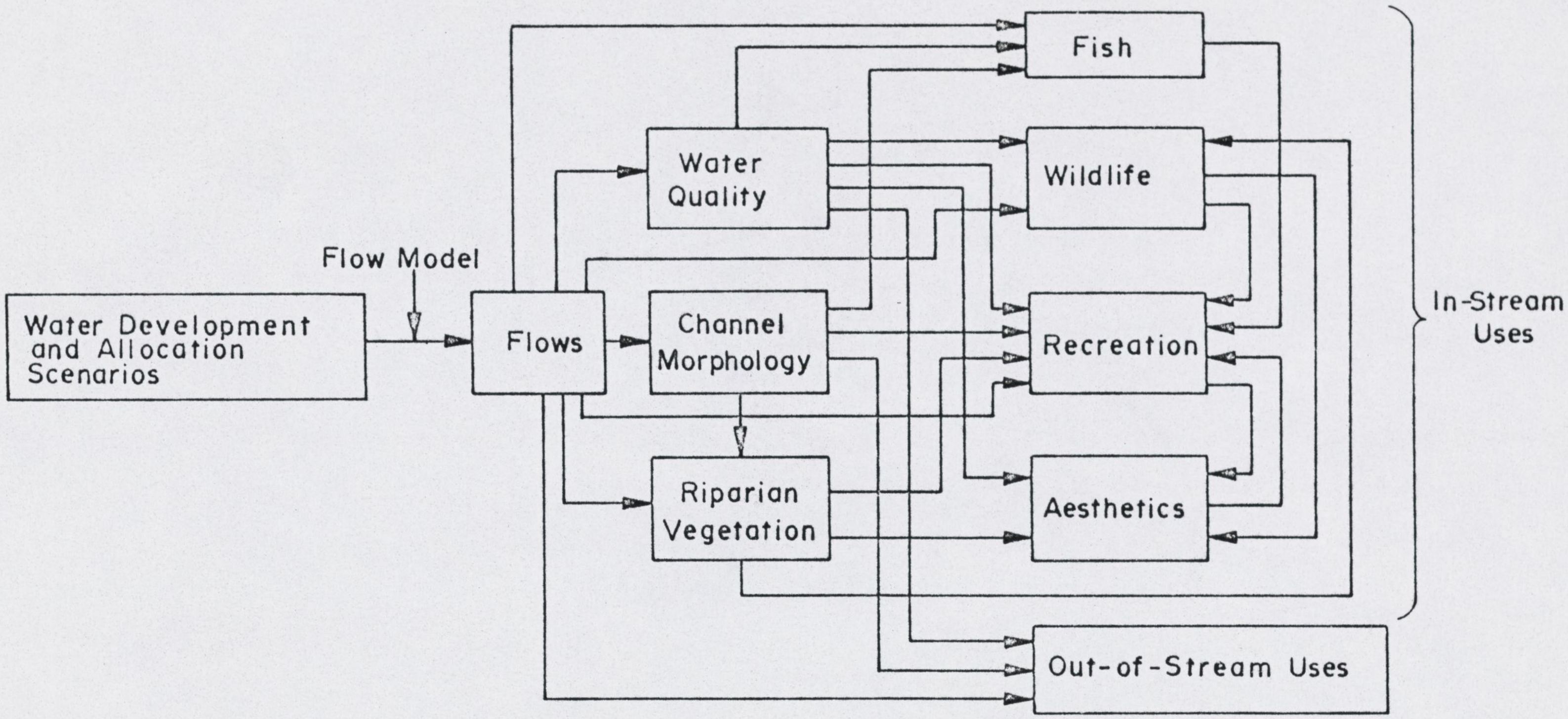


Figure 1. Interrelationships among streamflow uses and dependencies most effected by alterations of flow in a stream system.

Figure 2. Steps in establishing instream flow requirements (from Crutchfield et al. 1973).

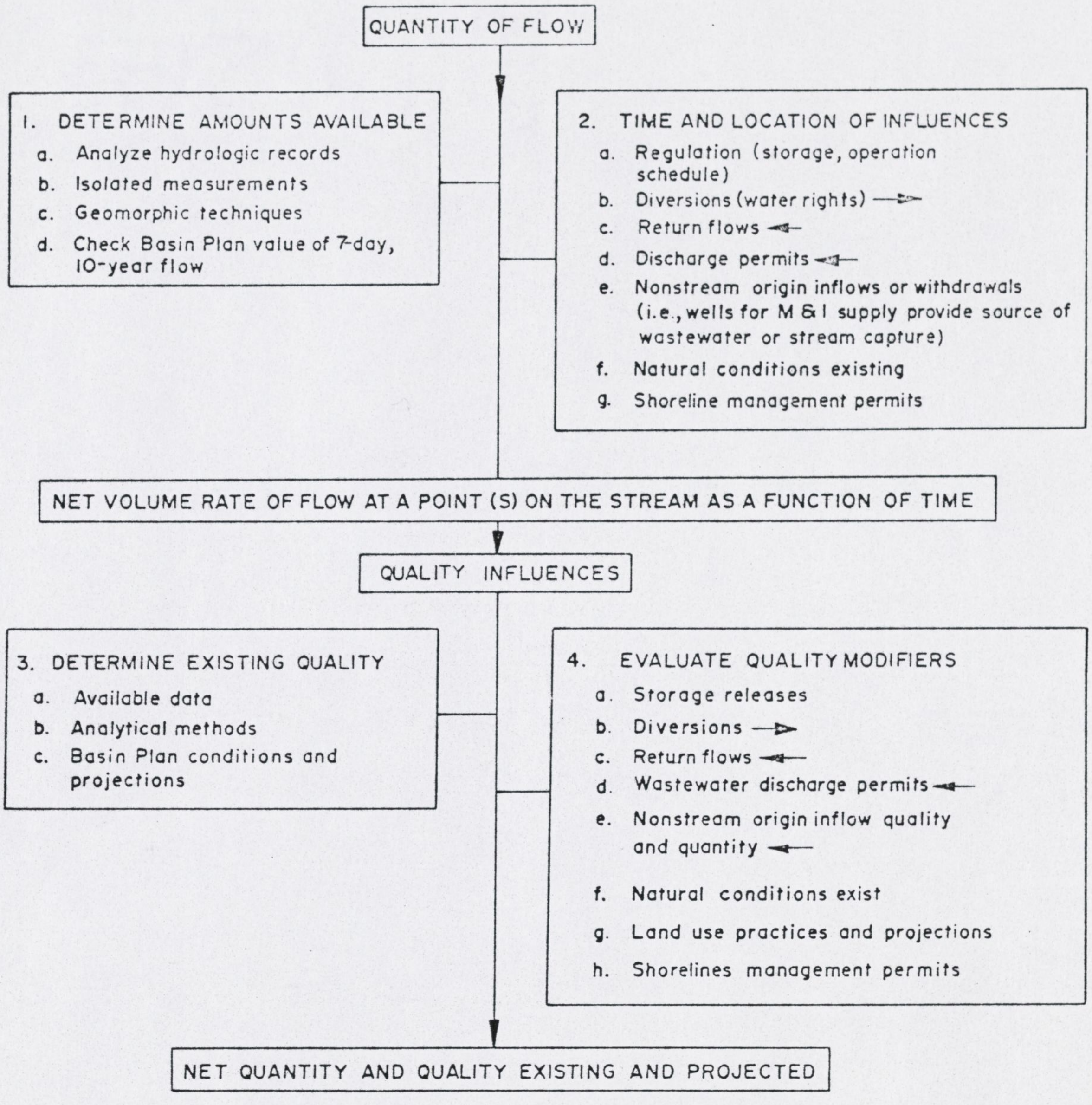
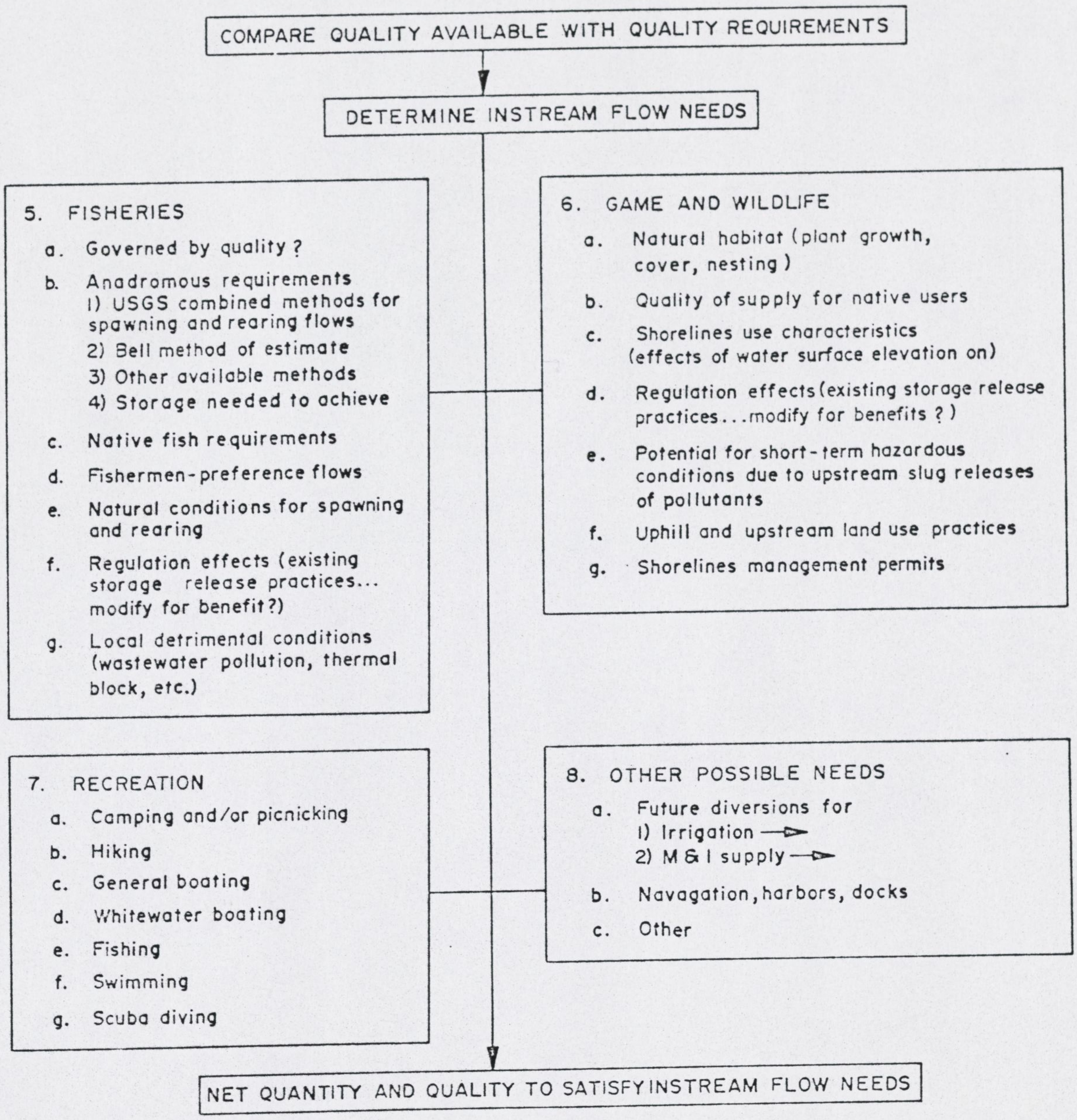


Figure 2. Continued.



with river basin commissions, states, and others in preparation of water and related land resource plans. Specific mention is made of fish, wildlife, ecological systems and recreation. In direct response to the Act, the Water Resources Council has established Principles and Standards for water and related land resource planning. The measurement of environmental quality effects stem from the basic requirement of the Principles and Standards for development of alternative plans for meeting two objectives (National Economic Development and Environmental Quality).

As a means of implementing directions from the Act, the Water Resources Council has defined the following levels of planning.

> A. Framework Studies and Assessments
> Framework studies and assessments are merged into the first and broadest level of planning. They are the evaluation or appraisal on a broad basis of the needs and desires of people for the conservation, development and utilization of water and related land resources, and will identify regions (hydrologic, political, economic, etc.) with complex problems which require more detailed investigations and analyses . . . *These studies will not involve basic data collection, cost estimating, or detailed plan formulation.* (italics added for emphasis)
>
> B. Regional or River Basin Plans
> A regional (political, economic, etc.) or river basin plan (hydrologic region) is a preliminary or reconnaissance level water and related land plan for a selected area. These are prepared to resolve complex long-range problems identified by framework studies and the National Assessment and will therefore vary widely in scope and detail; will focus on middle term (15 to 25 years) needs and desires; will involve Federal, State and local interests in plan development; and will identify and recommend action plans and programs to be pursued by individual Federal, State and local entities.
>
> They will be programmed only where problems are interdisciplinary and of such complexity that an intermediate planning step is needed between framework and implementation level studies.
>
> C. Implementation Studies
> Implementation studies are program or project feasibility studies generally undertaken by a single Federal, State or local entity for the purpose of authorization or development of plan implementation. These studies are conducted under normal Federal, State or local agency responsibilities and authorities, and implement findings, conclusions and recommendations of assessments and regional plans found needed in the next 10 to 15 years.
>
> Implementation studies encompass the broad spectrum from preservation to full development, and lead to administrative, legal, or other nondevelopment action programs, to structural meeting of needs and desires, and combinations thereof. (Water Resources Council, 1970:2-4)

The Principles and Standards apply to all levels of planning as defined by the Water Resources Council. This has provided a major impetus for developing methodologies for assessing instream flow needs and quantification of effect for "with" and "without" development plans.

The following series of quotes relay the evolution of thought within water planning circles relative to environmental quality and instream flow requirements.

> Many now recognize that if we are to plan for the development, conservation, use and management of our water resources, we must first have two things: (1) a well-conceived, acceptable land use plan and (2) adequate flow regulations to protect the quality of our Northwest streams for now and the foreseeable future. The adoption of minimum flow standards requires strict regulation and control to prevent withdrawals or uses that would reduce adopted minimums. Minimum flow regulation could probably be accomplished as a supplement to the existing state water quality programs. This is why it's so important that efficient study be given to methods of establishing minimum flows. The states involved must agree on the methodology to be used, since they will have to enforce whatever regulations are adopted. (Holmes, 1972:1)

Workshop participation at the Instream Flow Requirement Workshop focusing on fishery and recreational and water quality needs addressed the following questions as posed by the Pacific Northwest River Basin Commission (PNWRBC) staff.

> 1. Should the objectives in establishing instream flows be (a) the maintenance of existing quality and usage, (b) the return of the stream to some natural condition, assuming such return is an improvement, and (c) the enhancement of the stream to its optimal condition? 2. What methods should be used to measure instream flow? 3. What are the steps to use in developing a standard methodology for determining instream flow requirements? 4. Should all streams be evaluated for instream flow requirements? 5. If not, how does one determine which streams should be evaluated? Should there be a stream priority of evaluation? 6. How should one attempt to integrate various instream flow requirements? 7. How does one compare the cost of different ways of maintaining instream flow levels when natural flows are inadequate–i.e., storage, reduction of withdrawals, etc., with the benefits from flow regulation? 8. How does one evaluate instream flow requirement in relation to benefits forgone? 9. How does one standardize the quantification of instream water uses, contrasting fish and wildlife and recreation instream needs, for instance, with readily quantifiable withdrawal uses such as irrigation and M & I? 10. Because instream needs may change with the seasons, how should varying instream needs be established? 11. Where circum-

stances force the adoption of instream flow level substantially below the optimum, should established instream flow levels be compared to this optimum? How? 12. Should stream flow requirements be flexible to future changes in needs? How? (PNWRBC, 1972:65)

During an Instream Flow Methodology Workshop sponsored by the State of Washington Department of Ecology (November 1972), other disciplines were included to expand the dialog on instream flow methodologies (i.e., hydraulics, water quality, recreation, aesthetics). Here it was recognized that development of methodologies was only an aid to establishing resource maintenance flows.

> Concern was felt that recommended minimum flows should be within the stream's present natural flow, that critical survival flow should be stated, more favorable, and enhancement flows should also be given . . . Enhancement flow should be stated to account for future flow from reservoirs and water rights being dropped or changes, etc., that could enable more instream flow for fish. If a critical survival flow is not stated, then decision makers may not know in effect if lowering a flow beyond a certain minimum is critical, and they could error [err] ruining a fishery. (Bishop and Scott, 1972:108-109)

A recent report by an Ad Hoc Committee of PNWRBC recommended continuing programs of development and coordination for all aspects of instream flow evaluations with particular emphasis on meeting the following needs:

> 1. The need for concentrated support for the early determination of (a) stream resource maintenance flows under existing programs, and (b) instream flows for recreation, water quality esthetics, etc. 2. The need for development of low-cost methodologies for determination of (a) stream resource maintenance flows where existing methodologies are not applicable (warm-water fisheries, large streams, salmonid rearing, white sturgeon, etc.) and (b) instream flows for recreation, esthetics, etc. 3. Need to develop a creditable program, including methodology, for evaluation of impacts and benefits for increments of flow. 4. Need to develop recommendations for improvements to existing legal and institutional systems for the control of inter- and intrastate waters for the above purposes. (PNWRBC, Ad Hoc Instream Flow Study Evaluation Committee, 1974:24-25)

The Idaho Water Resource Board, in preparation of a State Water Plan, recognized that most instream uses exist within a range of tolerable flows.

> Most in-stream uses have an 'extinction point,' a minimum volume of water below which that use can not exist. Similarly, most in-place water uses have a 'flood' point where excess flows, or levels, effectively extinguish that water use. Somewhere between those two points lies an optimum, being that flow or level at which a water use is maximized. Water to sustain or enhance in-stream uses is often sought for diversion to augment food and fibre production, or to enhance commerce. A successful methodology must balance these competing demands. While a broad methodology is contemplated which will identify net gains (or losses) at all possible flow allocations, the particular purpose of the methodology is to identify that flow distribution which delivers a maximum benefit. (Trumbull and Loomis, 1973:6)

The major features of a functional methodology should include: 1) Analytical comprehensiveness, i.e., all relevant attributes of the factor being evaluated; 2) secondary impacts of changes in a factor or factors being assessed; and 3) the ability to relate one factor to other factors in natural resource evaluations. These abilities imply the inclusion of factors in an analysis of a system or model related to resource evaluation so that the mutual and relative effects of variables can be gauged. Also, it is necessary that especially sensitive factors in relation to natural resources are apparent (e.g., the limiting factor concept of the fishery scientist, auditory components of stream flow aesthetics). Finally, the methodology should be valid, reliable, feasible, and meaningful.

These criteria are stringent. In fact, no available methodology will meet all of them. They represent the characteristics of an ideal methodology and constitute a set of standards from which the strengths and weaknesses of actual methodologies can be ascertained. By using these, or additional criteria specific to streamflow evaluation, the comparative analysis of methodologies will be facilitated. These criteria would also provide a basis for specifying those parts of a methodology that most need improvement and indicate areas of methodology research that are most needed.

In addition to application of previously described criteria in analyzing methodologies for possible adoption or modification, the resource planner must first explicitly state the goals of the analysis and determine the purpose for which the methodology will be used. The degree of resolution necessary must be assessed, as this will have a bearing on the level of precision and time frame required.

As this report will point out in succeeding sections, the pursuit of a comprehensive methodology for assessing fisheries, wildlife, water quality, etc. is fruitless. The recommended approach includes the identification of a set of comprehensive methodologies best suited to the chosen level of planning, resolution, and category of analysis, and adoption of standard methods of assessing instream flow uses.

Reviews pertaining to the general subject of streamflow requirements and resource maintenance are available. Fraser (1972) reviewed the published literature relative to streamflow (velocity and depth) and its effects upon aquatic organisms. Hooper (1973) reviewed the effects of flows on trout ecology and summarized methodologies relating to spawning requirements. Giger (1973) reviewed the literature relevant to requirements of salmonids (especially juveniles) and summarized the various agency approaches to streamflow recommendations. Bovee (1974) reviewed the literature on requirements of warm water fisheries and proposed a methodology for establishing minimum flows for a warm water fishery.

Collectively, these reviews and the proceedings of the two workshops referred to above summarize many of the currently documented methodologies and concepts. Many other approaches to instream flow assessment have been used but, unfortunately, have not been documented or published.

This report examines existing techniques and methodologies and discusses each relative to its applicability to: 1) Reconnaissance studies (i.e., those evaluations constrained by short time and/or limited funds and resulting in low resolution); 2) on-site studies requiring limited field measures; and/or 3) intensive on-site studies requiring substantial and sophisticated field measurements (larger time and funding commitments resulting in high resolution).

The objective of this report is to document (reference) current methodologies, and critique them with emphasis upon identifying constraints. This document is not meant to be a manual of methods and procedures, but rather a state-of-the-art summarization to: 1) Provide the basis for further work toward the development of a manual of instream flow methodologies for use by management personnel; 2) Designate criteria for development of a comprehensive set of methodologies for determination of flow requirements for aquatic life, fisheries and wildlife, water quality and estaurine inflow and recreation and aesthetics; and 3) Define areas of research needs.

With the following quote in mind, the authors have attempted to pull together the considerable bank of knowledge and techniques relevant to methodological development and assessment of instream flow requirements for maintenance of aquatic life, fisheries, wildlife, water quality, estuarine inflows and associated recreation and aesthetics.

> It is difficult and perhaps unfair to attempt to compare or evaluate various methods of determining recommended streamflows based only on a general review of papers describing such methodology and on a perusal of literature on stream ecology. Nevertheless, a discussion pointing out methodology patterns and how these may relate to populations of organisms has value in suggesting areas of future study or modification of approaches. As happens frequently in biological investigation, methods have been diverse and have developed along separate lines, making summarization into reasonably well-defined categories a sizable task..(Giger, 1973:98)

This state-of-the-art report is not intended to include all materials that might have been written on the subjects of aquatic life, wildlife, water quality, recreation and aesthetics, but has certain limitations. First, highest priority in the search was given to materials most directly related to effects of streamflow variation. Second, materials were included that could be adapted to the methodological needs of flow assessment. This basic approach was constrained by the fact that in some areas no methodological materials were found that had been specifically developed for the purpose of evaluating the effects of differential streamflows. Third, the scope of the work (relative to fish and wildlife uses) was extended to determine how individuals in agencies are making current decisions and recommendations without specific standardized principles to follow.

Although emphasis will be on available methodologies, measurement techniques will be discussed as applicable to standardizing methodologies or as suggested steps in methodology development. Assessment of a component is a prerequisite to its analysis. If assessment is to be comparable, the measurement must be consistent.

Section 1 attempts to identify the terminology in general usage among various agencies, disciplines and personnel when discussing the problems of streamflow and instream requirements. It will suggest a standard set of appropriate terms and definitions for use in further discussions of instream flow problems as well as in the present text.

Section 2 discusses streamflow measurement in the context of establishing standard techniques of measuring stream discharge under different physical and time constraints. This section is included to contrast measurement techniques and methodologies (including analysis and interpretation). It should be considered a common point of reference from which the remaining sections discuss need assessment and methodology development and utilization.

Section 3 discusses modeling techniques and summarizes applications to hydrodynamics and water quality dynamics in rivers and estuaries. Models of flow, dissolved oxygen (DO), temperature, total dissolved solids (TDS), sediment transport, nutrient budgets and microbial ecology are included. Most of the comprehensive models discussed were originally constructed to examine the dilution needs for DO maintenance by expanding and modifying the classic Streeter-Phelps equation to fit variable BOD (biochemical oxygen demand) discharge circumstances.

Section 4 summarizes the methods and approaches as they have developed and are being utilized for assessment of the aquatic habitat. This section emphasizes the fauna and, more specifically, the fishes. Most of the methodology development to the time of this writing had concentrated upon particular life stages of the salmonids. Consequently, the organization of this section has been related to reproductive (spawning), migratory (passage), food (benthic insect-riffle production) and shelter (instream, micro-habitat, cover) needs of fishes.

Section 5 presents a discussion of methods that have been used to evaluate the effects of water resource and other developments upon wildlife populations. Emphasis is placed upon needed methodologies and current research applicable to the problem of stream flow alterations.

Section 6 is directed toward the measurement of recreational behavior (activity) and assessment of those social attitudes which affect demand or potential demand for stream-associated recreation resources. Other approaches are presented which attempt to determine the recreational opportunities that may be available.

Section 7 focuses upon aesthetic considerations of flowing streams (fluctuations in the waterscape) and the associated landscape.

Aesthetics, not necessarily involving activity, but rather sensitivity or emotional evaluations has been investigated more by psychological methods. Measurement of aesthetics is discussed with emphasis upon viewer evaluation (psychological scaling) and environmental qualities (classification). As is pointed out, methodologies for assessing stream aesthetics need to incorporate both techniques (methods).

To reiterate, this report will not specifically address the decision making process and the total planning concept, but will be restricted to a discussion of those techniques and methods used for assessing the effects of changing stream flows (i.e., those arrows shown on the right hand side of Figure 1).

REFERENCES CITED

BISHOP, R. A. and J. W. SCOTT [Cochairman].
1972. Proceedings instream flow methodology workshop. Washington Dept. of Ecology, Olympia, Wash. 130 p.

BOVEE, K. D.
1974. The determination, assessment and design of "in-stream value" studies for the Northern Great Plains region. Univ. Montana, Final Rep. EPA Contract No. 68-01-2413. 204 p.

CRUTCHFIELD, J. A., B. W. MAR, J. W. CROSBY III AND J. F. ORSBORN.
1973. A summary of quantity, quality and economic methodology for establishing minimum flows, Vol. I. Proj. Compl. Rep. OWRR Proj. No. B-037-WASH., Rep. No. 13, State of Washington Water Res. Center, Wash. State Univ./Univ. of Wash. 86 p.

FRASER, J. C.
1972. Regulated stream discharge for fish and other aquatic resources: an annotated bibliography. FAO Fisheries Tech. Paper, No. 112 (FIRI/T111), FAOUN, Rome, Italy. 103 p.

GIGER, R. D.
1973. Streamflow requirements for salmonids. Oregon Wildl. Comm., Job Final Rep. Proj. AFS 62-1. 117 p.

HOLMES, R.
1972. Instream flow requirement workshop, opening remarks. Pacific N.W. River Basins Comm., Port land, Oregon. 85 p.

HOOPER, D. R.
1973. Evaluation of the effects of flows on trout stream ecology. Pacific Gas and Elec. Co., Emeryville, Calif. 97 p.

PACIFIC N. W. RIVER BASIN COMMISSION.
1972. Instream flow requirement workshop. Pacific N. W. River Basins Comm., Portland, Oregon. 85 p.

PACIFIC N. W. RIVER BASIN COMMISSION, AD HOC INSTREAM FLOW STUDY EVALUATION COMMITTEE.
1974. Evaluation report: Need for a coordinated and expanded program of instream flow evaluation data in the Pacific Northwest. Pacific N. W. River Basins Comm., Vancouver, Washington. 28 p.

TRUMBULL, L. E. AND D. LOOMIS.
1973. Instream flow need for Idaho stream development of determinative methodology. Idaho Water Resour. Bd., Boise, Idaho. 77 p.

U.S. WATER RESOURCES COUNCIL.
1970. Water and related land resources planning: A policy statement. U.S. Water Resour. Council, Washington, D. C. 5 p.

1. NOMENCLATURE FOR INSTREAM ASSESSMENTS

J. L. ARNETTE

The nomenclature presented in this chapter is intended to provide a standard terminology for use by workers in the area of stream flow evaluation. Since this field of study is multidisciplinary, the need for an available and functional nomenclature is immediate. An initial set of definitions was presented to participants at a U.S. Fish and Wildlife Service sponsored Instream Flow Workshop, September 17-19, 1975. The comments and suggestions, both definitional and as reference sources, provided a sound base for finalizing the contents of this chapter.

The glossary is relatively comprehensive. The terms presented generally are those used in the text of the document; however, other appropriate terms are included to expand the clarity and usefulness of the glossary. The nomenclature, as a whole, will not be acceptable to all workers in all the involved disciplines. At this point in the development of such a diverse field as instream flow assessment, concensus of opinion on nomenclature cannot be expected. It is necessary and desirable that the terminology be continually refined and expanded where and when necessary.

The keynote of this chapter is brevity. Terms are defined once under the most appropriate word(s) and extensively cross-referenced to aid in locating words whose primary meaning is doubtful.

The references at the end of the chapter are those that provided assistance in compiling the glossary. Definitions were rarely accepted as found in the sources. The exception was the American Society of Civil Engineers (1962), Nomenclature for Hydraulics. A number of definitions are printed verbatim from this exceptionally useful source book.

GLOSSARY

accretion--A process of accumulation by flowing water, whether of silt, sand, pebbles, etc.

accretion, channel-flow–The gradual increase in the flow of a stream due to influent seepage.

acre-foot--A term used in measuring the volume of water, equal to the quantity of water required to cover 1 acre 1 foot in depth, or 43,560 cubic feet.

advection–Transfer by horizontal motion; motions that are predominently horizontal, resulting in horizontal transport and mixing.

aesthetics–An enjoyable sensation or a pleasurable state of mind, which has been instigated by the stimulus of an outside object, or it may be viewed as including action which will achieve the state of mind desired. This concept has a basic psychological element of individual learned response and a basic social element of conditioned social attitudes. Also, there can be ecological conditioning experience in that the physical environment also affects the learning process of attitudes.

algae–Primitive plants, one or many-celled, usually aquatic and capable of elaborating the foodstuffs by photosynthesis.

anchor ice–See ice, anchor

area, cross-section–See area, section, cross.

area, drainage--The area tributary to a lake or stream. Also called catchment area, watershed, and river basin.

area, section, cross--The area of a stream, channel, or waterway opening, usually taken perpendicular to the stream centerline.

attitude–A hypothetical or latent variable in human behavior, rather than an immediately observable variable. This may include beliefs about the nature of an object, person or group; evaluation of it and behavior toward it.

attitude scaling--See technique, scaling.

balance, oxygen–The relation between the biochemical oxygen demand of an effluent and the oxygen available in the diluting water. The difference between the total dissolved oxygen content and the total first-stage oxygen demand at a given point at the same time, or during the same time period.

balance, salt--The difference between the total dissolved solids brought to the land annually by irrigation water and the total solids carried away annually by the drainage water.

bar–An alluvial deposit or bank of sand, gravel, or other material, at the mouth of a stream or at any point in the stream itself which causes an obstruction to flow.

basin, catchment--See area, drainage; river and watershed.

basin, flood--That portion of a river valley outside of the natural stream bank which is subject to flooding.

basin, river--The area drained by a river and its tributaries. See area, drainage.

basin, tidal--A basin or bay connected with an ocean or tidal estuary, in which the water level changes with fluctuations of the tides.

bed–The bottom of a watercourse.

bed, movable–A stream bed made up of materials readily transportable by the streamflow.

bed, pervious--A bed or stratum that contains voids through which water will move under ordinary hydrostatic pressure.

bed, stream--The bottom of a stream below the usual water surface.

capacity, carrying, instream, biological--The maximum average number of a given organism that can be maintained indefinitely, by the habitat, under a given regime (in this case, flow).

capacity, carrying, discharge--The maximum rate of flow that a channel is capable of passing.

catchment--See area, drainage; basin, catchment; basin, river; watershed.

channel--A natural or artificial waterway of perceptible extent which periodically or continuously contains moving water. It has a definite bed and banks which serve to confine the water.

chute--An inclined drop or fall; a short, straight channel which by-passes a long bend in a river and formed by the river breaking through a narrow land area between two adjacent bends.

coefficient, roughness, Manning's--A factor used when computing the average velocity of flow of water in a channel which represents the effect of roughness of the confining material upon the energy losses in the flowing water. See equation, Manning's.

contour--A line of equal elevation above a specified datum.

course, water--A natural or artificial channel for passage of water. See channel.

cover, fish--A more specific type of instream cover, e.g., pools, undercut banks, boulders, water depth, surface turbulence, etc.

cover, instream--Areas of shelter in a stream channel that provide aquatic organisms protection from predators and/or a place in which to rest and conserve energy due to a reduction in the force of the current.

cover, riparian--Areas associated with or adjacent to a stream or river that provide resting shelter and protection from predators--e.g., overhanging vegetation, accumulated debris, etc. See riparian, riparian vegetation, drift.

critical flow--See flow, critical.

cross section--See section, cross.

cubic foot per second--A unit of measure equivalent to the discharge through a rectangular cross section, one foot wide and one foot deep, with a velocity of one foot per second.

current--The flowing of water, or other fluid. That portion of a stream of water which is moving with a velocity much greater than the average or in which the progress of the water is principally concentrated (not to be confused with a unit of measure, see velocity).

current, ebb--A current in a body of water or tidal stream that flows seaward or downstream.

current, flood--A current in a body of water or tidal stream that flows inland or upstream.

current, tidal--A current brought about or caused by tidal forces.

curve--A graphical representation of the changes in value of biological, physical or statistical quantities.

curve, duration--A curve which expresses the relation of all the units of some item such as head, flow, etc., arranged in order of magnitude along the ordinate, and time, frequently expressed in percentage, along the abscissa; a graphical representation of the number of times given quantities are equaled or exceeded during a certain period of record.

curve, flow duration--A duration curve of streamflow.

curve, frequency--A curve of the frequency of occurrence of specific events. The event that occurs most frequently is termed the mode.

curve, rating--A curve which expresses graphically the relation between mutually dependent quantities, e.g., a curve showing the relation between gage height (or stage) and discharge of a stream. See also nomograph.

cusec--An abbreviation for cubic feet per second.

cycle, hydrologic--The circuit of water movement from the atmosphere to the Earth and return to the atmosphere through various stages or processes as precipitation, interception, runoff, infiltration, percolation, storage, evaporation, and transpiration.

datum--Any numerical or geometrical quantity or set of such quantities which may serve as a reference or base for other quantities. An agreed standard point or plane of stated elevation, noted by permanent bench marks on some solid immovable structure, from which elevations are measured, or to which they are referred.

demand, oxygen, biochemical (B.O.D.)--The quantity of oxygen utilized in the biochemical oxidation of organic matter in a specified time and at a specified temperature.

depth, mean--The average depth of water in a stream channel. It is equal to the cross-sectional area divided by the surface width.

dewater--The draining or removal of water from an enclosure or channel.

discharge--The rate of flow, or volume of water flowing in a given stream at a given place and within a given period of time, expressed as cu ft per sec.

discharge, bankfull--Discharge corresponding to the stage at which the overflow plain begins to be flooded.

discharge, groundwater--Groundwater which is discharged directly from the zone of saturation upon the land or into a body of surface water.

discharge, mean-monthly--Discharge observed or interpolated and averaged over a calendar month.

discharge peak--The maximum discharge rate for a given flood event.

dispersion--An attribute referring to the internal pattern of a population; biologically, the numerical distribution in space and time; statistically, the distribution of items around the mean.

dispersion, transport by--Scattering and mixing. The mixing of a fluid with a large volume of water in a stream or other body of water.

drainage area--The entire area drained by a river or system of connecting streams such that all streamflow originating in the area is discharged through a single outlet. See basin, river, watershed.

drainage density--The relative density of natural drainage channels in a given area, usually expressed in terms of miles of stream channel per square mile of drainage area. The value is obtained by dividing the total length of stream channels in the area in miles by the drainage area in square miles. Generally, a drainage density of one or more indicates "good" drainage.

drift--A mass of matter which has been driven together by action of water.

drift, invertebrate--The aquatic or terrestrial invertebrates which have been released from (behavioral drift), or have been swept from (catostrophic drift) the substrate, or have fallen into the stream and move or float with the current.

duration curve--See curve, duration.

equation, Chezy--An empirical formula for the velocity of a uniform flow of water through a section of a stream in terms of the roughness, the hydraulic radius, and friction slope. The formula is usually written $V=C\sqrt{RS}$. See equation, Manning's.

equation, Manning's--In current usage, an empirical formula for the calculation of discharge in a channel (technically the Chezy formula with the Manning roughness coefficient). The formula is usually written $Q = \frac{1.49}{n} R^{2/3} S^{1/2} A$.

erosion, stream bed–The scouring of material from the water channel and the cutting of the banks by running water. The cutting of the banks is also known as stream bank erosion.

fines--The finer grained particles of a mass of soil, sand or gravel. The material, in hydraulic sluicing, that settles last to the bottom of a mass of water.

first-order decay--The rate of decomposition of a substance that is directly proportional to the concentration of the reacting substances.

first-order deficit--The difference between saturation and measured concentrations; this changes in proportion to the concentration difference.

first-order rate–The change in the concentration of a reactant proportional with time.

flood–Any flow which exceeds the bankfull capacity of a stream or channel and flows out on the floodplain; greater than bankfull discharge. See flow, overbank.

flow–The movement of a stream of water and/or other mobile substances from place to place; discharge; total quantity carried by a stream.

flow, average--See flow, mean.

flow, augmented–Any modified flow resulting in discharges greater than would occur under natural flows.

flow, base–That portion of the stream discharge which is derived from natural storage–i.e., groundwater outflow and the draining of large lakes and swamps or other sources outside the net rainfall which creates the surface runoff; discharge sustained in a stream channel, not a result of direct runoff and without the effects of regulation, diversion, or other works of man. Also called sustaining flow.

flow, critical--Flow at that velocity in excess of which the fluid is in turbulent motion and below which the fluid is in laminar motion; in reference to Reynold's critical velocities which define the point at which the flow changes from laminar to turbulent flow.

flow-enhancement--An improvement flow which provides for betterment over natural conditions for fish, wildlife, other aquatic organisms and/or related recreational activities. See also flow, improvement.

flow,flood–See flow, overbank.

flow, groundwater–Flow in an aquifer. That portion of the discharge of a stream which is derived entirely from groundwater, through springs or seepage. Groundwater flow usually forms the major part of base flow.

flow, high–See flow, peak.

flow, improvement--That discharge which will improve upon existing fish, wildlife, other aquatic organisms and/or related recreational activity by correcting for water quality deterioration and/or utilization pressures.

flow, increments of--Increases or decreases of discharge in relation to some identified reference flows.

flow, instantaneous--That discharge measured at any instant in time, applied to any recommended flow term when modified by the appropriate adjective.

flow, instream--See flow, stream.

flow, laminar–That type of flow in a stream of water in which each particle moves in a direction parallel to every other particle.

flow, low–The lowest discharge recorded over a specified period of time. Also called minimum flow.

flow, maximum–See flow, peak.

flow, mean–The average discharge at a given stream location, usually expressed in cubic feet per second, computed for the period of record by dividing the total volume of flow by the number of days, months or years in the specified period.

flow, median--The discharge at a given point for which there are equal numbers of greater and lesser flow occurrences during a specified period of time.

flow, minimum--See flow, low.

flow, modified–The regulated discharge at a given point in a stream resulting from the combined effects of all upstream and at-site operations, diversions, return flows and consumptive uses.

flow, natural--The flow of a stream as it occurs under natural as opposed to regulated conditions. See flow, regulated.

flow, optimum–The discharge regime which allows for the maximum expression of the carrying capacity of any specified use in a stream. Any flow above or below this flow becomes limiting to the use under consideration.

flow, overbank--The portion of streamflows which exceed the discharge carrying capacity of the normal channel and overflow the adjoining flood-plain(s). See flood.

flow, overland–The flow of water over the surface of the land before it enters a channel. Also called surface runoff.

flow, peak–The highest discharge recorded over a specified period of time. Often thought of in terms of spring snowmelt, summer, fall or winter rainy season flows. Also called high flow and maximum flow.

flow, preservation--That range of flows within a stream required to preserve the existing levels of fish, wildlife, other aquatic organisms and related recreational activities. Also called stream resource maintenance flow.

flow, reduced–Any modified flow resulting in discharges less than would occur under natural flows.

flow, reference–Any quantity or level of flow which serves as a "base" or datum from which other flows or flow data are determined. This is not synonymous with base flow.

flow, regulated--The flow in a stream that has been subjected to regulation by reservoirs, diversions or other works of man.

flow, steady--A flow in which the discharge of water passing a given point per unit of time remains constant; the velocity vector does not change in either magnitude or direction with respect to time at any point.

flow, stream–The discharge regime occurring within a natural stream channel. Also called instream flow.

flow, stream resource maintenance–See flow, preservation.

flow, subsurface–That portion of the water which infiltrates the soil surface and moves laterally through the upper soil horizons until its course is intercepted by the channel of the stream or until it returns to the surface at some point downstream of its point of infiltration.

flow, survival--That instantaneous discharge required to prevent death of aquatic organisms in a stream during specified short periods of time (e.g., 7 days) of extremely low flow.

flow, sustaining--See flow, base.

flow, turbulent–That type of flow in which any particle of water may move in any direction with respect to any other particle.

flow, uniform–A flow in which the velocities are the same in both magnitude and direction from point to point. Uniform flow is possible only in a channel of constant cross section.

flow, uniform, steady–A flow in which the discharge of water flowing per unit of time and the velocity are constant.

flow, unsteady–A flow in which the velocity changes with respect to both space and time.

flow, varied–Flow occurring in streams having a variable cross section or slope. When the discharge is constant, the velocity changes with each change of cross section and slope.

flow duration curve--See curve, duration.

flushing–The removing of deposits of material which have lodged in a channel by reason of inadequate velocity of flow. That discharge (natural or man-caused) of sufficient magnitude and duration to remove fines from the stream bottom gravel to maintain intragravel permeability.

frazil–See ice, frazil.

gage–A device for indicating or registering magnitude or position in specific units, for example: the elevation of a water surface, the velocity of flowing water, etc. A staff graduated to indicate the elevation of a water surface.

gauge–See gage.

glide–A calm stretch of water flowing smoothly and gently. See run.

gradient–The rate of change of any characteristic per unit of length. See slope.

gradient, hydraulic–The slope of the hydraulic grade line. For open channels, it is the slope of the water surface, and is frequently considered parallel to the channel bottom.

gradient, stream–The general slope, or rate of change in vertical elevation per unit of horizontal distance, of the water surface of a flowing stream.

habitat--The place where a population lives and its surroundings, both living and nonliving; includes the provision of life requirements such as food and shelter.

hardness--A characteristic of water, chiefly due to the existence therein of the carbonates and sulfates and occasionally the nitrates and chlorides of calcium, iron, and magnesium. It is commonly computed from the amounts of calcium and magnesium in the water and expressed as equivalent calcium carbonate per million parts of water.

hydraulic–Refers to water, or other liquids, in motion and their action.

hydraulic geometry–Those measures of channel configuration, including depth, width, velocity, discharge, slope, etc.

hydraulic radius–The cross-sectional area of a stream of water divided by the length of that part of its periphery in contact with its containing channel; the ratio of area to wetted perimeter.

hydrodynamics--Refers to the action of forces in producing motion in water.

hydrograph--A graph showing, for a given point on a stream, the discharge, stage, velocity or another property of water with respect to time. See curve.

hydrologic–Refers to water in all its states, its properties, phenomena, distribution and circulation through the hydrologic cycle. See cycle, hydrologic.

hydrologic regime–The climatic, lithologic, topographic, and vegetation factors, and the temporal distribution of seasonally variable factors, which determines the extent of stability between a stream and its drainage basin.

hyetograph–A graphical representation of average rainfall.

ice-anchor–Ice formed below the surface of a stream or open body of water, on the stream bed, or upon a submerged body or structure.

ice, frazil--Fine spicules of ice found in water too turbulent for the formation of sheet ice. Frazil forms in supercooled water when the air temperature is far below freezing (most often below -8°C).

ice, sheet--Ice formed on the surface of the water in lakes, ponds and streams where the velocity is low. It starts near the banks and then gradually extends towards the center.

impervious--A term applied to a material through which water cannot pass or through which water passes with great difficulty.

index–An indicator, usually numerically expressed, of the relation of one phenomenon to another.

instream use–Any and all uses of water (instream flows) in a stream channel (commercial boating, hydroelectric production, recreation, fish and wildlife, and other biological forms, aesthetics, etc.).

instream flow requirement--The flow regime necessary for all of the individual (when modified by an adjective specifying which use) and collective instream uses of water, including an acceptable range of water quality.

isohyet--A line connecting points of equal precipitation.

isohyetal map--See map, isohyetal.

landscape–A portion of land which the eye can comprehend in a single view.

line, channel--The route of strongest flow of a river. It usually coincides with the thalweg. See thalweg.

line, isohyetal--See isohyet.

load, bed--Sand, silt, gravel or soil and rock detritus carried by a stream on, or immediately above its bed.

load, bed-material--That part of the sediment load of a stream which is composed of particle sizes found in appreciable quantities in the shifting portions of the stream bed. See load, bed.

load, saltation--The portion of the stream load which bounces from the bed into the flow and is transported a short distance before it again falls to the bed, or is moved directly or indirectly by the impact of the bouncing particles.

load, stream–The mass of eroded material which is being transported by a stream.

load, suspended–The portion of stream load moving in suspension and made up of particles having such density or grain size as to permit movement far above and for a long distance out of contact with the stream bed. The particles are held in suspension by the upward components of turbulent currents or by colloidal suspension.

load, wash--In a stream system, the relatively fine material in near-permanent suspension, which is transported entirely through the system, without deposition. That part of the sediment load of a stream which is composed of particle sizes smaller than those found in appreciable quantities in the shifting portions of the stream bed.

map, isohyetal--A map which shows the variation and distribution of precipitation occurring over an area during a given period through the use of isohyets.

mean elevation of a drainage basin–The average elevation (feet MSL) of a drainage basin, computed by summing the products of the areas between contour lines and the average elevation between contours and dividing this sum by the total area of the drainage basin.

mean flow–See flow, mean.

mean water velocity–The average velocity of water in a stream channel, which is equal to the discharge in cubic feet per second divided by the cross-sectional area in square feet. For a specific point location, it is the velocity measured at 0.6 of the depth or the average of the velocities as measured at 0.2 and 0.8 of the depth.

median elevation of a drainge basin--The elevation (feet MSL) at which 50 percent of the drainage area is of a lower elevation and 50 percent is of a higher elevation.

microhabitat--Localized and more specialized areas within a community or habitat type, utilized by organisms for specific purposes and/or events. Expresses the more specific and functional aspects of habitat and cover that allows the effective use of larger areas (aquatic and terrestrial) in maximizing the productive capacity of the habitat. See cover types, habitat).

method--A systematic procedure, technique or mode of inquiry employed or proper to a particular science or discipline.

methodology--A body of methods, procedures, techniques, working concepts and postulates employed by a science or discipline (including analysis, synthesis and recommendations).

model--A hypothetical representation of a system. The organization of postulates, data, and inferences presented as a mathematical description of a system, entity or state of affairs.

nomograph--A diagram for the graphical solution of problems that involve mathematical formulas in two or more variables.

number, Froude's--A dimensionless numerical quantity used as an index to characterize the type of flow in a hydraulic structure that has the force of gravity (as the only force producing motion) in conjunction with the resisting force of inertia. It is the ratio of inertia forces to gravity forces. It is equal to the square of a characteristic velocity (the mean, surface, or maximum velocity) of the system divided by the product of a characteristic linear dimension, as diameter or depth, and the gravity constant, acceleration due to gravity--all expressed in consistent units in order that the combinations will be dimensionless. The number is used in open channel flow studies or where the free surface plays an essential role in influencing motion.

number, Reynolds', roughness--A dimensionless parameter employed in problems of unsteady open channel flow for ensuring that the same type of turbulent flow is obtained in the model as prevails in the prototype. It is equal to the height of equivalent sand roughness times the shear velocity divided by the kinematic viscosity.

overland flow--See flow, overland; runoff.

parameter--A variable in a mathematical function which, for each of its particular values, defines other variables in the function.

percolation--The flow of a liquid downward through a contact or filtering medium.

perimeter, wetted--The length of the wetted contact between the stream of flowing water and its containing channel, measured in a plane at right angles to the direction of flow.

phreatophyte--Plants which habitually take up water from the zone of saturation (below the water table) and by transpiration transport ground water directly to the atmosphere.

plain, flood--Nearly level land occupying the bottom of the valley of a present stream and subject to flooding.

plane, flood--The position occupied by the water surface of a stream during a particular flood. Also called flood level.

pool--A body of water or portion of a stream that is deep and quiet relative to the main current.

pool, plunge--A pool, basin, or hole scoured out by falling water at the base of a waterfall.

probability, flood--The probability of a flood of a given size being equaled or exceeded in a given period; a probability of 1 percent would be a 100-yr flood, a probability of 10 percent would be a 10-yr flood.

profile--In open channel hydraulics, it is a plot of water surface elevation against channel distance.

profile, velocity--A curve representing the velocity of flow at all points along a given line.

quality, scenic--Of or pertaining to the degree of beauty of natural scenery.

quality, water--A term used to describe the chemical, physical, and biological characteristics of water in respect to its suitability for a particular use.

radius, hydraulic--See hydraulic radius.

rating--The relation, usually determined experimentally and expressed either graphically or in the form of an algebraic formula, between two mutually dependent quantities, such as stage and discharge of a stream.

rating curve--See curve, rating.

reach--A comparatively short length of a stream, channel, or shore.

record, streamflow--A tabulation of the flow of a stream. Streamflow records are published annually by the USGS in their Water Supply Papers. Daily, monthly, annual, and instantaneous extremes of discharge are shown therein.

recreation--Behavior in which one engages from free choice, in leisure time; activity that is not necessary for existence, and which provides immediate gratification, enjoyment, diversion and/or refreshment.

regime--A regular pattern of occurrence or action; the condition of a river with respect to the rate of its flow as measured by the volume of water passing different cross sections in a given time. See regimen.

regimen--The characteristic behavior, orderly procedure or systematic plan of a phenomenon or process. The system or order characteristic of a stream in regard to velocity, volume, sediment transport and channel morphology changes. This implies a more systematic approach or process than does regime.

regions, hyetal--Divisions of the world into areas according to rainfall characteristics.

regulation (streamflow)--The procedure or actions involved in artificially modifying the natural flow of a stream so that its discharge at a specified point or points will serve a specified purpose or achieve a given objective.

resource maintenance flow--See flow, resource maintenance; flow, preservation.

resources, water--The supply of water in a given area or watershed, usually interpreted in terms of availability of surface and/or underground water.

riffle--A shallow rapids in an open stream, where the water surface is broken into waves by obstructions wholly or partly submerged.

rights, water--The right(s), acquired under the law, to use the water occurring in surface or groundwaters, for a specified purpose and in a given manner and usually within limits of a given period. While such rights may include the use of a body of water for navigation, fishing, and hunting, and other recreational purposes, etc., the term is usually applied to the right to divert or store water for some out-of-stream purpose or use, such as irrigation, generation of power, domestic or municipal water supply.

rights, water, adjudication of--The legal procedure followed in determining the quantities of water to which persons claiming water rights in a stream or other body of water are entitled, and in the case of rights of appropriation, the relative priority of each such right.

riparian--Pertaining to anything connected with or adjacent to the banks of a stream or other body of water.

riparian vegetation--Situated on the bank of a river or other body of water. Here extended to mean upland area influenced by a river or stream, no matter how rarely the channel contains water.

river, alluvial--A river which has formed its channel by the process of aggradation, and the sediment by which it carries (except for the wash load) is similar to that in the bed.

river, braided--A river of which the channel is extremely wide and shallow and the flow passes through a number of small interlaced channels separated by bars or shoals.

river, incised--A river which has cut its channel through the bed of the valley floor, as opposed to one flowing on a floodplain; its channel formed by the process of degradation.

river, mature--A stream whose slope is so reduced that the water velocities are just sufficient to carry debris delivered by the tributaries, which have steeper slopes than the main stream.

roughness, coefficient of--See coefficient, roughness.

run--A stretch of relatively deep (as opposed to a glide), fast flowing water, with the surface essentially nonturbulent. See glide, riffle.

runoff, annual, mean--The average over a period of years of the annual amounts of runoff discharged by a stream.

runoff, surface--See flow, overland.

scaling techniques--See techniques, scaling.

scenic quality--See quality, scenic.

second-foot--An abbreviated expression of cubic foot per second.

second-foot-day--The volume of water represented by a flow of 1 cu ft per sec for 24 hr. It is 86,400 cu ft, or nearly 2 acre-ft (actually 1.9835).

second-foot per square mile--The number of cubic feet per second flowing in a stream at a given time, divided by the area of its drainage basin in square miles.

section, cross-See area, cross, section.

slope--The inclination or gradient from the horizontal of a line or surface. The degree of inclination is usually expressed as a ratio, such as 1:25, indicating one unit rise in 25 units of horizontal distance.

slope, hydraulic--See gradient, hydraulic.

sounding, echo--In echo sounding, depths are measured indirectly by noting the time interval required for sound waves to go from a source of sound near the surface to the bottom and back again.

stage--The elevation of a water surface above or below an established datum or reference.

standing crop--the abundance or total weight of organisms existing in an area at a given time.

steady flow--See flow, steady.

streamscape--A portion of a stream which the eye can comprehend in a single view.

stream flow--See flow, stream.

stream, graded--A geomorphic term used for streams that have apparently achieved, throughout long reaches, a state of practical equilibrium between the rate of sediment transport and the rate of sediment supply. Such a stream is in regimen; a mature stream.

stream, thread of--The line equidistant from the edge of the water on the two sides of the stream at the normal stage of the water.

stream slope--See slope, gradient.

technique--See method.

technique, scaling--A means of measuring and/or assigning numbers to attitudes. An attitude scale consists of a series of related items or questions concerning the properties of one variable. Attitude measurement is the assessment of an individual's responses to these items or questions. The value assigned to the response is referred to as an item score and the number derived from the total item scores is the scale score or measure of the individual's response to the variable.

thalweg--The line following the lowest part of a valley, whether under water or not. Usually the line following the deepest part or middle of the bed or channel of a river or stream.

tidal current--See current, tidal.

tidal current, ebb--See current, ebb.

tidal current, flood--See current, flood.

tidal flow--See current, tidal.

uniform flow--See flow, uniform; flow, steady.

unsteady flow--See flow, unsteady; flow, uniform.

use, water, consumptive--The quantity of water absorbed by the crop and transpired or used directly in the building of plant tissue together with that evaporated from the cropped area. Also called evapotranspiration.

use, instream--See instream use.

velocity--The time rate of motion; the distance traveled divided by the time required to travel that distance.

velocity, critical, Reynold's--That velocity in a channel at which flow changes from laminar to turbulent.

velocity, fall--A general term which may apply to any rate of fall or settling. See velocity, settling; velocity, fall, standard.

velocity, fall, standard--The average rate of fall that a particle would finally attain if falling alone in quiescent distilled water of infinite extent at a temperature of 24°C. See velocity, fall.

velocity, mean--The average velocity of a stream flowing in a channel at a given cross section or in a given reach. It is equal to the discharge divided by the cross-sectional area of the section, or the average cross-sectional area of the reach. In the vertical, it is the average of the velocities observed at different depths.

velocity, settling--The velocity at which subsidence and deposition of the settleable suspended solids will occur. See velocity, fall.

watercourse--See course, water; channel.

water, ground--Subsurface water occupying the saturation zone, from which wells and springs are fed. In a strict sense, the term applies only to water below the water table.

water quality - See quality, water.

waterscape--See streamscape.

watershed--See area, drainage; basin, drainage; basin, river; catchment.

water year--See year, climatic.

wetted perimeter--See perimeter, wetted.

width, top--The width of the effective area of flow across a stream channel.

wildlife--All living things, as species, that are neither human nor domesticated; here most often restricted to wildlife species other than fish and aquatic invertebrates.

xerophreatophyte--A phreatophyte which is able to resist drought when necessary. See phreatophyte.

year, climatic--A continuous 12-month period during which a complete annual cycle occurs. The USGS uses the period October 1 to September 30 in the publication of its records of streamflow. Also called water year.

yield, water--The total outflow from a drainage basin through either surface channels or subsurface aquifers. See area, drainage.

REFERENCES

ALLEE, W. C., A. E. EMERSON, O. PARK, T. PARK and K. P. SCHMIDT.
1949. Principles of animal ecology. W. B. Saunders Co., Philadelphia, Pa., 837 p.

AMERICAN SOCIETY OF CIVIL ENGINEERS.
1962. Manuals and Reports of Engineering Practice. No. 43: Nomenclature for Hydraulics, 501 p.

HELLS CANYON CONTROLLED TASK FORCE.
1974. Discussion, conclusions and recommendations–Chap. 16. *In* Bayha, K. (ed). Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N. W. River Basins Comm. pp. 173-185.

MULLAN, J. W.
1975. Fisheries habitat plan for the Uintah and Ouray Indian reservation as affected by the Uintah and Upalco Units of the Central Utah Project. FWS, Salt Lake City, Utah. 132 p.

ODUM, E. P.
1953. Fundamentals of ecology. W. B. Sauders Co., Philadelphia, Pa., 546 p.

SELLTIZ, C., M. JAHODA, M. DEUTSCH and S. W. COOK.
1951. Research methods in social relations. Holt, Rinehart and Winston, Inc. N.Y., 622 p.

SHAW, M. E., and J. M. WRIGHT.
1967. Scales for the measurement of attitudes. McGraw Hill, N.Y., 604 p.

WEBSTER'S NEW COLLEGIATE DICTIONARY.
1961. G. and C. Merriam Co., Springfield, Mass. 1174 p.

WESCHE, T. A.
1973. Parametric determination of minimum stream flow for trout. Water Resour. Res. Inst. Rep., Univ. of Wyoming, Laramie, Wyoming, 102 p.

ADDENDUM

Legal Definitions[1]

appropriation – A right to use a specific quantity of the water of a public source of supply for a specified purpose at a specified place, if that quantity is available in the source and free from claims of prior appropriation. [Note: Sometimes defined by description of the elements of a typical appropriation, as follows: a water right obtained by diversion of the water from its source, accompanied by an intent to appropriate, notice to others of the appropriation, compliance with required state procedures, and the application of the water, with reasonable diligence and within a reasonable time, to a beneficial use. Such definitions are unsatisfactory since some appropriations have been allowed without a diversion, some (as for storage) without application to beneficial use, etc.]

beneficial use – In appropriation law, a use of water that fulfills a lawful need or desire of man. The benefits must be substantial in the light of other demands for water at the time and place an appropriation is made. Although some historically sanctioned uses (e.g., domestic, irrigation, mining and power) are always characterized as beneficial, the category is not a closed one. Lists of particular beneficial uses do not exclude others, and application of water to purposes unknown during historical developments of the law may be added to the lists.

diversion – In appropriation law, a withdrawal from or obstruction of a body of water that substantially changes its natural state, by means of a ditch, dam, pump or other man-made contrivance. In riparian law, diversion can have the same meaning, but it can also mean a change in the course of a stream or a substantial part of it by turning it into an artificial,or alternate natural channel.

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[1] Personal communication. 1975. F. J. Trelease, Dean, School of Law, University of Wyoming, Laramie, Wyoming 82071.

2. BASIC STREAM FLOW MEASUREMENTS AND RELATIONSHIPS

C. B. STALNAKER AND J. L. ARNETTE

CONTENTS

Basic to an understanding of stream flow assessment and discharge recommendation is some knowledge of stream flow components (hydraulic and hydrologic), their relationships and how they are measured. Almost invariably, with the exception of strictly occular/judgmental approaches, specific flow assessment methodologies are based on assumptions concerning one or more hydraulic and associated stream parameters, e.g., the significance of water velocity to aquatic organisms. This section very generally outlines basic flow concepts and definitions, commonly used data collection techniques and examples illustrating the variety of approaches to flow assessment. Also included is a description of the measurement and/or calculation of common hydraulic parameters that are essential to instream flow work. This section provides an overview of the basics of hydraulic and hydrologic techniques that are appropriate to the application of the methodologies discussed in the following sections. It is not intended as an in-depth examination of the hydraulic and hydrologic sciences, but as an overview of critical principles that pertain to a discussion of instream flow assessment methodologies. Some readers, particularly those with expertise in hydrology and/or hydraulics, may question the completeness and, possible, the necessity for, this section. It must be pointed out that the majority of the readers of this document will be state and Federal management personnel in several disciplines, with a limited knowledge of hydrodynamics. The authors feel that it is absolutely necessary for workers in the aquatic field to have a common base of knowledge (understanding) of the fundamental principles of hydrology and hydraulics as they relate to instream flow.

OPEN CHANNEL FLOW

Flow in streams is referred to as open channel flow. Although open channels include partially full, closed conduits, this discussion is only concerned with stream channels. Stream channel configuration—e.g., pools, riffles, overbank areas and bottom roughness— can dramatically affect flow characteristics and must be considered in quantitative flow assessment. Although the shapes of open channels are often quite different from elementary geometric forms, it is necessary and usually possible to correlate a stream channel to relatively simple shapes for analysis (Figure 1).

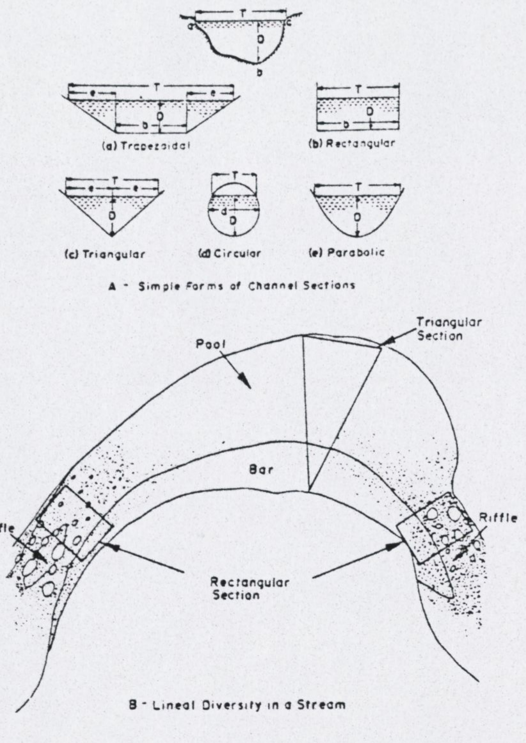

Figure 1. Reaches of river and appropriate geometrical approximation of stream cross sections.

In addition to configuration, open channel flow analysis involves the effects of an interface (free surface) between fluids with different specific weights—in this case, air and water. Because of the effects of configuration, free surface and other factors, such as slope, four classifications of open channel flow are considered:

> (1) uniform or nonuniform, (2) steady or unsteady, (3) laminar or turbulent, and (4) tranquil, rapid, or critical.
>
> *Uniform flow* in open channels has no change with distance in either the magnitude or the direction of the velocity along a streamline. Otherwise the flow is *nonuniform*, or *varied*. . .The depth of uniform flow is called *normal depth*.
>
> *Steady flow* occurs when the velocity at a point does not change with time. Otherwise, the flow is *unsteady*, such as traveling surges and flood waves in an open channel.
>
> Whether *laminar flow* or *turbulent flow* exists in an open channel depends upon the Reynolds number of the flow. . .turbulent flow may be over either a smooth boundary or a rough boundary, depending on the relative size of the roughness elements as compared with the thickness of the laminar sublayer.
>
> Unlike laminar and turbulent flow, *tranquil flow* and *rapid flow* occur only with a free surface or interface. The criterion for this classification of flow is the Froude number $Fr = V/\sqrt{gy}$. . .When Fr = 1.0, the flow is *critical*; when $Fr < 1$, the flow is *tranquil*; when $Fr > 1$, the flow is *rapid*.
>
> Uniform flow in an open channel occurs with either a *mild*, a *critical*, or a *steep slope*, depending on whether the flow is tranquil, critical, or rapid, respectively. (Chow, 1964: 7-23)

These definitions are theoretical and often must be modified for practical cases of real fluids. True steady flow is found only with laminar flow, which rarely occurs in natural systems. In turbulent flow, there are continual fluctuations in velocity and pressure at every point. However, if the values fluctuate equally on both sides of a constant average value, the flow is considered steady.

Likewise, the strict definition of uniform flow can have little meaning (i.e., rarely exists) for the flow of a real fluid where the velocity varies across a section. But when the size and shape of cross sections are constant in the length of channel under consideration, the flow is said to be uniform. Steady (or unsteady) and uniform (or nonuniform) flow can exist independently of each other so that any of four combinations is possible.

Throughout the remainder of this chapter, flow refers to turbulent open channel flow unless otherwise indicated. For a thorough discussion of theory and assessment of open channel flow, see King and Brater, 1963; Chow, 1964.

FLOW DATA COLLECTION

A common approach to flow recommendation is based on existing records obtained from the USGS. The USGS flow data are obtained from stage recording gaging stations on streams where channel geometry and flow rate are known. Stage gages are either the nonrecording type, which must be read by observers, or the recording type, which produce time stage graphs. A typical recording gage installation consists of a continuous stage recorder over a well, on the stream bank, connected to the stream by intake pipes (Chow, 1964). The object of the gaging station is to determine the flow of water past the station by measuring stage. Stage is then converted to discharge by using a curve of the stage-discharge relationship actually measured at or near the station. Because the stage recorder provides continuous flow records, it is especially helpful in observing peak and low (minimum) flows as well as variations in flow and mean flows. These data are available annually through the state office of the USGS and can be obtained more frequently through local river basin USGS offices.

Besides actual measurements of flow for a particular time, records of flow obtained over specified intervals of time can be utilized to estimate flow conditions. These are usually based on USGS records, reservoir releases [power, Tennessee Valley Authority (TVA), U.S. Bureau of Reclamation (USBR)] or diversion measurements [irrigation companies, State Engineer (water rights), USBR]. Table 1 gives the more common sources of available flow data.

STATISTICAL AND PROBABILITY ANALYSIS

Quantitative scientific data may be classified into two kinds; experimental data and historical data. The *experimental data* are measured through experiments and usually can be obtained repeatedly by experiments. The *historical data*, on the other hand, are collected from natural phenomena that can be observed only once and then will not occur again. Most hydrologic data are historical data which were observed from natural hydrologic phenomena. . .The mounting quantities of hydrologic data can suitably be expressed in statistical terms and be treated with probability theories. Furthermore, natural hydrologic phenomena are highly erratic and commonly stochastic in nature, and therefore are amenable to statistical interpretation and probability analysis. . .One of the important problems in hydrology deals with interpreting a past record of hydrologic events in terms of future probabilities of occurrence. This problem arises in the estimates of frequencies of floods, droughts, storages, rainfalls, water qualities, waves, etc; the procedure involved is known as *frequency analysis*. (Chow, 1964:8-23)

Hydrograph

A graph showing stage, discharge, velocity, or other properties of water flow with respect to time is known as a *hydrograph*. When the stage is plotted against time, the graph is a *stage-time graph* or *stage hydrograph*, which is usually shown on the recorder chart from a recording-gage station. When the discharge is shown against time, the graph is a *discharge hydrograph*, or commonly called simply a "hydrograph." By use of the stage-discharge relation at a gaging station, the discharge hydrograph can be obtained by conversion from a given stage hydrograph. (Chow, 1964:14-8)

Time Series

A *time series* is a sequence of values arrayed in order of their occurrence which can be characterized by statistical properties. . .The daily hydrograph is a graphical representation of a time series of daily discharges. . .A time series may be a function of time explicitly or a function of any single variable which takes the place of time. Examples of sequences ordered by distance rather than time are the width and roughness of a stream channel as a function of distance. . .Most of the statistical methods used in hydrologic studies are based on the assumption that the observations are independently distributed in time. The occurrence of an event is assumed to be independent of all previous events. This assumption is not always valid for hydrologic times series. Observations of daily discharges do not change appreciably from one day to the next. There is a tendency for the values to cluster, in the sense that high values tend to follow high values and low values tend to follow low values. Thus the daily discharges are not independently distributed in time. The dependence between monthly discharges is less than that between daily discharges, and the dependence between annual discharges is less than that between monthly discharges. Thus the dependence between hydrologic observations decreases with an increase in the time base. (Chow, 1964:8-78, 79)

Streamflow is a continuous process which varies with time, and thus streamflow data are said to

Table 1. Sources of stream flow data.

Agency	Hydraulic Data	Water Quality Data
U.S. Geological Survey topographic maps and data for each state are available in USGS office in state capital, published as Volume I Flow Data and Volume II Water Quality Data	1. Gaging stations a) Flow records b) Stage-discharge curves c) Channel cross-sections 2. Topographic maps a) River distances (travel times) b) Channel slopes c) Location of tributaries, point loads and point diversions.	1. Water Quality stations a) Cation and anion balances b) Other data
Environmental Protection Agency		1. STORET data: Water quality raw data and statistics. 2. Specific water quality reports are available, when performed at region offices.
State Agencies		1. State Engineers Office a) Water Use Data b) Irrigation district 2. State Environmental Regulatory Agency a) 303e studies b) 208 studies 3. State Wildlife Resources and State Parks
U.S. Fish and Wildlife Service	Regional Offices	Regional Offices
U.S. Bureau of Reclamation	Usually uses USGS data but reservoir releases, etc. and research reports are important	Research Reports
U.S. Bureau of Land Management	Environmental Impact Statements and specific research projects	Environmental Impact Statements and specific research projects
U.S. Forest Service		USFS River Basin Planning Studies
Universities	Applied and Basic Research Projects	Applied and Basic Research Projects

form a time series. A plot of streamflow against time would show a pattern of variation recurring each year; that is, high flows tend to occur at particular times of the year and low flows at others in response to climatological characteristics which also vary seasonally. (Riggs, 1968:36)

Stream flows are not discrete values. Therefore, a hydrograph must be divided into parts which are then considered as individual streamflows. The parts of the hydrograph all have characteristics which must be considered in any analytical treatment. The part in most common usage

> ...is the daily mean discharge. A daily mean discharge is related to the discharge of the previous day and lies within a range which depends on the time of year. In statistical terms, daily mean discharge is a serially correlated variable, that is, it is nonrandom. The daily mean discharges for a year are also not homogeneous; they are more likely to be larger at one time of the year than at another. Data are considered homogeneous if any subgroup to which certain of these data may be logically assigned has the same expected mean and variance as any other subgroup of the population.
>
> Monthly mean discharges for different calendar months are also serially correlated and nonhomogeneous. Annual mean discharges may be homogeneous values. They may or may not be serially correlated, depending on the amount of basin storage at the time that the hydrologic year begins.
>
> Instead of a streamflow variable made up of adjacent segments of a hydrograph, [one] may consider variables such as July mean, annual peak discharge, or annual minimum flow. These variables are made up of one individual from each year and thus are independent of the yearly cycle of streamflow. They are also independent of each other (with the possible exception of annual minimum flows which include effluent from ground-water recharge of a previous year).
>
> Precipitation, temperature, sediment discharge, water quality, transpiration, evaporation, and solar radiation vary throughout the year; indices describing them may be nonrandom and nonhomogeneous. (Riggs, 1968:36)

Flow-duration Curve

> When the values of a hydrologic event are arranged in the order of their descending magnitude, the per cent of time for each magnitude to be equalled or exceeded can be computed. A plotting of the magnitudes as ordinates against the corresponding per cents of time as abscissas results in a so-called *duration curve*. If the magnitude to be plotted is the discharge of a stream, the duration curve is known as a *flow-duration curve* . . . In a statistical sense, the duration curve is a cumulative frequency curve of a continuous time series, displaying the relative duration of various magnitudes. The slope of the duration curve depends greatly on the observation period used in the analysis. The mean daily data will yield a much steeper curve than annual data as the latter tend to group and smooth off the variations in the shorter-interval daily data.
>
> Figure [2] shows a typical flow-duration curve. Such a curve may be considered to represent the hydrograph of the average year with its flows arranged in order of magnitude. For example, the flow in the average year to be equalled or exceeded 20 percent of the time is 2,500 cfs. (Chow, 1964:14-42)

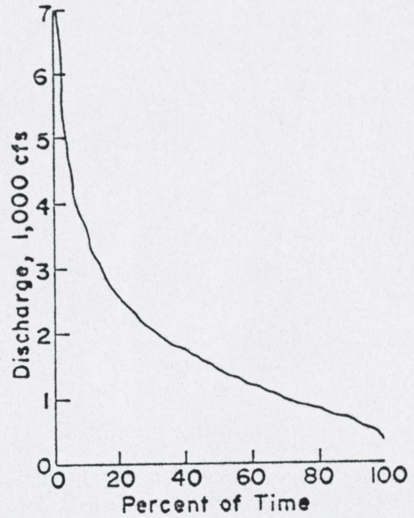

Figure 2. Typical flow duration curve (from Chow, 1964).

Flow duration analyses can be made using all of the daily data in a year, from any given month (e.g., June), week (e.g., 26th week of the year), day (e.g., June 7), or any other specific annual interval. Monthly average flows can be utilized as well as annual flows.

> The shape of a flow-duration curve may change with the length of record. This property can be used to extend the flow information on a given stream for which short-term records are available and for which simultaneous and long-term records are available on at least one adjacent stream which is believed to be under similar hydrologic conditions. By comparing the flow-duration curves constructed of the short-term record of the given stream and of the corresponding short-period record on the adjacent stream, the flow-duration curve for the long-period record of the adjacent stream can be proportionally adjusted to produce an approximate flow-duration curve for the given stream for the corresponding long-period record.
>
> Similarly, if a hydrograph is given at a station *A*, the corresponding hydrograph at an adjacent station *B* can be estimated by comparing the

flow-duration curves of a same period of record at both stations. If there is no flow record at station *B*, the flow-duration curve at this station can be estimated by the above-mentioned method. From the flow-duration curve for station *A*, the per cent of time for a discharge on the given hydrograph is first found. For the same per cent of time on the flow-duration curve of station *B*, the corresponding discharge is estimated. Repeating this procedure for a number of discharges obtained from the given hydrograph for station *A*, an estimated hydrograph for station *B* for the corresponding storm can be thus constructed. (Chow, 1964:14-44)

HYDROLOGIC MODELS, PROCESSES, AND SYSTEMS

Hydrologic models considered here are mathematical formulations to simulate natural hydrologic phenomena which are considered as processes or as systems.

Any phenomenon which undergoes continuous changes particularly with respect to time may be called a *process*. As practically all hydrologic phenomena change with time, they are *hydrologic processes*. If the chance of occurrence of the variables involved in such a process is ignored and the model is considered to follow a definite law of certainty but not any law of probability, the process and its model are described as *deterministic*. On the other hand, if the chance of occurrence of the variables is taken into consideration and the concept of probability is introduced in formulating the model, the process and its model are described as *stochastic* or *probabilistic*. For example, the conventional routing of flood flow through a reservoir is a deterministic process and the mathematical formulation of the unit-hydrograph theory is a deterministic model. (Chow, 1964:8-9)

Average flow records (annual, monthly, etc.) are of considerable value for reconnaissance approaches to discharge assessment and recommendation. These approaches, based upon synthesized flow data, have the advantage of allowing evaluation of necessary flows with little or no field work. However, the major constraint of flow records is their availability and duration. When a stream is not gaged, or has not been gaged for a suitable period of time, flow data must be calculated from records other than on the stream in question and become less accurate and/or require field measurements.

Regression Analysis

A method of estimating flows at a site without a continuous record or with a record too short for flow duration analysis is regression analysis. Regression techniques usually provide results that are quite acceptable considering the limited nature of the data. Riggs (1972) provides a complete treatment of regression analysis for hydrologic systems.

Average Annual Flow

Estimates of average annual flow (QAA) may be obtained from measurements made on topograph maps or aerial photographs and an estimate of average annual precipitation over the watershed in question. Statewide isohyetal maps may be used to estimate average annual precipitation.

Then QAA = cPA . . . . (1)

where QAA = average annual discharge in cfs, P = average annual precipitation in inches, A = the watershed area in square miles, and c is a constant which increases with increased precipitation.

c can readily be determined from a log - log plot of QAA vs P · A for gaged streams (c = y intercept) and then used to estimate QAA for ungaged streams in the same hydrologic province using Equation (1) (Figure 3). Orsborn (1974) found that c varied from 0.014 to 0.059 from arid to humid portions of the state of Washington.

The above technique has greatest utility in humid areas where mean runoff is more closely

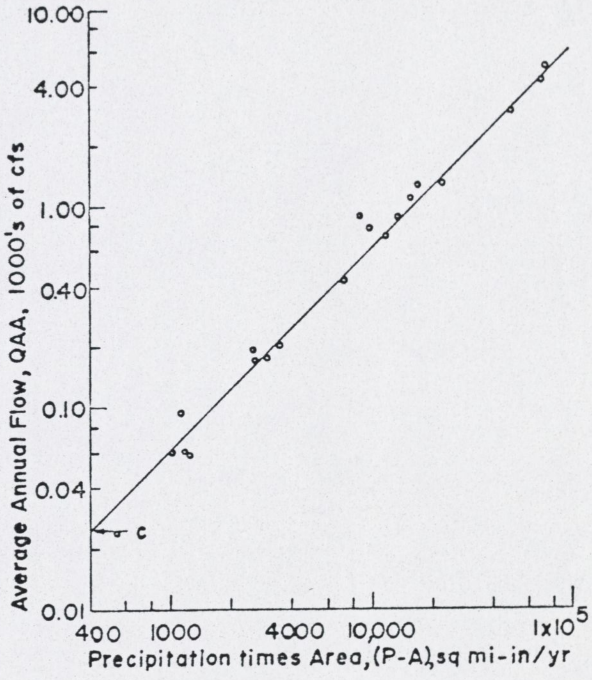

Figure 3. Average annual flow related to precipitation and drainage area (from Orsborn, 1974).

related to drainage area and the maximum deviation is on the order of 10 percent. In the mountainous western United States, where annual precipitation may range from < 5 to 40+ inches over various portions of a watershed, relationships of mean flow to drainage area are less acceptable. Estimates of the mean flow of ungaged streams in those regions, based on drainage area might be in error 100 percent or more (Riggs 1969).

An annual mean flow can be estimated (as described by Riggs, 1969) within approximately 10 percent of actual measured value even though both the gaged and ungaged streams are affected by diversions and have different runoff characteristics. Riggs utilized the following steps to estimate annual mean flow: 1) Estimate 12 individual monthly flows from one discharge measurement per month; 2) compute the annual mean from the estimated monthly means; and 3) use a relationship based on gaging station records to estimate the long-term mean (mean flow of record) from the one annual mean.

ESTIMATING MONTHLY MEANS AND MEAN ANNUAL FLOWS

The following method is as described by Riggs (1969) using data from two streams in southern Idaho. This method allows the determination of mean monthly discharge and mean annual discharge for an ungaged stream when historical records of flow are available for a nearby stream.

Discharge must be measured at the point of interest on the ungaged stream and on the same day at the gage station on a nearby gaged stream. At least 12 sets of such measurements are necessary over a 12-month period (one for each month). These data are plotted on log-log paper as is shown in Figure 4. Using Figure 4 and the data in Table 2, an example for estimating mean monthly and annual flow in an ungaged stream follows.

To compute mean monthly discharge for a particular month (in this example July), first construct a 45° line through the point labelled 7/15 in Figure 4. Secondly, read in the monthly mean discharge of the gaged stream (East Fork Jarbidge River) for that month (122 cfs from station records) on the X axis and move up to the 45° line and over to the Y axis and directly read the estimated monthly mean flow for the ungaged stream (East Fork Bruneau River). This process is continued for the other 11 months. Annual mean discharge is then estimated by averaging the 12 monthly discharges. From Table 2 this is seen to be 47 cfs, which compares favorably with the 51.8 from historical records.

Table 2. Field-measured flow data from two southern Idaho streams (from Riggs, 1969).

Daily mean discharge cfs			Monthly mean discharge, cfs					
Date	E. F. Bruneau River	E. F. Jarbidge River	Month	E. F. Jarbidge River (Measured)			E. F. Bruneau River Computed	E. F. Bruneau River Measured
10/15/56	7.7	9.9	10	10.5			8	7.6
11/15	9.0	8.3	11	10.6			11	9.2
12/15	12	15	12	12.0			10	11.1
1/15/57	10	9.1	1	8.6			9	8.9
2/15	30	15	2	15.0			30	21.0
3/15	28	25	3	26.7			30	29.7
4/15	79	101	4	74.5			58	69.6
5/1	76	170						
					224	170		
5/15	327	222	5	284			230	229
					340	290		
6/1	248	471						
					435	190		
6/15	105	258	6	364			133	115
					292	76		
7/1	57	305						
7/15	16	112	7	[122]			[17]	22.7
8/15	12	23	8	23.9			13	12.8
9/15/75	11	12	9	12.8			12	11.3
				80.5			[47]	51.8

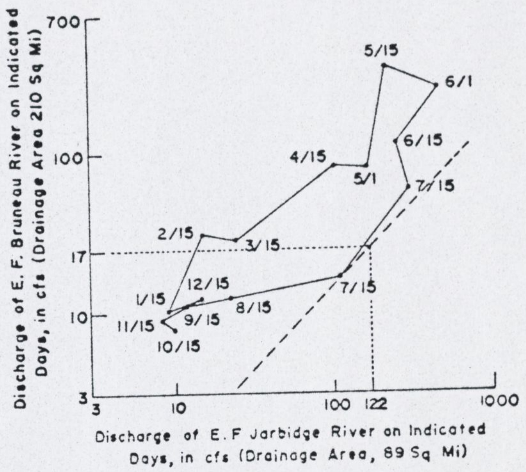

Figure 4. Concurrent discharges from Table 2 (from Riggs, 1969).

ESTIMATING LONG-TERM MEAN FLOW FROM ONE ANNUAL MEAN

From records of gaged streams in the vicinity of the ungaged stream, first plot mean flow for the water year of concern versus the long-term annual means, as is shown in Figure 5. Then simply read in

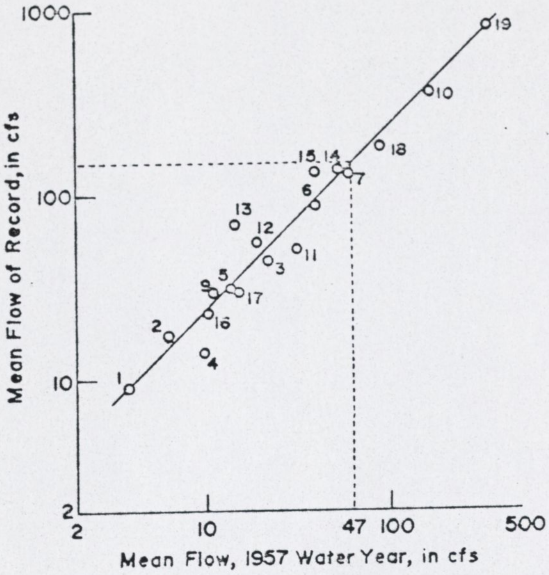

Figure 5. Relationship between one annual mean flow to mean flow of record (from Riggs, 1969).

the computed annual mean (47 cfs from Table 2 above) on the X axis and proceed to the regression line and over to the Y axis to directly read the estimated mean annual flow of record.

Flood Flows

Flood flows (QF) may be estimated for ungaged streams from the following formula (Bodhaine and Thomas, 1964):

$$QF = cA^{b_1} R_A^{b_2} L^{b_3} G \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where QF = flood discharge in cfs at the downstream point of the watershed; c is a constant; A = drainage area in square miles; R_A = average annual runoff in inches/year; L = the area of lakes, as a percent of total drainage area with 0.01 as a lower limit; G = geographical factor; b's are coefficients.

The USGS has divided the conterminous United States into 14 major drainage basins (Figure 6). Specific constants and coefficients for use in Equation (2) are unique for each major drainage. The USGS is developing annual runoff and geographic factor maps which have isopleth lines indicating areas of equal values. By interpolation from the maps, R and G values can be determined and utilized in a nomograph (Figure 7) and QF directly estimated.

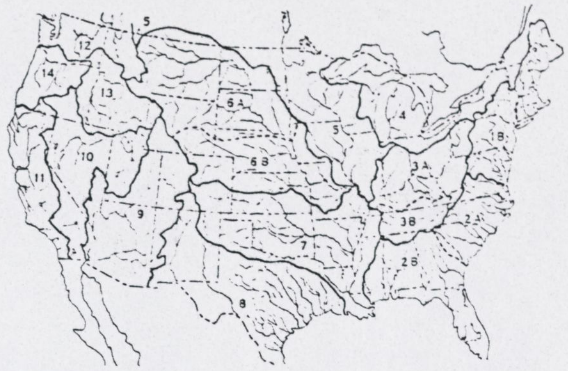

Figure 6. Map of conterminous United States showing 14 major drainage basins (from Bodhaine and Thomas, 1964).

Flood flows (QF) for the Pacific slope basins in Washington have been predicted for ungaged basins using the following data with Equation (2):

$$QF = 0.638A^{0.889} R^{1.135} L^{-0.037} G$$

Low Flows

> That low-flow characteristics of streams in adjacent basins may be greatly different but not be discernible from known basin characteristics. The principal terrestrial influence on low flows is geology (the lithology and structure of the rock formations), and the principal meteorological influence is precipitation. So far it has not been possible adequately to describe the effect of geology on low flow by an index. . . (Riggs, 1972:10)

Since heavy demands for irrigation and other uses occur during periods of low flow in many western streams (Figure 8), the average low flow with 1-, 2-, 10-, and 20-year recurrence intervals is an important consideration when establishing instream flow needs.

Even though estimates of low-flow characteristics from basin characteristics generally are of low accuracy, the often immediate demand for such estimates justifies development of regional relationships where conditions allow.

Orsborn (1972, 1974) has presented techniques for predicting low flows in ungaged streams, using the following expression:

$$Q\,7L2 = \emptyset\left[\frac{(AH)^{0.5}\ Q\,7L1P}{300p}\right]^m \quad \ldots\ldots\ldots\ldots (3)$$

in which Q 7L2 is the 7-day average low flow (cfs) of 2-year recurrence interval, Q 7L1P is the 7-day average low flow (cfs) of 1-year recurrence inter-

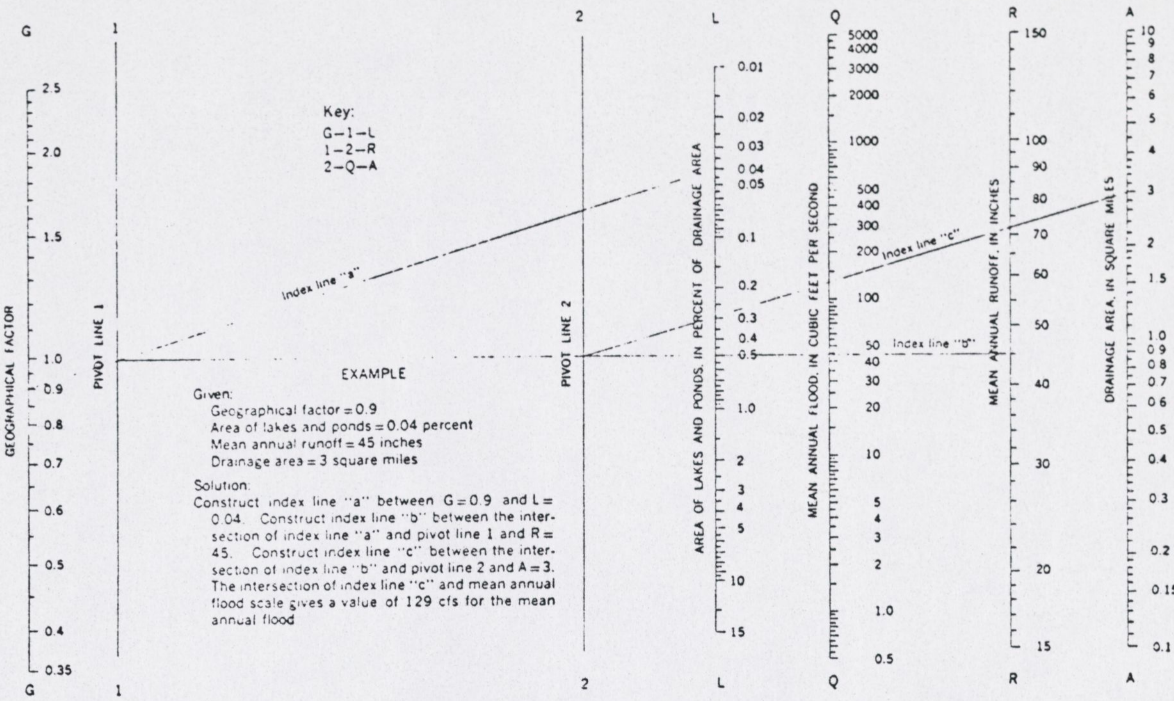

Figure 7. Drainage areas of 0.1 to 10 square miles in Pacific slope basins, i.e., area 12 in Figure 6 (from Bodhaine and Thomas, 1964).

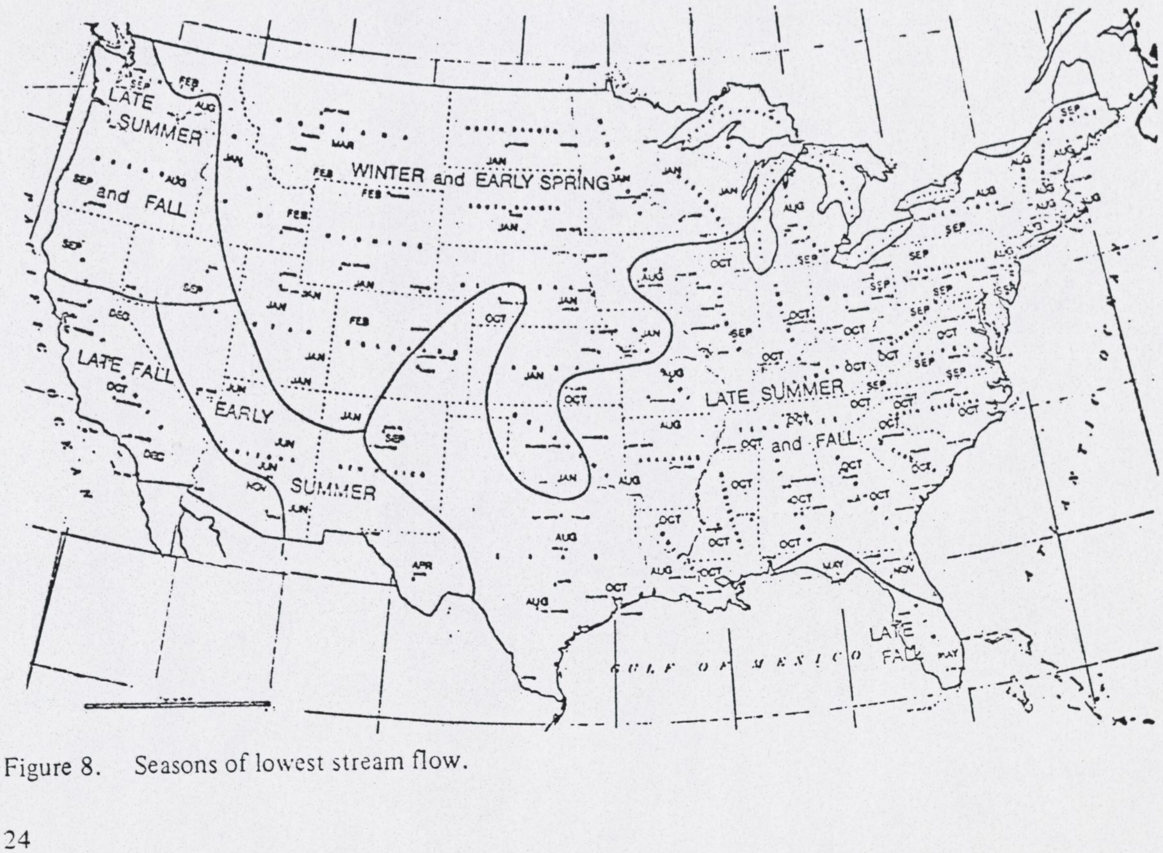

Figure 8. Seasons of lowest stream flow.

val, A is the drainage basin area in square miles, H is the basin relief (the deviation difference between the headwaters and the outlet in miles), and p is the slope of the recurrence interval curve (Figure 9).

Equation (3) is simplified to:

$$Q\ 7L2 = \phi\ \chi^{m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where $\chi = (AH)^{0.5}$ Q 7L1P/300 p.

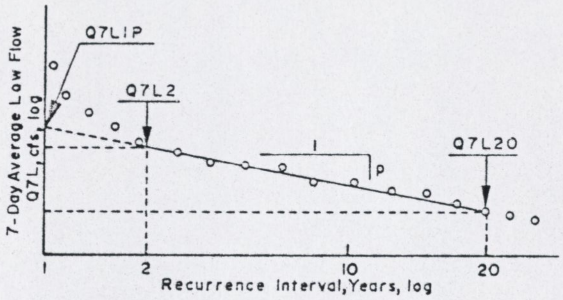

Figure 9. Low-flow recurrence interval graph (from Orsborn, 1974).

Procedures for estimating low flows for ungaged streams are given below as described by Orsborn (1973).

1. Measure the following parameters for the stream basin from maps of 1:24,000 and/or 1:62,500 scales; length of first order (unbranched) streams (L1); total length of streams (LT); basin relief (H); and drainage area (A).

2. Determine which of the following basin parameters most closely correlate with (Q 7L2) in nearby gaged stream basins: 3/2 (L1 · H); (LT) $(H)^{0.5}\sqrt{DD}$ (L1) where DD = LT/A (by plotting and fitting by eye).

3. Using the basin parameter(s) best correlated with (Q 7L2) in step 2, use the same parameter(s) measured on the ungaged basin to make first estimates of (Q 7L2).

4. Estimate (Q 7L1P) for the ungaged stream based on the ratios of (Q 7L1P) to (Q 7L2) from nearby gaged streams.

5. Plot (Q 7L2) and (Q 7L20) for each gaging station in nearby streams on a log-log recurrence interval graph (e.g., Figure 9) and determine the slope p and Q 7L2 = $\phi\chi^{0.60}$ relationships.

6. With the above relationship from nearby gaged streams, derive p for the ungaged stream by p = $(AH)^{0.5}$ (Q 7L1P)/300χ, where p is the slope of the log-log recurrence interval plot between (Q 7L2) and (Q 7L20) for the ungaged stream.

7. Estimate the ungaged value of (Q 7L20) based on the slope index of (Q 7L2)/(Q 7L20) in gaged streams.

8. Plot (Q 7L2) on log-log graph paper and project the slope of the line (p) towards (Q 7L20). If the intercept of the projected line and the value of the ordinate (Q7L) at the 20-year recurrence interval line show agreement with the estimated value of (Q 7L20) from step 7, the solution is complete. If not reiterate.

A recent paper by Orsborn et al. (1975) describes the relationship among low, average and flood flows using the equation.

$$c(QAA)^3 = (Q7L2)\ (QF2)^2 \quad \ldots\ldots\ldots\ldots (5)$$

where QAA is average annual flow, Q7L2 is the 7-day average low flow with a 2-year recurrence interval, QF2 is the flood flow with a 2-year recurrence interval, and c is a coefficient. The coefficient (c) was the only term which showed much variation between hydrologic regions.

It is possible to synthesize flow duration curves by estimating low, average and flood flows by the above methods and direct comparison with duration curves from nearby gaged streams.

STREAM FLOW MEASUREMENT

Measurement is a key phase of evaluating flow requirements for the satisfaction of instream needs. Measurements necessary for the determination of flows include stream velocity, cross-sectional area, slope, wetted perimeter, and hydraulic radius. Flow measurements range from very crude and inaccurate techniques using visual estimates of width (W) and mean depth (D) to obtain the cross-sectional area (A), and estimates of mean stream velocity ($\overline{V}$) to obtain flow (Q),

Where

$$Q = \overline{V}A = \overline{V}W\overline{D} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

to very sophisticated and accurate stream flow measurements as in special flumes where water discharge is calibrated to a water stage. Methods recommended by USGS for measuring average velocity and discharge are given by Corbett (1943).

Transect Measurements

Transects (line intercepts) as a means of collecting data (physical, chemical or biological), receive considerable use by field workers in the aquatic area. Management personnel have used several varieties of the transect approach to generate input data for analysis in flow assessment methodologies. These techniques vary from hand level-rod surveying or a stretched tape on smaller streams to the sag tape or transit-stadia rod surveying for intermediate to large streams and rivers. Whatever the approach to differing needs and/or field conditions, a transect is simply a line established (by tape, surveying, etc.) across a stream or river under which measurements are taken or observations made.

HAND LEVEL-SURVEYING ROD

Transect data can be obtained by the use of a hand level (Abney type) and a small surveying rod. This technique can be used on small, wadable streams. This is a common approach described adequately in any standard surveying manual.

TIGHT TAPE

This procedure consists of tightly stretching a tape across a stream and taking necessary measurements at intervals along the tape. Transect end points are established and marked at the water level, estimated bankful, or other locations on each bank of the stream. The end of the tape is set or held on the marker at one bank point and the tape is tightly stretched across the stream and held directly on the marker on the other bank. Measurements and/or observations such as depth, velocity, and substrate are made at intervals along the tape. Bottom type and size or any other variable can be measured or sampled under the transect intervals. By establishing permanent bank marks (individually identified) and using the same tape intervals, some degree of comparability between data collection times and conditions can be achieved. This approach is useful on small wadable streams where a tape can be tightly stretched and in-channel measurements can be taken. When these two considerations cannot be attained, other procedures must be used.

SAG TAPE

This technique is a modification of the basic transect approach and is useful for establishing measurements across streams that are too wide to use the tight tape technique. As presently designed one man can conduct all necessary field work. The sag tape technique can be used to provide input data for a computer program R2 CROSS. Portions of the following description are included for completeness in the event the data may be used as computer input. However, computerized computation of sag tape (or other transect) data is not a necessity. These data can be used in manual calculations. Precautions and sources of error mentioned for computer precision also stand for manual computations. This description has been taken and/or modified from an unpublished USFS mimeo (Anonymous, 1974).

Special Equipment for Data Collection

Steel Tape or Chain – A 100-foot reel tape is normally used. It is necessary to know or determine the *weight in pounds* for a 1-foot section of the tape. If this value cannot be obtained, use .0107 lbs/ft (this weight is required if sag tape data are used as computer input). *Tension Scale* – A small spring scale (20-30 lb. capacity) used to measure the tension applied when stretching the tape between the two stakes of the transect (Figure 10). *Tape Clamp* – A modified (spoonbill) "vice-grip" to hold the tape in tension. *Transect Stakes* – Metal stakes 24 to 36 inches in length. *Measuring Rod* – Any device suitable for measuring the distance in feet and tenths of feet from the tape to the channel bottom. *Abney Hand Level* – This is necessary for leveling the tape and for determining stream gradient.

Once the transect point on the stream is established, a steel tape is stretched from the top of a transect stake to a tape clamp and spring scale, which is attached to another stake on the opposite stream bank (Figure 10). Tension is applied as the tape is drawn up and clamped. *The tension shown on the scale must be at least 5 pounds, plus one pound for each 10 feet of transect length,* i.e., stake to stake distance. (The computer will correct for depth errors due to tape sag if it is given the weight of the tape in lbs/ft., the length of tape across the transect, and the tension in-lbs on the spring scale. Use the Abney level to

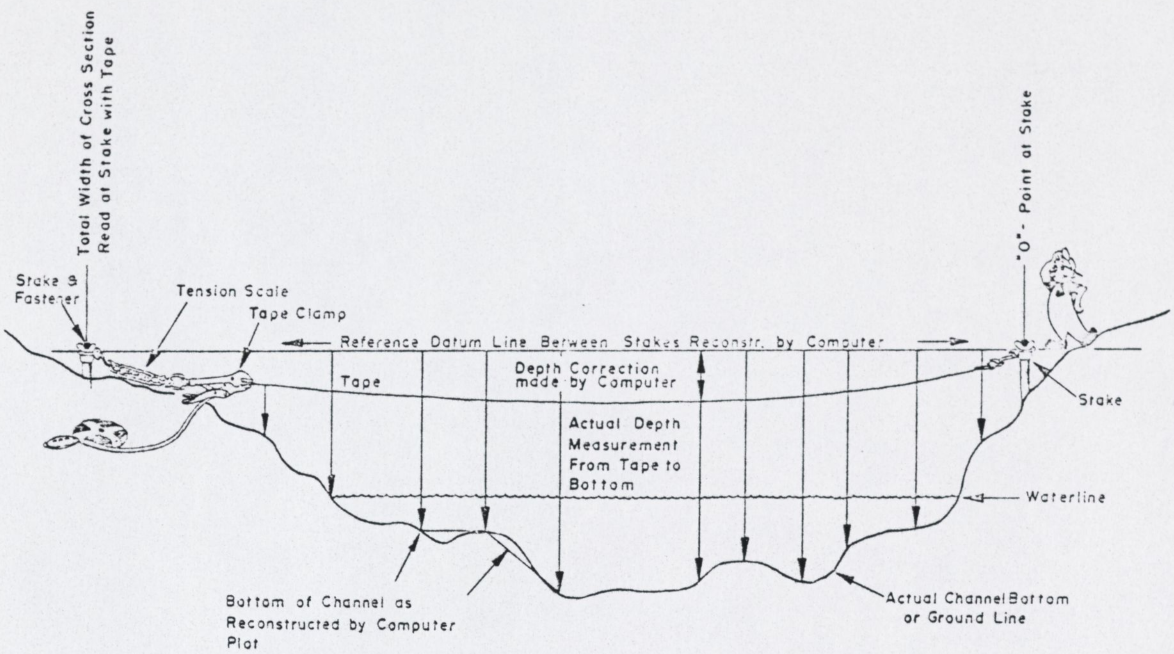

Figure 10. Sag-tape schematic (from Anonymous, 1974).

make sure the ends of the tape are level.)

Depth measurements are taken from the tape to the ground surface or channel bottom and recorded in feet and tenths of feet. The *first* and *last* measurements are always taken at the transect stakes. Measurements may be taken along the tape at fixed intervals, or at any interval desired to show changes in the existing ground surface or channel bottom.

Sources of Measurement Error When Using Sag Tape Data as Computer Input

Tape Tension – Be sure to have *at least* 5 pounds plus 1 pound for each 10 feet of transect. *Level Transect Stakes* – The tops of the two transect stakes should be on the same level line, or nearly so to prevent an inadvertent skewing of the programmed or manual output data. *Distance* – The "0" distance mark on the tape must be actually at the "0"-point stake of the transect. This is a key reference point in program procedure. *Streambank-Waterline Intersect Distance from "0"-Point* – It is extremely important to accurately locate the distance from the "0"-point at which the first and furthest waterlines are encountered across the width of the channel. Measure to the nearest tenth of a foot. *Velocity Measurement* – If the water depth is under 2.5 feet, use the .6 method; if over 2.5 feet, use the .2-.8 method. The number of measurements can be variable as long as no more than 10 percent of the total flow is between two measurements. *Note* – On long cross-sections, the depth from tape to bottom at the waterline points may not be the same on both sides of the channel due to tape "sag," and if the actual water channel is off-center of the total cross-section. It is extremely important to avoid inadvertent lifting or depression of the tape which may disturb the natural "sag."

TRANSIT – STADIA ROD

On large, unwadable streams or rivers, where the above approaches cannot be implemented, surveying techniques must be used to gather cross-sectional data. Descriptions of this technique are available in standard surveying manuals.

Large riveer environs present a particular problem in measuring streamflow parameters and channel features. Available techniques are not functional for gathering data in large rivers where the use of a boat is a necessity. However, by establishing surveying transects (transit-stadia rod) and using echo sounding equipment to determine channel configuration, input data can be collected for most methods of analysis.

Determination of Depth

> Depth is measured by several methods. They include graduations on [a] wading rod, tags on [a] cable which supports [a] meter-and-weight assembly, or a mechanical indicator attached to the reel on which the supporting cable is wound. (Chow, 1964:15-16, 17)

WADING ROD

> The wading rod is graduated in tenths of a foot, with the zero at the bottom of the base plate. The depth is read by estimating the point at which the level surface of the water intersects the rod... Observations can usually be made to half-tenths with good accuracy. (Chow, 1964:15-17)

CABLE AND WEIGHT

> [A] meter-and-sounding-weight assembly is supported on a steel cable. This is fastened to a rubber-covered two-conductor cable which serves as a hand line for making measurements with 15- and 30-lb sounding weights. If heavier weights are required, the steel cable is wound on a sounding reel. When the hand line is used, the steel cable is tagged at 2-ft intervals from the bottom of the weight, thus facilitating the determination of depth. The sounding reel is equipped with a mechanical counter so that the depth may be read directly. (Chow, 1964:15-17)

FATHOMETER

> The fathometer has proved successful in the determination of stream depths. A small transducer has been adapted for installation in a sounding weight, and the depth can be read from the fathometer by placing the weight and the transducer just beneath the water surface. A sounding weight is still necessary for the setting of the meter. If the river is too deep or swift to permit setting the meter at the 0.8 depth for an observation, readings may be taken at 0.2 depth and adjusted. With a fathometer, it would not be necessary to depend on a cross-section developed at a lower stage for computation of meter setting. The two principal sources of error are oversounding in alluvial streams from the sounding weight sinking into the stream bottom and apparent oversounding in swift streams caused by drag on the line and the meter-and-weight assembly. Also, if the meter is raised and lowered in the same spot or held within close proximity of the bottom, the scouring action caused by the velocity disturbance tends to cause the formation of a hole beneath it. (Chow, 1964:15-17)

Average stream depth (D) is often an important parameter for estimating habitat availability as well as for estimating stream reaeration rates. It can be calculated by substituting mean depth and width equivalents into Manning's equation, rearranging, and solving by trial and error or by use of tables. For a rectangular cross section with known data for width, slope and flow and an estimate of Manning's n, the average depth (D) can be calculated from the following equation:

$$\frac{D^5}{4D^2 + 2DW + W^2} = \frac{Q^3 n^3}{1.49^3\, S^{3/2}\, W^5}$$

$$\frac{D^5}{D^2 + \tfrac{1}{2}DW + \frac{W^2}{4}} = \frac{4Q^3 n^3}{1.49^3\, S^{3/2}\, W^5} \quad .\ .\ .\ .\ (7)$$

This equation is reduced with relative ease when substitutions are made. For a stream with Q = 2000 cfs, n = 0.025, slope = 0.05, and width (w) average 40 feet, one would calculate average depth in the following fashion:

$$\frac{D^5}{D^2 + \tfrac{1}{2}D\,40 + \tfrac{1}{4}(40)^2} = \frac{(2000^3)\,(0.025^3)}{1.49^3\ 0.05^{3/2}\ 40^5}$$

$$\frac{D^5}{D^2 + 20D + 400} = \frac{(8 \times 10^9)\,(1.5625 \times 10^{-5})}{(3.307949)\,(0.01118)\,(1.024 \times 10^8)}$$

$$\frac{D^5}{D^2 + 20D + 400} = \frac{12500}{3.787 \times 10^6} = 0.33$$

By trial and error, a close enough estimate of 2.8 feet (34 inches) of a mean depth is obtained.

Determination of Velocity

The rotating meter is the most common device used for the gaging of streams. This type operates with a high degree of precision; however, it is not suitable for velocities below about 0.10 ft/sec. or under conditions of extreme turbulence.

The use of a current meter for estimating the *average velocity in a section* is either the measured velocity at the 0.6D (depth), the average of the velocity at 0.2 D and 0.8 D (two-point method), or the average of the two estimates above (three-point method).

Also it should be noted that the *average velocity (V) at a given cross section* is the discharge (Q) divided by the area (A)–i.e., Q = V x A, or V = Q/A.

Other techniques for estimating velocity are also available; examples are dyes, timing a float such as a stick or crocketball, etc. (Table 3). Various chemical and electrical methods have been developed for the measurement of stream flows. The chemical methods include salt velocity, salt dilution, and the detection of radioactive tracers. The electrical devices include oxygen polarography, the hot-wire anemometer, electromagnetic voltage generation, and supersonic waves (Chow, 1964). The electromagnetic flowmeter operates on the principle that an electrical conductor, water, passing through a magnetic field has a current generated within it. The generated current is gathered by two electrodes set with their axes at right angles to the direction of flow and the magnetic field. The electronic signal is translated to a direct velocity measurement by a meter or digital readout. Although still quite costly this type of instrument should prove quite useful as a field instrument for measuring velocity in large rivers.

Table 3. Common methods of estimating natural stream flows, listed in order of most useful (from Linsley and Franzini, 1972).

Method (References)	Types of Streams	Techniques Involved	How to Obtain Data	Time Lag in Getting Data	Data Requirements and Functional Relationships
1. (a) USGS stream gages (b) USBR, TVA, Corps of Engineers, River Authorities, Power Companies, and Federal Power Commission	Small (jumpable), wadeable, and large streams, reservoir releases	Staff gage, rating curve establishing relation between flow and stage (elevation of water surface). Releases from reservoirs would be a good source of downstream flow data.	Stations are marked on quadrangle maps, listed by river basin in USGS publications (published annually by state) or obtained in river basin office. USBR where reservoir releases occur.	Available to public annually in reports or within 2-3 months from river basin office. Occasionally arrangements may be made with local office to accompany engineer on his calibration trips to obtain data immediately.	Stage height with time, Q = f(stage height, time) usually calculated from graphs.
2. Weirs or measuring flumes	Small and some wadeable streams	Construction of a weir with known hydraulic capacities so that stream flow as a function of stage can be determined. Need to measure stage height.	Usually constructed for a specific purpose. U. S. Forest Service, Fish & Game agencies, irrigation companies, and USGS use these.	Usually immediate if relationships are known.	Q = VA, A is a function of stage, V is a function of stage.
3. Tracer studies used primarily to measure mixing rates or changes in flow. With precise additions can measure flow by dilution.	Small, wadeable, and large streams	Fluorescent dyes, salt, radioactive tracers, man-made or natural conservative pollutants (e.g., point source discharges).	Field analysis: Fluorometer; conductivity meter; other measurement devices as appropriate. Sampling devices: Sample bottles; timer. A boat is needed for larger streams.	Time to measure and calculate Q.	Flow changes between points 1, 2. $Q_2 = Q_1 [C_1/C_2]$ Flow rate $Q = Q_t [(C_1 - C_2)/(C_2 - C_0)]$ where Q_t is the steady dosing rate of tracer, C_0 is background concentration of tracer, C_1 is concentration in feed, C_2 is concentration in the stream.
4. Three point method	Wadeable and large streams (for small streams only a single measurement is usually made)	Measured at a particular time. Stream depth and velocity are determined at quartile points on the stream. Velocity is estimated at 0.6 depth with a current meter (e.g., Price Current Meter).	Sometimes agencies responsible for water resources have equipment and reaches defined for such measurements. Tape, depth and current meters are needed. A boat is needed for larger streams. Timer.	None.	Calculate mean depth, mean velocity, and measure width. Q = V·W·D
5. Flow assessment	Small, wadeable, and large streams	Estimate (actually measure when possible) depth and width (1) based on experience estimate velocity, or (2) use an orange or similar object which barely floats and time the passage past two measured points.	Field analysis. Should have at least a tape, timer.	None.	Q = V·W·D

Average stream velocity can be calculated using the Manning equation, which is expressed mathematically as follows:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where V is velocity, R is the hydraulic radius, S is the energy loss per foot of stream length, and n is the roughness coeficient.

The hydraulic radius (R) is the cross-sectional area divided by the wetted perimeter and can be obtained from tables or by estimation; in shallow streams (< 2-3 feet) the wetted perimeter (p_w) can be approximated by a rectangle ($p_w = 2D + W$) or other geometric shapes (Figure 1). For wide shallow streams, R is ≅ to average depth.

Slope (S) must be defined over a distance of flow, the greater the distance the better. A transit or other sighting device may be necessary to obtain a good estimate of slope. Reasonable approximations of S can be obtained by use of a hand level (Abney type) and rod. For open channels with very small slopes, S may also be defined as the slope of the energy gradient. For uniform flow, it is equal to the drop in channel per limit length.

The factor n is either the average across the stream channel or, if large variations occur across the channel, it should be treated by appropriate partitioning techniques. Manning's n is very small for smooth channels and increases as roughness increases (Table 4). For natural stream channels, the roughness coefficient n, as computed from the Manning equation, may vary considerably with change in water stage. Therefore, a variable n value should be used in calculating discharge at different stages (see Discharge-Variable Roughness Coefficient).

Table 4. Values of n to be used with the Manning equation (from King and Brater, 1963).

Surface	Best	Good	Fair	Bad
Uncoated cast-iron pipe	0.012	0.013	0.014	0.015
Coated cast-iron pipe	0.011	0.012*	0.013*	
Commercial wrought-iron pipe, black	0.012	0.013	0.014	0.015
Commercial wrought-iron pipe, galvanized	0.013	0.014	0.015	0.017
Smooth brass and glass pipe	0.009	0.010	0.011	0.013
Smooth lockbar and welded "OD" pipe	0.010	0.011*	0.013*	
Riveted and spiral steel pipe	0.013	0.015*	0.017*	
Vitrified sewer pipe	{0.010, 0.011}	0.013*	0.015	0.017
Common clay drainage tile	0.011	0.012*	0.014*	0.017
Glazed brickwork	0.011	0.012	0.013*	0.015
Brick in cement mortar; brick sewers	0.012	0.013	0.015*	0.017
Neat cement surfaces	0.010	0.011	0.012	0.013
Cement mortar surfaces	0.011	0.012	0.013*	0.015
Concrete pipe	0.012	0.013	0.015*	0.016
Wood stave pipe	0.010	0.011	0.012	0.013
Plank Flumes:				
Planed	0.010	0.012*	0.013	0.014
Unplaned	0.011	0.013*	0.014	0.015
With battens	0.012	0.015*	0.016	
Concrete-lined channels	0.012	0.014*	0.016*	0.018
Cement-rubble surface	0.017	0.020	0.025	0.030
Dry-rubble surface	0.025	0.030	0.033	0.035
Dressed-ashlar surface	0.013	0.014	0.015	0.017
Semicircular metal flumes, smooth	0.011	0.012	0.013	0.015
Semicircular metal flumes, corrugated	0.0225	0.025	0.0275	0.030
Canals and Ditches:				
Earth, straight and uniform	0.017	0.020	0.0225*	0.025
Rock cuts, smooth and uniform	0.025	0.030	0.033*	0.035
Rock cuts, jagged and irregular	0.035	0.040	0.045	
Winding sluggish canals	0.0225	0.025*	0.0275	0.030
Dredged earth channels	0.025	0.0275*	0.030	0.033
Canals with rough stony beds, weeds on earth banks	0.025	0.030	0.035*	0.040
Earth bottom, rubble sides	0.028	0.030*	0.033*	0.035
Natural Stream Channels:				
(1) Clean, straight bank, full stage, no rifts or deep pools	0.025	0.0275	0.030	0.033
(2) Same as (1), but some weeds and stones	0.030	0.033	0.035	0.040
(3) Winding, some pools and shoals, clean	0.033	0.035	0.040	0.045
(4) Same as (3), lower stages, more ineffective slope and sections	0.040	0.045	0.050	0.055
(5) Same as (3), some weeds and stones	0.035	0.040	0.045	0.050
(6) Same as (4), stony sections	0.045	0.050	0.055	0.060
(7) Sluggish river reaches, rather weedy or with very deep pools	0.050	0.060	0.070	0.080
(8) Very weedy reaches	0.075	0.100	0.125	0.150

*Values commonly used in designing.

Estimating Discharge

Table 3 summarizes the common methods for estimating discharge.

Reliable estimates of discharge (Q) are made when velocity is actually measured (as with a current meter) and Manning's equation back calculated for n. Using Equation (8), the roughness coefficient n can be expressed as:

$$n = \frac{1.49\,(R^{2/3}S^{1/2})}{V} \quad \ldots\ldots (9)$$

Discharge is then calculated for any desired water level (stage):

$$Q = \frac{1.49}{n} R^{2/3} S^{1/2} A \quad \ldots\ldots (10)$$

where R ≅ to average depth in ft., and A ≅ cross-sectional area in sq. ft. Cross-sectional area can be approximated by geometric figures (Figure 1).

Approximate estimates of discharge can be made for visually determined depths above (or below) a field measured reference flow using the following formulae:

$$Q = k[D(1 + \frac{\Delta W}{10})]^{3/2} \quad \ldots\ldots (11)$$

where the reference flow has an average velocity > 1.1 fps, $k = Q/D^{3/2}$, and ΔW = change in stream width from reference flow measurement in ft.;

$$Q = k[D(1 + \frac{\Delta W}{10})]^{5/3} \quad \ldots\ldots (12)$$

where the reference flow has an average velocity of 0.9 to 1.1 fps, and $k = Q/D^{5/3}$;

$$Q = k[D(1 + \frac{\Delta W}{2/\bar{A}})]^{5/2} \quad \ldots\ldots (13)$$

where the reference flow has an average velocity < 0.9 fps, and $k = Q/D^{5/2}$.

DISCHARGE – VARIABLE ROUGHNESS COEFFICIENT

Discharge can be computed as shown in Equation (10), for varying water levels (stages). However, in natural stream channels, the roughness coefficient n, as computed from the Manning equation, may vary considerably with change in water stage level. Therefore, a variable n value should be used in calculating discharge at different stages.

$$n = c\sqrt{\frac{Z}{R}} \quad \ldots\ldots (14)$$

where n is Manning's roughness coefficient, Z is mean rock diameter, R is the hydraulic radius, and c is a constant.[1]

[1]Personal communication. 1975, Allen Isaacson. USFS, Coeur d'Alene, Idaho.

To use the variable n, the following steps must be completed: 1) Along a transect over the stream study reach, measure depth, width and wetted perimeter up to bankfull; 2) at one foot intervals along the transect to the bankfull level determine the average rock size; 3) from a known discharge and stage [or by measuring velocity (V) directly], compute n from Manning's equation; 4) using this computed n, calculate c from Equation (14); 5) at each stage level for which additional discharges are to be computed, calculate the average rock size, wetted perimeter, cross sectional area and a new n value; 6) with a different n for each stage calculate discharge using Manning equation.

COMPUTER PROGRAMS

At least two programs, Water Surface Profile (WSP) and R-2 CROSS, are currently available that, with sufficient field input data, will calculate changes in stream hydraulic characteristics and parameters that occur at differing flows. The WSP program was developed to computerize calculations needed for the determination of tailwater and backwater elevations at dams and reservoirs. The R-2 CROSS is a modification of two programs designed to compute before/after sediment volumes in a debris basin. Both programs have been adapted to instream situations.

Water Surface Profile Program

The program is calibrated to a specific stream section using one or two observed flows, cross-sectional (transect) data and water surface elevations at various locations in the stream section. The stream characteristics determine the number of cross sections needed to cover any given distance. The following description was taken and/or modified from Dooley, 1975 and Spence, 1975.

FIELD DATA REQUIREMENTS

Field data needed for input to the WSP program include the information previously mentioned plus a physical description of the stream section. Quality of the field data determines the accuracy of the computed results. These field data include:

1) Cross-section survey data (see Transects); 2) distance between cross sections (transects); 3) measured discharge in cubic feet per second, if gaging station data is available, otherwise measure velocity and compute discharge using Equation (10); 4) water surface elevations at all cross sections; 5) description of the stream bottom at each cross section; 6) description of bank and overbank material and vegetation; 7) identification of points where streambed material, vegetation, and stream bank change within the cross sections.

If elevations are taken within ± .1 of a foot, the predicted water surface elevations will be within ± .1 foot. Transects should be established at right angles to the stream flow. Distance between cross sections should be measured along the thalweg. Measurements should also be made at the inside and outside of stream meanders. Critical or control sections should be included as a cross section. Where specific information is desired, e.g., a spawning area, feeding area, or a resting area, include cross sections of that area (this program has partitioning capabilities).

In order for the output to be of more use, specific segments of the stream cross sections should be identified. This will enable the user to get specific information for that segment. At least one velocity measurement should be made when taking the field data. This measurement must be identified with the water surface elevation at the time of measurement. The water surface elevations at the other cross sections should also be noted at the time velocity measurements are being taken. It is useful to also observe high water marks and tie them into the cross sections. This will give another set of elevations to add to the field data and help determine the proper energy slope of the specific stream reach being studied.

If log jams or debris dams are included in a study reach, cross sections should be taken above and below these areas. These areas will have some form of control for a least part of the study reach. When islands are included in a reach, cross sections should be taken upstream and downstream from the island and at the points where the channels around the island begin and end.

Cross sections should originate from the same side of the stream. Left and right streambanks should be identified, and cross sections should be taken consistently in an upstream or downstream order.

When field data collection is completed, the individual cross sections should be plotted. The scale used is not particularly important. These plots should include identification of streambed material, types of vegetation on overbank, and left and right streambank identification.

AVAILABLE OUTPUT

Available output from WSP includes specific data for each cross-section and tabular summaries of data for all flows included. Specific cross-section output includes water surface elevations, flow velocities, tractive force (amount of force exerted upon stream bottom), conveyance areas and widths, hydraulic radii, and discharges. The predicted values are based on and within the precision of the field data.

From the output data, a water surface profile showing water surface elevations, thalweg, and cross-section location (by station) is plotted. A rating curve for the most downstream section is also plotted.

R-2 CROSS Program

This program is designed to calculate a series of hydraulic parameters from transect data (presently used with sag tape data) and Manning's discharge formula. The program steps were written assuming the use of sag tape data (Anonymous, 1974).

FIELD DATA REQUIREMENTS

1) Distance in feet from 0-point (see Figure 10) to last depth measurement (usually at opposite stake); 2) total length (feet) of tape spanning the cross section (may be same as 1); 3) Manning's n value, roughness coefficient (use .055 or another selected or calculated value); 4) slope (gradient) of the stream.

PROGRAM STEPS AND OUTPUT

Step 1. The basic computer plot of the measured cross section – Step 1 produces a channel cross-section printout, and if desired a plot (from a Cal Comp Plotter) of the measured cross section. The printout will also provide cross-section *area* in sq. ft., *maximum depth* in ft. (from the water level to channel bottom), *wetted perimeter* in ft., *hydraulic radius* (area/wetted perimeter) in ft., measured *slope* or gradient of the stream reach in percent, selected or calculated *Manning's* n (roughness coefficient), water *flow* in c.f.s., and *average velocity* in feet/second.

The maximum depth value given on the Step 1 printout is used to establish the reference datum line (Figure 10) on the graph paper plot (or the cross-section printout). Maximum depth is measured, with a scale, vertically up from the deepest point shown on the cross section. A line drawn perpendicular to this vertical is the *reference datum* line and represents the computer corrected tape line. For those hydraulic data listed on the Step 1 printout, the computer has assumed a water level equal to the reference datum line. Measurements from the reference datum line to the actual water level, or selected water levels are used in program Steps 2 and 3.

Step 2. Developing information from which to calculate Manning's n value – In order to complete the CROSS program analysis, it is necessary to have obtained accurate field measurements of the stream discharge or flow. It is also important to have noted on the field form the distance from the 0-point or stake at which both the first and furthest waterlines in the cross section are encountered (see Transects-Sag Tape). The waterline or level, as interpreted from the field notes, is drawn directly on the graph paper plot, or in the event a Calcomp plotter is not available, the cross-section printout can be used. The necessary data to run Step 2 includes: *A depth value,* identified in the program writeup as "depth to water," which is the difference between the maximum depth from the reference datum to the channel bottom and the actual water depth at that point. In effect, this value is the distance to the nearest tenth-foot from the computer corrected tape level to the waterline; *two distance values,* the distance in feet from the 0-point to the first streambank–waterline intersect, and the distance in feet from the 0-point to the furthest streambank–waterline intersect. These data are obtained from the cross-section plot on which the waterline has been drawn; *total length of tape* spanning the cross section, in feet, from stake to stake, or 0-point to end point; *a selected or theoretical Manning's n* (roughness coefficient) value. A value developed from field observations may be used, or if unknown use .055 for Step 2; *the slope or gradient* in percent of the stream reach immediately up and downstream from the cross section.

The purpose of Step 2 is to provide a list of the above described hydraulic parameters for the cross section as it existed at the time of measurement, along with a second cross-section printout. Once the data from Step 2 are obtained, it is used to refine the estimated Manning's n value (used in Steps 1 & 2) for use in the final Step 3. Manning's formula is solved for n, using the *area, hydraulic radius,* and *slope* data from the Step 2 print-out, and the *field measurement* of stream discharge for the Q value in equation (10).

Step 3. Stream discharge and hydraulic parameters at various or selected water stages, above or below the waterline existing at the time of field measurement – The purpose of Step 3 is to provide a range of hydraulic parameter values related to changes in the water stage of the cross section.

To run Step 3, simply change the depth to water value (the distance from the reference datum to the new or selected water line) and determine the corresponding changes in waterline-streambank intercept distances using the plot from Step 1 (or the cross-section printout). The remaining information necessary for running Step 3, includes the same total length of tape and slope data as used in Step 2. Step 3 will produce a cross section and printout with the above described hydraulic parameters for each new or selected water stage.

The program produces a computer plot of the measured cross section; and with completion of the three program steps, computes 1) stream discharge, 2) average flow velocity, 3) wetted perimeter, 4) cross-sectional area, 5) maximum water depth, and 6) hydraulic radius for the actual streamflow at the time of measurement as well as for various selected water stages.

As stated earlier, the primary purpose of this section is to introduce the reader (assumed to have a limited background in hydrologic and hydraulic concepts) to the basic, but salient, points concerning streamflow measurements and relationships in order to facillitate comprehension of the methodologies presented in the remainder of this document. Much additional information could have been included; however, only the necessary concepts and techniques are described. For an indepth treatment of particular points, the reader is referred to specific references in the text.

Certain material that could have been included her is described in a more appropriate section. Methods for estimating chemical and nutrient stream loading, and a number of hydrodynamic models, for example, are presented in Section 3.

REFERENCES CITED

ANONYMOUS.
1974. R-2 Cross Program, a sag-tape method of channel cross section measurements for use with minimum instream flow determination. USFS, Reg. 2, Denver, Colorado.

BODHAINE, G. L. and D. M. THOMAS.
1964. Magnitude and frequency of floods in the United States, Pacific slope basins in Washington and upper Columbia River basin, Part 12. USGS, Water Supply Paper, 1687.

CHOW, V. T.
1964. Handbook of applied hydrology. McGraw-Hill Book Co., N. Y., 1000+p.

CORBETT, D. M., and OTHERS.
1943. Stream gaging procedures, a manual describing methods and practices of the Geological Survey. USGS, Water Supply Paper 888, 245 p.

DOOLEY, J.
1975. Use of W. S. P. in Montana Fish and Game Department fishery studies. Paper presented at the Technical Assistance Workshop, Jan., 1975, Billings, Montana.

KING, H. W. and E. F. BRATER.
1963. Handbook of hydraulics. McGraw-Hill Book Co., N. Y., 450 p.

LINSLEY, R. K., and J. B. FRANZINI.
1972. Water resources engineering. 2nd ed., McGraw-Hill Book Co., N. Y., 690 p.

ORSBORN, J. F.
1972. Hydrology studies. In: Proc. Instream Flow Methodology Workshop. State of Washington, Dept. of Ecology, pp. 46-71.

ORSBORN, J. F.
1973. Low flows. In: Technical Supplement, Hydrographic Atlas, Lewis River Basin Study Area, pp. 36-48.

ORSBORN, J. F.
1974. Determining stream flows from geomorphic parameters. J. Irrig. Drainage Div., ASCE Vol. 100, No. IR4, Proc. Paper 10986, pp. 455-475.

ORSBORN, J. F., M. Th. ARCE, F. D. DEAN and J. P. AHLERS.
1975. Relationships of low, average and flood flow for streams in the Pacific northwest. Proj. Completion Rep. for OWRT, Allbrook Hydraulics Lab. Wash. State Univ. Pullman. 33 p.

RIGGS, H. C.
1968. Some statistical tools in hydrology. USGS, Tech. Water-Resour. Invest., Book 4, Chap. A1. 39 p.

RIGGS, H. C.
1969. Mean streamflow from discharge measurements. Bull. Internat. Assoc. Sci. Hydrol., XIV, 4:95-110.

RIGGS, H. C.
1972. Low flow investigations. USGS, Tech. Water-Resour. Invest. Book 4, Chap. B1. 18 p.

SPENCE, L. E.
1975. Guidelines for using Water Surface Profile program to determine instream flow needs for aquatic life. Montana Fish and Game Dept. Envir. and Infor. Div., Prelim. draft. 22 p.

APPENDIX I

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3. WATER QUALITY RELATIONSHIPS TO FLOW–STREAMS AND ESTUARIES

W. J. GRENNEY, D. B. PORCELLA,
AND M. L. CLEAVE

CONTENTS

This chapter provides state-of-the-art information about quantitative relationships that exist between flow alternations and changes in specific and selected water quality parameters. It is not a manual for evaluating flow changes. We include only methodologies that have been published and actually utilized in stream or estuary management studies. Readers are expected to include water quality, fishery, and wildlife managers and field workers at Federal, state, and local levels; engineers and biologists in research areas; and policymakers. It is necessary to assume some level of technical ability on the part of the reader or his colleagues to minimize the number of pages in this section. However, there is expected to be a wide range of expertise among readers.

Because managers have to predict the potential effects of flow alterations on water quality, quantitative relationships between flow and water quality parameters must be available. Qualitative relationships provide some idea of how a specific parameter is likely to change, but specific defensible proposals about the effects of flow alterations require quantitative estimates. These functional relationships can be used to qualitatively estimate the effects of flow changes, but the management of streamflows must be based on quantitative relationships. In managing water quality, the preservation of other uses (fishing, drinking water, etc.), not water quality *per se,* is the goal, but water quality is used as an index of possible uses.

The prediction of flow change effects on water quality in streams and estuaries involves parameters that most affect aquatic and riparian communities or that affect beneficial uses. Those water quality parameters plus macrophytes and macroinvertebrates that relate to beneficial uses and have been most thoroughly examined in regard to flow and to analysis of water quality problems are defined in Table 1. Because flow is the independent variable of concern here, all water quality parameters are evaluated in terms of their relationships to flow. This implies that a model (any physical or mathematical relationship) exists relating the parameters to flow.

The key to understanding flow requirements for regulating aquatic ecosystems is the definition of flow itself (see Introduction and Section 2). In addition to the absolute quantity of flow, the physical characteristics of the system in question modify significantly the concentrations of the relevant parameters (Table 1). These physical characteristics include channel geometry, velocity, streambed slope, and the longitudinal and lateral distribution of channel characteristics such as width and depth, stream cover, and streambed irregularities (holes, rocks, and boulders) (see Table 2).

Table 1. Water quality parameters in relation to analytical methodologies.

Water Quality Characteristics	Level of Current Analytical Approaches: Level I*	Level II**
Dissolved gases – O_2, N_2, CO_2		a
Temperature		√
Sediment		
Suspended	c	
Bedload	c	
Total dissolved solids		b
Nutrients	d	
Detritus	e	
Toxic materials	√	
Bacteria		
Pathogens	√	
Decomposers	√	
Algae		
Planktonic	√	
Sessile	√	
Macrophytes	not available	
Macroinvertebrates	f	

*Level I – low to moderate accuracy, less precise.
**Level II – highly accurate, precise.

[a]With the exception of benthic O_2 production and demand.

[b]With the exception of chemical phenomena such as $CaCO_3$ solution and precipitation.

[c]With the exception of methods for channel change effects (bank sloughing, aggradation, migration).

[d]Techniques at Level II are available in many situations.

[e]Limitations with measurement and characterization.

[f]Available only with extensive and careful data acquisition.

Evaluation of methods dealing with water quality characteristics as affected by flow and in relation to stream and estuary morphology leads to three levels of approach: 1) A qualitative judgment based on past experiences about the

Table 2. Models for predicting flow effects on water quality in aquatic systems.

Types of Models	Related to	Relation to Other Systems
Flow Models	Stream Character *f* (hydrologic-hydraulic, topographical, e.g., velocity, depth, dilution, cover, etc.	All Others
DO Models	*f* (flow, temperature, wastes, microbial activity)	Fish, Wildlife
Temperature Models	*f* (flow, insolation, wastes, cover)	Fish, Wildlife
TDS Models	*f* (flow, evaporation, uses, wastes)	Beneficial Uses
Sediment Transport Models	*f* (flow, sediment type)	Beneficial Uses, Aesthetics, Recreation
Nutrient Budget Models	*f* (flow, temperature, DO, nutrients)	Microbial-Ecologic
Microbial Ecologic Models	*f* (flow, nutrient budgets, DO, temperature, sediment transport)	Other Ecologic Models, Recreation, Aesthetics

likely effects of flow alterations; 2) the use of quantitative functional relations between stream or estuary quality parameters and their independent variables (including flow) and the solution of these relations using nomographs for the simple cases; and 3) the use of computer models for the complex case. The qualitative approach is inadequate for management decisions, but is necessary when judging the relative merits of performing such analyses, and the relative sophistication needed for the analysis (nomographs vs computers). The complexity of the analysis varies significantly with the available money, data and desired level of precision, but the reader should be aware that a computer model can be made less complex more easily than a nomographic approach can be made more complex. In all cases of analyses, the manager and his colleagues should be aware that the model output must be tempered by common sense and experience (judgmental analysis and interpretation).

In this section, methodologies for evaluating water quality in streams and estuaries in relation to flow changes are examined. All of these methodologies are essentially either direct measurements or models. We first define terms relating to: 1) Evaluation of instream flow effects on water quality based on actual measurements of flow; and 2) simulation models and their application and relationship to flow requirements.

MEASUREMENT AND RELATIONSHIPS OF WATER QUALITY PARAMETERS

Direct measurements of dissolved oxygen (DO), temperature, total dissolved solids (TDS), sediments, nutrients, or microbes are meaningless except relative to standards or to extreme flow conditions (stream dewatering, flooding, zero dilution), or in the quantitative sense of modeling. Except for modeling, the effects of flow changes on direct measurements of these parameters are not addressed in this report because: 1) Water quality standards relate to public health or environmental requirements, not to flow; and 2) extreme cases are self-evident and outside the scope of this report. We therefore restrict ourselves to evaluating the relationships between models of the selected water quality parameters and flow requirements.

All models, however, require input of basic data, notably streamflow and the direct measurements of the specific parameters mentioned. In addition, a qualitative understanding of the parameters and how they vary is necessary to determine whether further analysis, by nomograms or computer models, will be productive.

Dissolved oxygen (DO) is a measure of the amount of oxygen gas dissolved in water. The measure of microbial activity in relation to the oxidation of organic wastes is termed biochemical oxygen demand (BOD). BOD includes both carbonaceous BOD (CBOD), organic carbon compounds that are oxidized to CO_2 and H_20; and nitrogenous BOD (NBOD), which are reduced nitrogen compounds (ammonia, amines) that are oxidized to NO_2 (nitrates) and then to NO_3 (nitrates) and H_2O.

Chemical oxygen demand (COD) reflects the amount of chemically oxidizable organic matter present in the water. Good quality water would have high DO readings and low BOD and COD readings. Terms describing the amount of oxygen in the environment are used frequently in the literature. Anoxic and anaerobic describe a state of oxygen deprivation, while aerobic describes an environment with oxygen present.

Dissolved oxygen is the most important water quality parameter. It is produced by photosynthesis, used for respiration, and its concentration affects succession in the community. In freshwater the saturation concentration is largely a function of atmospheric pressure and temperature. Salinity must be taken into account when salts approach estuarine levels because DO saturation varies inversely with salinity. The rate of oxygen uptake (or loss) in water is a function of the concentration difference between the saturation concentration and the actual concentration. In a stream or esturary, DO is often below saturation (having an oxygen deficit) because of respiration of BOD and COD, on plant respiration in the dark in eutrophic systems, or it is super-saturated due to photosynthesis. Also, the natural saturation DO can be quite low because of temperature and salt conditions and the concept of an oxygen deficit (d) may be used; thus, waste additions reduce DO, resulting in a deficit (Figure 1) in the aquatic systems relative to the saturation concentration (the deficit is zero at saturation).

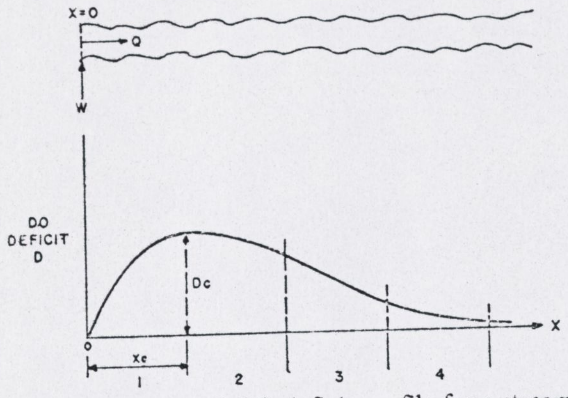

Figure 1. Typical DO deficit profile for a stream (from EPA, 1971).

The first acceptable attempt to quantitatively measure oxygen dynamics in a natural aquatic ecosystem was by Streeter and Phelps (in Nemerow, 1974). They developed a relationship in which utilization of BOD resulted in an oxygen deficit (below saturation) and reaeration (oxygen input from the atmosphere) restored DO to the saturation concentration. This model, with refinements and subsequent further verification and explanation, is the basis for all recent models of DO in aquatic ecosystems.

Flow changes have the following major impacts on DO: 1) Changed dilution of waste materials; 2) shallow flows equilibrate with the atmosphere faster than deep flows (all other factors being the same); 3) higher velocity flows "reaerate" faster than lower velocity flows; 4) any flow change that affects temperature will have an effect on stream DO irrespective of waste loadings.

Natural surface water temperature (Figure 2) is affected by waste loadings (thermal changes) and dilution can change the effects of such loadings. Water depth and velocity also have important effects because of insolation, streambed thermal loadings, etc. Differences in shading (cover) will affect insolation and, thus, stream temperature.

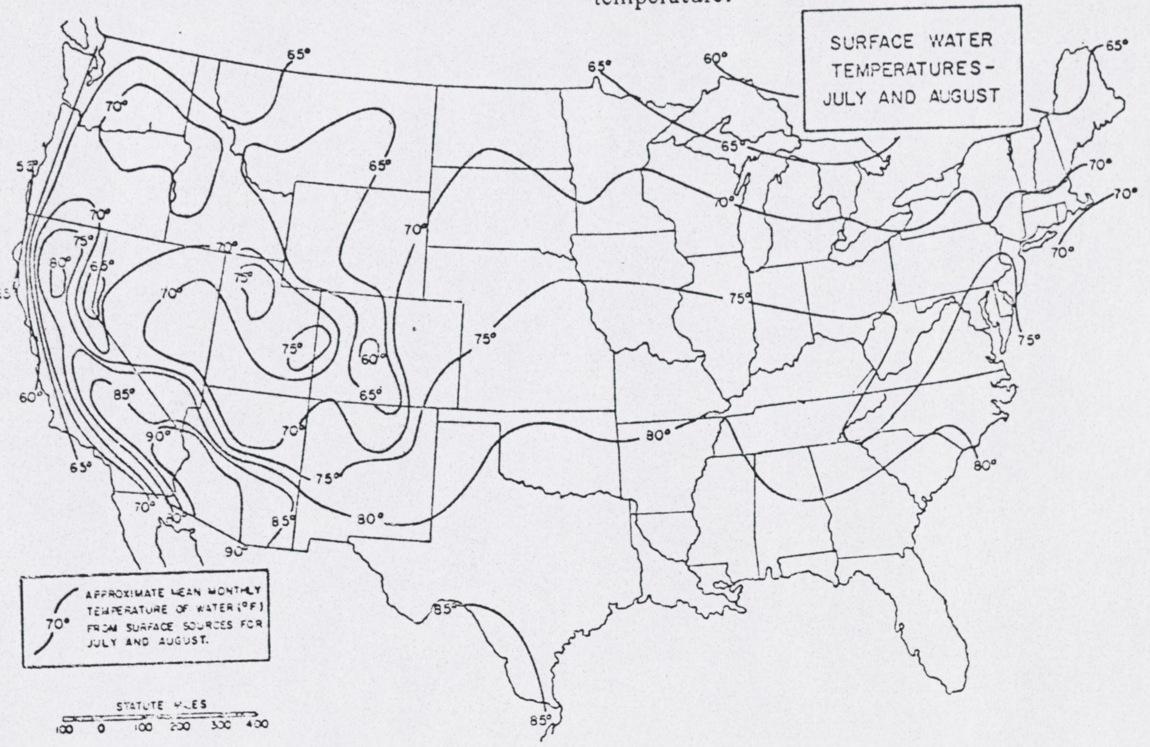

Figure 2. Conterminous U.S. surface water temperatures – July and August (from EPA, 1971).

Nutrients include all elements required by plants and animals for optimum growth, but in terms of ecosystem function and productivity, they are usually limited, for geochemical reasons (Hutchinson, 1973), to consideration of phosphorus and nitrogen compounds. Phosphorus is important because it is often a limiting factor to growth of microbial populations. Nitrogen fills diverse functions. Additions of nutrients are considered herein relative to how they affect aquatic productivity, especially with respect to the problem of eutrophication. Eutrophication results in greater plant productivity, which, in turn, affects DO concentrations, the composition and quality of the aquatic community, and potential beneficial uses. Light, temperature, and hydraulic mixing are also important to productivity and in the succession of specific producers. Flow changes affect these parameters significantly.

Different chemical types of phosphorus in water can be measured in dissolved or particulate forms. Measurements are commonly taken of orthophosphates (o-$PO_4^{\equiv}$), which is the most elemental form of the phosphates. Condensed phosphates (pyro- , meta- , and polyphosphates) are better known as acid-hydrolyzable phosphates and theoretically reflect only the more complex inorganic phosphates available in the water. Total phosphorus (total PO_4) includes both inorganic and organic phosphates.

Three major forms of nitrogen are of interest as water quality parameters. Ammonia (NH_4^+) is a product of microbial activity or can be a result of waste inputs. At low levels, it can exert an oxygen demand (NBOD). At high levels, such as those encountered in feedlot runoff or certain waste effluents, it can be toxic to the aquatic community. Nitrite (NO_2) is produced in the process of nitrification of reduced nitrogen or during denitrification in anaerobic environments. It is an intermediate step in the nitrogen cycle. Nitrate (NO_3) is the end product of oxidation of organic nitrogenous compounds (nitrification). Under anaerobic conditions, it may serve as an oxygen source for microbial activity (denitrification).

Nitrification is an important aspect of the DO concentration, as ammonia usually constitutes the major portion of NBOD. Theoretical changes in the composition of nitrogen compounds in a stream are shown in Figure 3 for the process of nitrification; all the forms noted can be utilized by algae during growth by enzymatic reduction to amino groups.

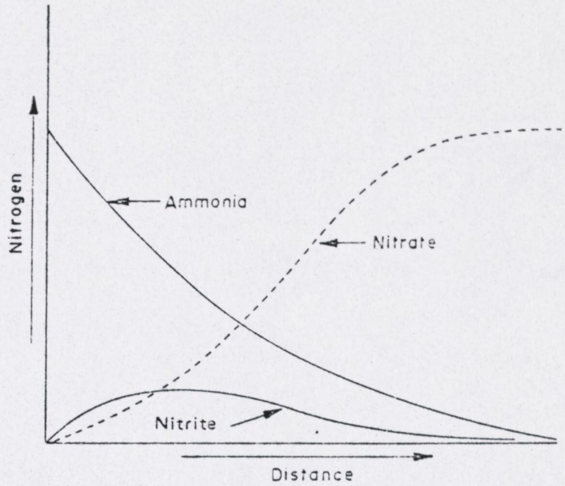

Figure 3. Sequential reactions in nitrification (from EPA, 1971).

Flow changes affect nutrients by changing the diluting capacity of the system. The interrelationships between temperature and productivity can result in faster nutrient cycling, changes in populations to less desirable organisms, or to less nutrients because of decreased solubility. Thus, flow changes that affect temperature will affect productivity and community composition. Perhaps even more important, but as yet not understood, is the effect of stream velocity on the plant standing crop in a stream. In a given stream with a given nutrient concentration and composition, low velocity sections will be considerably lower in plant biomass than are high velocity sections. Lastly, the effects of flow on residence time for nutrients in a system as well as mass inflow (loading) can be significant. Many unquantified phenomena need explanation before streamflow effects on water quality can be interpreted.

Toxic materials include pesticides, heavy metals, chlorinated compounds from wastewater chlorination, and organisms and have toxic impacts at specific trophic levels or through food chain accumulation. Inhibition is a concentration-time relationship, which is expressed differently at different life cycle stages. Each toxicant is usually assessed as a single factor, but multiple factors have different impacts (Chen and Selleck, 1969).

Microbial-ecologic parameters include bacteria from fecal pollution, primary producers as affected by nutrient loading, and other microscopic members of the community upon which higher organisms are often dependent (protozoans, fungi). For example, decomposers in general have an important role in DO relationships and nutrients cycling. Only coliforms will be discussed at this point because we lack good data about definition of qualitative and quantitative relationships that would allow us to assess flow change effects on other microscopic members of the aquatic community.

The coliform group of bacteria includes fecal and soil bacteria and serves as an *indicator* of the sanitary quality of water. This group is differentiated into smaller units by testing procedures. The fecal coliform group represents organisms present in the digestive tract and feces of vertebrates. Fecal streptococci are another subset representing fecal pollution.

Because of its comparative rarity, fecal pollution can usually be easily recognized and traced using coliform concentrations as an index. Models are simplistic and consist of inputs coupled with flows (mass flow rates) and the concept of "coliform die-away," a first order decay type relationship. Often, such relationships are not entirely useful because of bacterial "regrowth" (growth in the stream or estuary), breakup of particles having many bacteria, diffuse source inputs (from other mammals such as grazing cattle, wildlife, etc.), or benthic inputs. Flow changes that modify dilution or viability, or have other related effects (temperature, community changes which affect predation) would affect coliform concentrations and, hence, are public health hazards.

The effects of reduced or augmented flows on the critical water quality parameters described in this section can be summarized as follows: 1) Where no man-caused pollution occurs, reduced flows will generally diminish water quality due to warming, reduced DO capacity, greater impact of evapotranspiration, better light penetration, and reduce velocities; generally, siltation patterns change; 2) where man-caused pollution is a factor, lower flows usually mean less dilution and greater impacts, but increased depth results in less unit reaeration for DO. In general, augmented flows result in better water quality and reduced flows result in poorer water quality.

Although several studies of measured streamflow variation effects on reaeration, temperature, and sedimentation are available (Biology Department, Heidelberg College, 1971; Clark and Snyder, 1969; Water Resources Engineers, Inc., 1969; Eustis and Hillen, 1954; USDA, 1974), little has been reported for other water quality parameters. Apparently, observations of aquatic communities below dams have been related to flow releases from the reservoirs, but other than for reaeration, gas bubble problems, and temperature effects, the effects of flow variation below dams are relatively unstudied.

Problems of reaeration, temperature, and gas bubbles have been viewed primarily from the point of view that a reservoir has caused problems, not from the point of view that the parameters might be a function of streamflow. Estuarine inflow variation effects on water quality and ecosystem integrity have been mentioned as commentary to other problems, but have not been considered in a specific sense. Questions about water quality effects of streamflow changes have been addressed (or been addressable) almost exclusively from the point of view of simulation models. Controlled discharges from reservoirs can be used to measure and verify the short-term effects of streamflow variation on water quality parameters in well designed studies. Similarly, long-term effects should be studied under the appropriate conditions. Groundwater or overland flows can affect stream temperature if the relative flows are similar or temperature differentials are great enough (Comer and Grenney, 1975). Because of the effect of temperature on DO, temperature is an important parameter in any DO model as well as being important for biological reasons.

Particulate solids or stream sediments in the water include inorganic sediment load and organic materials such as debris, bacteria, algae, and small invertebrates. The inorganic sediment load is composed of bedload and suspended sediments. Suspended solids (SS) refer to solids suspended in the water that are large enough to be filtered out (APHA, 1971). If the filter is then exposed to high heat, and all the organics are burned off, the measure of these organics is known as volatile suspended solids (VSS).

Although attempts to model stream sedimentation have continued for a long time, no good "downstream" models showing variation in SS with distance currently exist. Generally, lowered stream velocities or the construction of reservoirs have diminished downstream sedimentation problems.

Sediment transport models have been developed for forested watersheds because sedimentation is the most serious water quality problem in such ecosystems (Rosgen, 1975a). These models are very flow sensitive and relate flow to watershed area, stream slope (grade line), soil structure, and activities in the watershed (construction, vegetation removal and replacement).

The total solids dissolved in water (TDS) can be measured and used to estimate the amount of salts in the water. Conductivity can also be used to estimate the amount of salts in water.

TDS values increase from natural reasons as well as from waste loadings. Consumptive use of water by evaporation and transpiration will leave the salts behind. Flow reduction increases the impact of evapotranspiration. Models are generally based on simple mass balance or salt routing equations. Observation of water quality parameters at downstream points in relation to reservoir releases or other diversions seems to be an important means of verifying current velocity effects, flow effects, and stream depth effects on factors and parameters related to water quality modeling.

MODELING CONCEPTS

Mathematical models (whether expressed by nomographs or computers) are being used more and more in water quality investigations to represent the dynamic responses in aquatic systems. The primary purpose of these models is to simulate interactions among various chemical and biological constituents of the water. When a model has been developed to the point where it is thought to accurately represent the physical phenomena occurring in the body of water, it can be used as a management tool to establish policies for the control of environmental practices. Models have been used to gain additional insights into the mechanisms influencing a particular system, to predict the impact of a future waste load on a system, to evaluate alternative methods of improving an existing polluted situation, and as part of optimization programs to determine the most economical method of avoiding or alleviating problems in a particular area. It is important, therefore, that the ability of a particular model selected to represent a system be suited to the purposes for which the model will ultimately be used.

A large number of mathematical models have been developed to represent the transport and transformation of chemical and biological constituents in aquatic systems. These models vary considerably in the degree of refinement (or resolution) with which they represent the physical world. Low resolution models represent general trends for a few linked dependent variables over a limited set of boundary conditions. An example of this type of model is the application of the Streeter-Phelps equation to represent average monthly dissolved oxygen concentrations in a river (Texas Water Development Board, 1970). High resolution models are much more flexible and may represent the responses of a large number of linked dependent variables over a much wider set of boundary conditions. Such models may provide spacial distributions of instantaneous peak concentrations and be dependent on diurnal variations in environmental conditions. An example of this type of model is represented by the application of a hydraulic and water quality model to San Francisco Bay, California (Feigner and Harris, 1970).

As the order of resolution of a model increases, so does the difficulty and cost of its application. The differential equations become complex, and usually nonlinear, and time-consuming numerical techniques are required to obtain solutions. The number of coefficients in the model increases and estimation of coefficient values from observed data is complicated by the nonlinearities in the equations. Relatively large amounts of field and laboratory data must be collected because, obviously, the realism of model responses cannot exceed the degree of accuracy of the data used to validate the model. The development of a model for a particular situation, therefore, requires value judgments about acceptable tradeoffs between the practicability and economy of model application and the amount and refinement of information to be provided by the model responses.

Model responses can predict the impact of pollution loads on river water quality during critical flow periods or as the result of future user demands. Because of the complexity of aquatic systems, mathematics models are useful tools for this purpose. Mathematical simulation is achieved by using differential equations to represent the various processes and functions of the prototype (real world) system, and by linking these equations into a systems model. Computer simulation is basically a technique of analysis whereby a model is developed for investigating the behavior or performance of a dynamic prototype system subject to particular constraints and input functions. The model behaves like the prototype system with regard to certain selected variables, and can be used to predict probable responses when some of the system parameters or input functions are altered. Computer simulation has the following important advantages:

1. A model provides a basis for coordinating information and the efforts of personnel across a broad spectrum of scientific disciplines.
2. A model approach requires a clear identification of problems and objectives associated with the system being examined.
3. Insight into the system being studied is increased. In particular, the relative importance of various sytem processes and input functions is suggested.
4. Priorities and adequacies are indicated in terms of planning objectives and data acquisition.
5. A model can quantitatively facilitate progress toward system definition and conceptual understanding.
6. Proposed modifications of existing systems can be nondestructively tested.
7. Many planning and management alternatives and proposals can be studied within a short time period.
8. Hypothetical system designs can be tested for feasibility or comparison with alternate systems.

Disadvantages include:

1. Models can involve significant additional expense to a management organization.
2. There are difficulties in obtaining adequate and accurate data.
3. A model is a simplification of the real system and the user must be careful to insure the "reasonableness" of the computer output, i.e., compares with the prototype.
4. Models are often not trusted or understood and thus not effectively implemented.
5. Poor models can be worse than no model.
6. Models may cause stochastic events to appear deterministic.

In essence, proper development and application of a mathematical model to a river or estuarine system can provide a structure for the systematic consideration of the many diverse aspects of water quality phenomena.

MODELING, AND ITS USE IN MANAGEMENT

Models are defined as stochastic or deterministic, as simple or sophisticated. Stochastic models are those that recognize the random nature of many parameters, such as flow or storm intensity. Deterministic models describe a specific functional relationship between one measurement and another where the relationship forces a response. Since most models are deterministic, stochastic variables such as rainfall are handled by using measured or estimated data as input to the deterministic model. Then the output from the model is used to simulate the natural system. The model is "verified" by comparing a simulation to the natural system. When a simulation is manipulated to duplicate (as nearly as possible) the natural system measurements, the model is being "calibrated." Both verification and calibration are necessary to perform management studies of the various options or alternatives associated with questions such as, "Do we build a reservoir here?" or "What are the effects of various minimum flows on stream quality or estuarine quality?"

Because the type of model chosen depends on the purpose to which the model is to be addressed, the type of aquatic environment involved, the parameters of interest, and the specific data requirements, much thought must go into the choice of an approach. The days of sitting in City Hall or standing on a river bank with no data in hand and deciding whether or not to permit certain activities are long past. Such decisions need factual justification. However, it is not economical to use complex, time-consuming, costly modeling to answer questions that require little data or sophistication (Figure 4). Increasing problem complexity obviously is correlated with an increasing need for data and parameter output for analysis (Figure 5).

The process of evaluating flow requirements in relation to water quality in streams or estuaries requires the following steps: 1) Collect flow data (estimations, records or models); 2) develop DO data (data retrieval–STORET, measure and/or model) as a major aquatic parameter for setting standards and maintaining the integrity of fish and wildlife; 3) compile temperature records (essential because of effects on DO and basic stream ecology); 4) acquire TDS and sedimentation data;

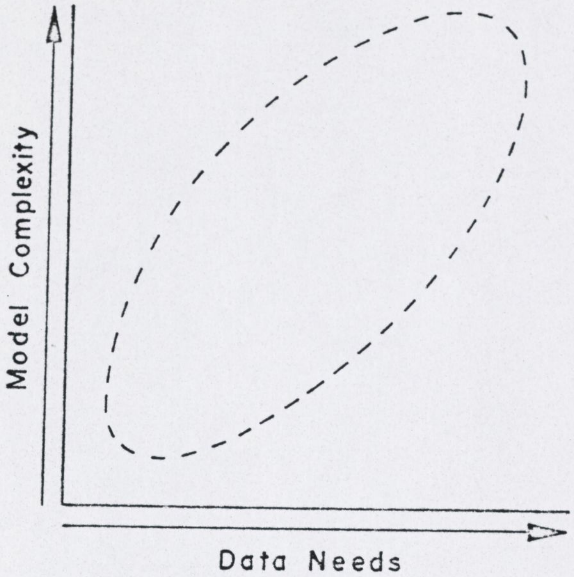

Figure 4. Methodology Array

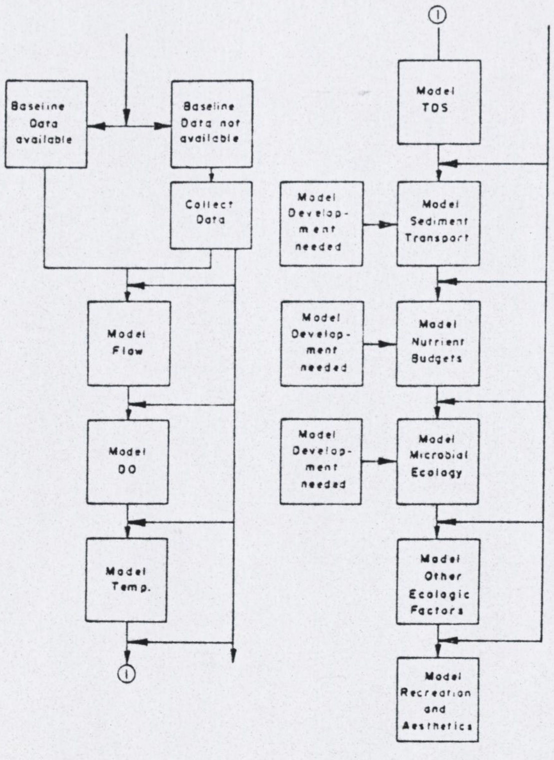

Figure 5. Predicting the effects of flow on water quality.

and 5) gather information on nutrients, microbial interactions, and ecological factors, as these affect and are affected by DO and temperature as well as flow. The higher organisms included in any ecologic model are usually the targets (such as sport fish) of laymen, management authorities, water quality engineers, and others. Thus, recreation and other societal activities are linked to the ecologic models and the parameters that affect those models. Inclusion of questions about ecosystems and society interrelationships in a problem should be evaluated in terms of the *need* for answers and the availability of "adequate" data and funds to support the background studies.

Before considering in detail specific methodologies for evaluating flow requirements, the categorization (from the literature) of models in terms of study types and the parameters examined relative to streams (Tables 2, 3 and 4) and estuaries (Tables 5 and 6) should be examined. Although appropriate literature has been classified as to its level of precision (Level I—low to moderate reliability and completeness; Level II—high reliability and essentially complete description of natural system variables), *any* pre-existing model can be used for a particular level of effort if that level of effort requires less data or information input than did the original. As described in the Introduction, methods are considered in terms of their appropriateness for reconnaissance studies and on-site field studies (limited or intensive). Depending on the parameter and the availability of a model, Level I or Level II could be used for reconnaissance or on-site field studies as appropriate in terms of costs, time and data availability and precision and accuracy level of the answer. The use of less sophisticated models would lower the accuracy and precision of the results as costs decrease (Figure 6). For more detail on modeling approaches to water quality management, see Thomann (1972).

Reconnaissance Approaches

The reports selected for discussion in this section are essentially basinwide overviews that allow a reasonable "first-cut" estimate of ecosystem impacts of flow changes.

Chesapeake Bay Center for Environmental Studies (1973, 1974, 1975) used color and infrared aerial photography to identify and measure percent cover of saltwater marsh vegetation. Productivity estimates from this method are being

Table 3. Methods and models for predicting flow changes in streams

Water Quality Characteristic / Analytical Approach	Hydraulics
Level I	EPA, 1971 EPA, 1972 Orsborn et al., 1973
Level II	Battelle, 1974 a,b Biswas, 1974 Chen and Wells, 1974 Chow, 1964 Dooley, 1975 Enviro Control, Inc., 1971 Fread, 1973 Fread, 1974 Grenney, 1975 Hooper, 1973 Hoppe, 1975 Hydrologic Engineering Center, 1974 Idaho State Study Team, 1973 Jeppson, 1974 Jeppson, 1975 Johnson, 1974 Kadlec, 1971 King and Brater, 1963 Lehmann, 1974 Linsley and Franzini, 1972 Lombardo, 1973 Masch and Associates, 1971 Nemerow, 1974 Orsborn et al., 1973 Rutherford and O'Sullivan, 1974 Shearman and Swisshelm, 1975 Stochastics, Inc., 1971 Texas Water Development Board, 1971 Texas Water Development Board, 1974 Trumbull and Loomis, 1973 USDA, 1974 USDI, 1968 U.S. Forest Service, 1973 Woffinden and Clyde, 1971

Table 4. Methods and models for predicting effects of flow changes on water quality in streams – literature matrix

Water Quality Characteristic / Analytical Approach	Dissolved Gases	Temperature	Sediment	Total Dissolved Solids Nutrient Budgets Microbial Ecology
Level I	EPA, 1971 EPA, 1972	Chandler et al., 1970	Chandler et al., 1970 Rosgen, 1973	Chandler, 1970 EPA, 1971 EPA, 1972
Level II	Adeney and Becker, 1919 Adeney and Becker, 1920 Battelle, 1974 a,b Bayer, 1974 Biswas, 1974 Bovee, 1974 Chen and Davis, 1975 Chen and Wells, 1974 Churchill et al., 1962 Crevensten et al., 1973 Enviro Control, Inc., 1971 Fair et al., 1968 Grenney, 1975 Grenney and Porcella, 1975 Harper, 1972 Huck and Farquhar, 1974 Hwang et al., 1973 Hydrologic Eng. Center, 1974 Idaho State Study Team, 1973 Kadlec, 1971 Langbein and Durum, 1967 Lehmann, 1974 Lombardo, 1973 Masch and Assoc., 1971 Nemerow, 1974 Orsborn et al., 1973 Rutherford and O'Sullivan, 1974 Stochastics, Inc., 1971 Streeter and Phelps, 1925 Texas Water Dev. Board, 1971 Texas Water Dev. Board, 1974 Trumbull and Loomis, 1973 Tsivoglou and Wallace, 1972 Velz, 1970	Battelle, 1974 a,b Biswas, 1974 Bovee, 1974 Brown, 1969 Brown, 1972 Chen and Wells, 1974 Comer and Grenney, 1975 Dingerman and Assur, 1967 Edinger and Geyer, 1968 Elder et al., 1968 Enviro Control, Inc., 1971 Gerber, 1967 Grenney, 1975 Grenney and Porcella, 1975 Harleman et al., 1973 Harper, 1972 Hydrologic Eng. Center, 1974 Jobson and Yotsukura, 1972 Kadlec, 1971 King, 1970 Lehmann, 1974 Lombardo, 1973 Lorenzen et al., 1974 Masch and Assoc., 1971 Morse, 1970 Novotny and Krenkel, 1973 Orsborn et al., 1973 Paily et al., 1974 Raphael, 1962 Reaeration Research Prog. Management Team, 1975 Rowell, 1975 Texas Water Dev. Board, 1971 Texas Water Dev. Board, 1974 Timofeyev and Malevsky-Malevich, 1967 Wicks, 1975	Bagnold, 1966 Biswas, 1974 Battelle, 1974 a,b Chen and Wells, 1974 Chih, 1973 Chow and Zvi, 1973 Colby, 1964 DeVries, 1954 DuBoys, 1879 Einstein, 1950 Enviro Control, Inc., 1971 Eustis and Hillen, 1954 Graf, 1971 Grenney, 1975 Grenney and Mandavia, 1975 Hydrologic Eng. Center, 1974 Idaho State Study Team, 1973 Kadlec, 1971 Kalinski, 1947 Kondrat'ev, 1962 Lehmann, 1974 Lombardo, 1973 Masch and Assoc., 1971 Nordin, 1975 Pfankuch, 1973 Rosgen, 1973 Rosgen, 1975b Sakham et al., 1971 Schoklitsch, 1930 Shen, 1971 Shields, 1936 Simons and Richardson, 1966 Soil Conservation Serv., 1964 Straub, 1936 Toffaleti, 1969 Trimble, 1972 Trumbull and Loomis, 1973 Tywoniuk, 1972	Baca, 1974 Bain, 1968 Battelle, 1974 a,b Biswas, 1974 Chen, 1970 Chen and Orlob, 1972 Chen and Sellneck, 1969 Chen and Wells, 1974 DiToro et al., 1970 Elder et al., 1968 Enviro Control, Inc., 1971 Grenney, 1975 Grenney and Porcella, 1975 Harleman et al., 1968 Hickman, 1974 Hydrologic Eng. Center, 1974 Idaho State Study Team, 1973 Johnson, 1972 Kadlec, 1971 King and Sartoris, 1973 Lassiter, 1975 Lehmann, 1974 Lombardo, 1973 Lorenzen et al., 1974 Mahloch, 1974 Masch and Assoc., 1971 Middlebrooks and Porcella, 1971 Middlebrooks et al., 1973 Nemerow, 1974 O'Connor and DiToro, 1970 O'Connor and Thomas, 1965 O'Neill et al., 1970 Orsborn et al., 1973 Patten, 1968 Porcella et al., 1970 Riley et al., 1949 Siedal and Crites, 1970 Stratton, 1968 Stratton and McCarty, 1967 Stratton and McCarty, 1968 Sverdrup et al., 1942 Texas Water Dev. Board, 1971 Thomann et al., 1975 Trumbull and Loomis, 1973 USDI, 1968 Vollenweider, 1966 Wezernak and Gannon, 1968

Table 5. Methods and models for predicting flow changes in estuaries

Water Quality Characteristic / Analytical Approach	Hydraulics
Level I	Louisiana Cooperative Fishery Research Unit, 1974 EPA, 1971 EPA, 1972 Welby, 1975 (Personal Communication. N. Carolina State University)
Level II	Alexander et al., 1974 Asano, 1967 Bain, 1968 Battelle, 1974 a,b Bella, 1968 Bella and Dobbins, 1968 Biswas, 1974 Callaway et al., 1969 Clark and Synder, 1969 Dornhelm and Woolhiser, 1968 Dresnack and Dobbins, 1968 Feigner and Harris, 1970 Fischer, 1970 Fisher, 1969 Grenney and Bella, 1970 Grenney and Bella, 1972 Hann and Young, 1972 Harleman et al., 1968 Holley, 1969 Ippen, 1966 Kadlec, 1971 King et al., 1973 Leeds and Bybee, 1967 Lehmann, 1974 Lombardo, 1973 O'Connor, 1965 O'Connor et al., 1968 Orlob et al., 1967 Pence et al., 1968 Penumalli et al., 1975 Riggs, 1972 Schofield and Krutchkoff, 1974 Shubinski et al., 1974 Thayer and Krutchkoff, 1967 Thomann, 1963 Thomann, 1967 Wang et al., 1973 Wang and Connor, 1974 Wang and Connor, 1975 Wastler and Walter, 1968 Water Resources Engineers, 1965 Water Resources Engineers, 1966

Table 6. Methods and models for predicting effects of flow changes on water quality in estuaries – literature matrix

Parameter / Analytical Approach	Dissolved Gases	Temperature	Sediment	Total Dissolved Solids Nutrient budgets Microbial Ecology
Level I	EPA, 1971 EPA, 1972			EPA, 1971 EPA, 1972
Level II	Alexander et al., 1974 Battelle, 1974 a,b Bureau of Fisheries Nacote Creek Res. Sta., 1975 Callaway et al., 1969 Dornhelm and Woolhiser, 1968 Dresnack and Dobbins, 1968 Feigner and Harris, 1970 Grenney and Bella, 1972 Hann and Young, 1972 Holley, 1969 Lehmann, 1974 Lombardo, 1973 O'Connor, 1960 Olufeagba and Flake, 1975 Orlob et al., 1967 Pence et al., 1968 Schofield and Krutchkoff, 1974 Shubinski et al., 1974 Thayer and Krutchkoff, 1967 Thomann, 1963 Thomann, 1967 Water Resources Engineers, 1965 Water Resources Engineers, 1966	Alexander et al., 1974 Battelle, 1974 a,b Biswas, 1974 Bureau of Fisheries Nacote Creek Res. Sta., 1975 Callaway et al., 1969 Clark and Snyder, 1969 Dailey and Harleman, 1972 Edinger and Geyer, 1968 Feigner and Harris, 1970 Gerber, 1967 Harleman et al., 1968 Jobson and Yotsukura, 1972 Lehmann, 1974 Lombardo, 1973 O'Connor et al., 1968 Schofield and Krutchkoff, 1974 Schubinski et al., 1974 Water Resources Engineers, 1965 Water Resources Engineers, 1966	Battelle, 1974 a,b Biswas, 1974 Bureau of Fisheries Nacote Creek Res. Sta., 1975 Feigner and Harris, 1970 Lehmann, 1974 Lombardo, 1973 O'Connor et al., 1968 Owens and Odd, 1970 Schofield and Krutchkoff, 1974 Shubinski et al., 1974 Water Resources Engineers, 1965 Water Resources Engineers, 1966	Armstrong et al., 1975 Bailey, 1970 Battelle, 1974 a,b Bella, 1970 Biswas, 1974 Bureau of Fisheries Nacote Creek Res. Sta., 1975 Callaway et al., 1969 DiToro et al., 1970 Feigner and Harris, 1970 Fisher, 1969 Grenney, 1975 Grenney and Bella, 1972 Harleman et al., 1968 Kadlec, 1971 Lehmann, 1974 Lombardo, 1973 Middlebrooks et al., 1973 O'Connor, 1972 O'Connor et al., 1968 Odum et al., 1963 Orlob et al., 1967 Patten, 1968 Riley et al., 1949 Steele, 1958 Sverdrup et al., 1942 Thomann et al., 1970 Schofield and Krutchkoff, 1974 Schbinski et al., 1974 Water Resources Engineers, 1965 Water Resources Engineers, 1966

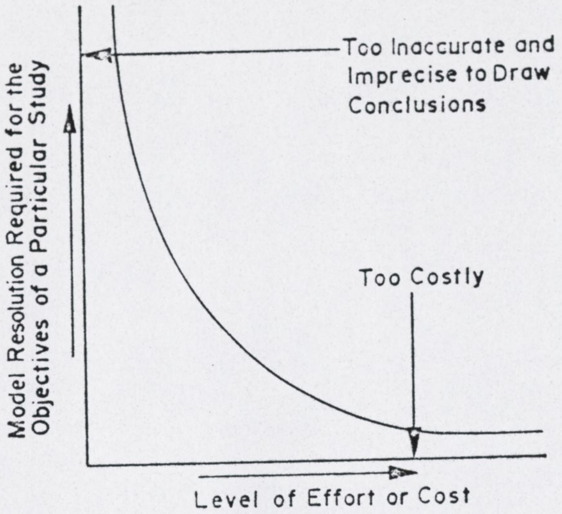

Figure 6. Graphic representation of the concept of spending less effort or dollars and obtaining a less usable result for a given model.

perfected; however, salinity measurements from water samples are still necessary supplements to the aerial measurements.

Louisiana Cooperative Fishery Research Unit (1974) currently has research under way to construct a usable "area inundated" curve for selected sections of Louisiana coastal marsh by correlating ERTS imagery information with observed water depths at the time the imagery was obtained.

Chabreck, (1972) reports the Louisiana coastal region was divided into nine hydrologic units by drainage basin and by four vegetative units. In each unit, the soil was characterized for chemical constituents and percent organic matter. Soil waters were analyzed for total salts. Total vegetative and water coverages were recorded. The vegetative coverage was identified to the species level and the water coverage was categorized by hydrologic units.

STATE-OF-THE-ART MODELING TECHNIQUES

In this report, the term "mathematical modeling" includes all quantitative techniques that are being used to analyze relationships between flows and water quality. The term "resolution" indicates the degree of complexity involved in applying the model. Low resolution models use relatively simple mathematical relationships, require limited amounts of input data, and may be solved quickly using a graphical technique such as standard curves or nomographs. High resolution models utilize complex mathematical relationships, require extensive amounts of input data, and are usually solved with digital computers. Low resolution models provide considerably less information to the decision-maker than high resolution models.

Figure 7 shows the general arrangement of most water quality models. They invariably have two components: 1) The hydraulic submodel; and 2) the water quality submodel. These two submodels are linked in order to provide an integrated response that is sensitive to both the system hydraulics and the water quality characteristics. The resolution of each of the two submodels may be developed to a high, moderate, or low degree. The best combination for a particular application depends on the characteristics of the system and the objectives of the study.

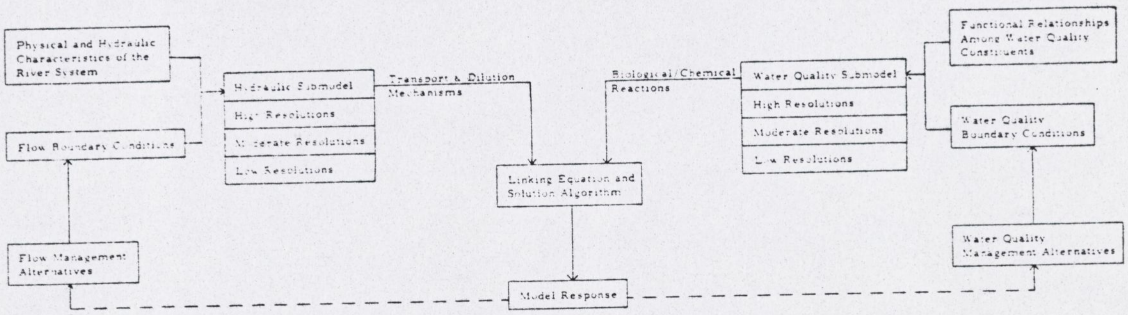

Figure 7. The general arrangement of water quality models.

The function of the hydraulic submodel is to describe the physical transport and dilution characteristics of the river system in question. For example, high and low resolution hydraulic submodels may represent unsteady nonuniform and steady uniform flow conditions, respectively.

Two types of input data are required for a hydraulic submodel regardless of its degree of resolution: 1) Physical/hydraulic characteristics; and 2) flow boundary conditions. The physical hydraulic characteristics include tributary network configuration, stream channel geometry, stream bed slope, hydraulic friction, etc. For low-flow analyses, these characteristics are usually assumed to be independent of proposed management alternatives.

Flow boundary conditions represent flows entering the modeled system at upstream boundaries (i.e., reservoir releases), entering or leaving laterally from diffuse surface and groundwater flows (i.e., agricultural runoff), entering as point loads (i.e., municipal waste treatment facilities), and leaving as point diversions. Usually some combination of these boundary conditions are varied to determine the impact on system hydraulics (and, hence, indirectly on water quality) of proposed management alternatives.

The function of the water quality submodel is to represent the biological/chemical interactions and transformations occurring among constituents as they are transported downstream. High resolution models represent complex nonlinear relationships among constituents, and low resolution models usually represent first order linear relationships. Similar to the hydraulic submodel, the water quality submodel requires two types of input information: 1) The functional relationship among water quality constituents; and 2) the water quality boundary conditions.

Because biological relationships are extremely complex, they are difficult to predict reliably even with high resolution models. Simplified low resolution models may be completely inadequate and even misleading, which explains the current popularity of relatively sophisticated computer models. Once the functional relationships among constituents are defined in a model, they are independent of management alternatives.

The water quality boundary conditions represent the concentrations of the various constituents in the boundary flows. These concentrations may be controlled by various management alternatives. For example, concentrations in point loads can be controlled by the construction of wastewater treatment plants and concentrations in diffuse flows may be controlled by land management practices.

The effects of the hydraulic submodel and the water quality submodel are integrated with a linking equation. The most common linkage is the mass balance equation, which can be expressed in one dimension as follows:

$$\frac{\partial AC_i}{\partial t} = -\frac{\partial UAC_i}{\partial x} + \frac{\partial}{\partial x}\left(DA\frac{\partial C_i}{\partial x}\right) + S + R \quad . \quad .(1)$$

in which C_i is the concentration of the constituent, x is the space dimension, U is velocity, A is area, D is the dispersion coefficient, S represents transport of mass across the system boundaries, R represents biochemical transformations within the system, and t is time. Time and spacial dimensions are the independent variables in the system being considered. The constituent concentration (C_i) is the dependent variable being simulated in time and space by the model. If more than one constituent is being modeled, an equation similar to Equation 1 must be written for each, and all equations solved simultaneously. The hydrodynamics of the system are linked to the equations through the A, U, and D coefficients. The S coefficient allows for mass transport across the boundaries of the system. The biological and chemical reactions are linked to the equation through the R coefficient. All coefficients may be time and space variables, or the coefficients may be replaced by more complex terms which in themselves contain large numbers of additional coefficients. These terms may be expressed as functions of any or all dependent variables being modeled. These equations may be modified to become either very complex and difficult to solve or relatively simple, depending on the objectives of the model application.

A wide variety of deterministic simulation models have been applied to characterize and predict water quality parameters in rivers and estuaries. General differences in resolution among models are associated with the degree of time and space resolution, with the number and type of water quality parameters included in the model, and with the mathematical solution technique. For any specific model application, there is some optimal combination of these three considerations.

The following particular model applications were selected as representative of currently applied techniques. The list is not comprehensive and it should be noted that many individuals are successfully applying other models to similar situations. The models summarized herein, however, encompass most of the techniques and functional relationships in current use. Techniques for hydraulic submodels will be discussed first, followed by those for water quality submodels and then those used to couple flow and water quality.

HYDRAULIC SUBMODELS

Estuaries present the most complex conditions for hydrodynamic modeling and much of the developmental effort has been exerted in this area. The literature associated with estuary modeling provides some of the best descriptive material available and is therefore cited in this review. All of the modeling techniques described in the estuary sections have been utilized in one form or another for river situations.

Estuaries–Two Dimensional

All three basic types of two-dimensional model approaches: 1) Finite-difference uniform grid; 2) finite-difference link-node; and 3) finite-element, have large detailed data requirements. Hann and Young (1972) provide a good summary review of uniform grid models using both implicit and explicit solution techniques. Models were applied to the Houston Ship Canal and calibrated for data from a Rhodamine-B (fluorescent dye) tracer study. The main thrust of the research was the comparison of implicit and explicit solution techniques. The hydraulic properties (flow, velocity, and depth) may be modeled as a function of time and location. Input includes time-varying coefficients and boundary conditions.

The link-node technique was developed by Orlob to represent water quality in the Sacramento-San Joaquin Delta (Water Resources Engineers, 1965, 1966; Shubinski et al., 1974). The model uses finite-difference approximations to simplified, one-dimensional forms of the equation of motion and the equation of continuity. A network of channels are linked at nodes to describe the area covered by the estuary. The method is more convenient for representing irregular configurations than is the uniform grid approach. The model has subsequently been applied to other bodies of water including San Diego Bay (Feigner and Harris, 1970), the Columbia River estuary (Callaway et al., 1969), and the Willamette River (Battelle, 1974a,b). Feigner and Harris (1970) have documented the model for the Environmental Protection Agency. The hydraulic properties (flow, velocity, and depth) are modeled as a function of time and location. Input includes time-varying coefficients and boundary conditions.

The finite-element technique has been applied to Massachusetts Bay by Wang and Connor (1975). In the finite-element method, the original continuous problem is reduced to a system of ordinary differential equations in time (Kawahara, et. al., 1975). These can be solved by traditional techniques. Due to the fundamentals of the finite element formulation, completely arbitrary geometries may be modeled. Thus, spacial programming is not required in order to fit highly irregular boundaries. In addition, the feature of variable element size may be used to create a fine mesh of elements in areas of high variable gradient in order to obtain the desired accuracy and detail in very sensitive regions. Common boundary conditions are also handled easily by the finite element method. In the Wang and Connor study, the effect of wind was explicitly included in the formulation, and the tide, which was considered as a long wave, was accounted for by the prescribed boundary conditions.

Estuaries–One Dimensional

Two distinctly different types of time scales are used in one-dimensional estuary modeling. One includes velocity variation caused by tidal action directly in the model, thus making pollutant distribution a function of tidal elevations. In these models, concentrations in the channel can be calculated at any time during a tidal cycle.

The other time scale includes only average net water movements over a period of time equal to or greater than one tidal cycle. Since intertidal velocities are excluded, their effects on the concentration distribution are considered to be represented by the dispersion coefficient, D. In these models, concentrations in the channel can be calculated only at a time of slack water.

In the following review, methods for solving the one-dimensional form of Equation 1 have been divided into three categories: Analytical or exact, numerical, and others. Both of the abovementioned time scales can be utilized by these methods.

EXACT METHODS

Exact solutions to Equation 1 can be separated into three general categories, according to the assumptions applied to the parameters, A (area), U (velocity), and D (dispersion).

The first category includes solutions based on the assumption that equilibrium conditions exist in the estuary and that all parameters are constant with time and distance (Asano, 1967; Bain, 1968). A modified version of Equation 1 was solved with steady-state dissolved oxygen (DO) relationships in the Delaware River (O'Connor, 1960) and relatively close agreement was obtained between model predictions and observed yearly slack water concentrations. This type of model is often of limited value, however, because only long-term average concentrations are involved and most practical applications require knowledge about short-term critical concentrations.

The second category of analytical solutions hold U and D constant and allow A to vary as a simple algebraic function of X. Solutions of this type were applied to the Delaware, Upper East, and James Rivers (O'Connor, 1965) where U was set equal to the average freshwater flow over the study period. A more recent study (O'Connor et al., 1968) utilizes similar analytic techniques. However, in this case the channel was divided into segments, the analytical solution applied to each segment, and the resulting system of simultaneous equations solved by matrix algebra. This type of model is limited to the extent that only slack-water concentrations are considered and velocity fluctuations due to the tide are ignored.

The third category of analytical solutions to Equation 1 is based on the assumption that A is constant and that D and U vary as algebraic functions of time. Holley (1969) used this approach to investigate slack-water buildup associated with unsteady, uniform flow. He varied the pollution injection rate as a simple algebraic function of time. The major limitation of this approach is that the cross-section area of the channel is considered uniform throughout the length of the estuary.

NUMERICAL METHODS

Due to the irregular geometry and unsteady flows in estuaries, Equation 1 defies analytical solution for most practical applications. Therefore, numerical methods have been utilized to obtain solutions with greater freedom in parameter variation. Several basic approaches to general finite-difference modeling were presented by Dresnack and Dobbins (1968) and Thomann (1963).

An implicit central-difference scheme was applied to Equation 1 for studies of the Potomac River Estuary (Harleman et al., 1968). The stream channel was divided into equal-length segments and average cross-section areas (A) were estimated for each segment. Velocity (U) was represented as a sinusoidal function of time, the dispersion coefficient was given as a linear function of velocity, and the injection rate was a combination of continuous and slug injections.

Grenney and Bella (1972) developed a one-dimensional, explicit finite-difference model and applied it to the Yaquinta River Estuary near Newport, Oregon. In the model, tidal waves were propagated upstream as attenuated sine waves, similar to methods suggested by Ippen (1966). The buildup of pollutants during slack water was studied as a function of freshwater inflow and tidal hydraulics. The model incorporated a unique technique for correcting numerical errors associated with advection (Grenney and Bella, 1970).

In studies of the Delaware Estuary (Pence et al., 1968), Equation 1 was combined with an oxygen balance equation and expressed as a differential-difference equation. These equations were solved numerically by fourth-order Runge-Kutta methods. Stream velocities were based on freshwater flow without consideration of tidal fluctuations. An attempt was made to incorporate the effect of tides by introducing an "advection coefficient (ξ)" into the finite difference portion of the equation. When ξ is changed from 1.0 to 5.0, the difference scheme changes from the backward to the central difference equation. Hence, the lower the value of ξ, the more dependent the concentration in a particular segment becomes on downstream concentrations. Application indicated close agreement between model and prototype for long-term average DO concentrations.

Dornhelm and Woolhiser (1968) combined Equation 1 with the continuity and momentum equations for unsteady free-surface flow. Their system of equations was solved by an implicit difference scheme. Instability and long periods of computer time are the major disadvantages of this method.

Application of Equation 1 to a two-dimensional estuary was attempted by Orlob et al. (1967). A square grid was superimposed on the estuary and each line segment was considered to be a one-dimensional channel. Tidal velocities in the channels were calculated by a separate computer model. The pollution distribution was simulated by representing Equation 1 in explicit finite-difference form and applying it to each channel. Two types of numerial errors were discovered in the model: oscillations and spreading of the distribution. A sensitivity analysis comparing the central difference and quarter-point difference schemes indicated that when one error was reduced the other was generally increased.

Because of the errors introduced when Equation 1 is represented by numerical methods, some investigators have applied numerical techniques directly to the stream channel using Equation 1 only as a guide. Bella and Dobbins (1968) conceived the channel as a series of cells, each containing a known volume and uniform concentration during finite time increments. Convection and dispersion were simulated by average transport of material across cell boundaries and decay by reduction of cell concentrations during each time increment. A multi-step procedure is allowed the effects of each term to be determined independently. Numerical errors can be readily recognized by this procedure and a method for correction is available.

A Lagrangian concept has been developed for predicting pollution dispersion in Bolinas Lagoon, California (Fisher, 1969). The embayment was segmented into a two-dimensional pattern, although flow within each segment is considered to be one-dimensional. Each time increment included a convection step, a dispersion step, and a decay step. Convection was simulated by slugs of water moving at this average water velocity over each finite time increment, and numerical errors usually associated with the convection step were greatly reduced. Dispersion became an empirical relationship based on the concentration gradient.

OTHER METHODS

Leeds and Bybee (1967) developed a solution to Equation 1 using digital computer programs designed to solve electrical network problems. They approximated Equation 1 by a set of ordinary differential equations obtained by replacing the differentiation with respect to the space variable with finite-differences. Stream velocities were based on freshwater flow without consideration of tidal fluctuations. Effects of mixing due to tidal action were assumed to be included in an "eddy diffusivity coefficient." Significant errors are inherent in this method, especially for the simulation of a continuous outfall (Bella, 1968).

A statistical time-series analysis was applied to concentrations in the Delaware Estuary (Thomann, 1967). Analytical techniques such as Fourier and power spectrum computations were used to calculate DO with average daily water temperatures. The greatest amount of variance was accounted for by the annual harmonic. Frequencies at the low end of the spectrum were analyzed in detail in order to obtain a "first estimate" of the expected short-term DO distribution around a mean value. Given this variance, an administrator could decide on the basis of water-use goals whether a particular mean DO concentration were sufficient in view of occasional fluctuations to critical values.

A similar type analysis was applied to Charleston Harbor (Wastler and Walter, 1968). In this work, the objective was to determine effects of reduced freshwater inflow on water quality. Chloride intrusion was correlated with freshwater inflow by power spectrum analysis and a significant relationship was shown to exist between the two variables.

A stochastic model has been divided to describe the probabilistic distribution of the biochemical oxygen demand (BOD) and DO concentrations (Thayer and Krutchkoff, 1967). The model was based on the assumptions that all parameters are constant and that the system has reached steady-state conditions. Although the model is inadequate for direct application to most practical estuary problems, it does present one interesting result in that variance in DO concentrations is highest when the average DO concentration is low. In other words, the greatest amount of uncertainty exists at critical concentrations.

Penumalli et al. (1975) described a way to link a water quality simulation model (estuary) with an optimization (nonlinear) technique formulated as a control problem. The discretized version of such a problem can be formalized as a large-scale operation problem suitable for solution by large-scale mathematics programming techniques. They presented a good summary of simulation and optimization modeling techniques. A two-dimensional hydrodynamic model was applied to Corpus Christi Bay, Texas, in which a water quality model for phosphorus was linked with the hydrodynamic model. This water quality model was then used in conjunction with an optimization model to minimize costs of phosphorus treatment from waste discharges around the bay and at the same time meet water quality phosphorus standards in the bay.

Rivers

All of the above estuary modeling techniques can be applied to rivers. In this section we describe several modeling techniques that are specific for rivers. Methodologies presented in the literature relate various properties of flow regime in open channel flow (free surface flow) to gross flow rates. In using these techniques, flows are usually stipulated at the boundaries, and flow and other properties are calculated at desired downstream points. These properties include depth of flow, velocity of flow, width of the streambed under water and other hydraulic properties. Inputs for these models generally include the flow rate at the boundaries and definition of channel characteristics, including slope, bed roughness, and cross-sectional area to depth relationships.

Jeppson (1974) provides a good summary of computer models for hydraulic simulation as well as developing one of his own. He states that the unsteady one-dimensional Saint-Venant equations are solved by an implicit finite difference scheme to handle general channel and river flows. The initial conditions for the unsteady flow are provided by solving the steady varied flow equation for the specific boundary conditions. The solution for unsteady flow allows any of eight separate boundary conditions to be specified. These boundary conditions are composed of combinations that specify the depth or discharge as a function of time at either the upstream or downstream end, and the stage-discharge relation or constant depth and flow rate at the other end. The model was applied to Temple Fork Creek near Logan, Utah. The channel's geometry slope and roughness coefficient were input to the model. (These values may vary with respect to distance along the channel.) Typical solutions showing spatial and time dependency of such flow characteristics as flow rate, depth, and velocity were given by Jeppson (1974).

Fread (1974) developed an implicit dynamic routing technique for streamflow forecasting. He computed the stage and discharge by solving the complete one-dimensional differential equations of unsteady flow by an implicit four-point finite difference method which necessitates the solution of successive systems of nonlinear equations. An extrapolation technique along with a special quad-diagonal Gaussian elimination procedure was used in conjunction with the Newton-Raphson method and provided an efficient solution technique for the nonlinear systems. Time and space increments need not be constant. According to Fread (1973), the specified time interval is not limited by computational stability, although accuracy constraints may limit its size. The technique has been demonstrated and tested on some recent floods and hurricane surges that occurred in the lower portion of the Lower Mississippi River.

A digital computer model was developed and specifically used to simulate extreme flow data which would be adequate to determine the low flow characteristics on the Kentucky River near Winchester, Kentucky, for 31 years of regulating conditions (Shearman and Swisshelm, 1975). Model inputs consisted of (1) reservoir operation criteria for an existing reservoir, and (2) observation of streamflow data for 21 years of natural and 10 years of regulated conditions. These modeling techniques are also suitable for studying alternative streamflow regulation streams and expanding networks of homogeneous streamflow data for regional analysis.

Steady flows are frequently used as the hydraulic component of a water quality model. Flows at all points in the system are obtained by a water budget in which all of the boundary flows are assumed known. Simultaneous flow measurements must be made at numerous key locations, and ideally under several flow conditions. If a sufficient number of USGS gaging stations are located in the basin being modeled, additional field measurements may not be necessary. The desired order of resolution of the model is also relevant. The probable frequency of a particular high or low flow condition is of interest in many modeling situations. Discharge frequency curves (Chow, 1964) are often valuable tools in establishing critical flow conditions (see Section 2). The flows shown in Figure 8 are based on the evidence that a sequence of dry years is not random, but tends to occur in clusters. In Figure 8 the annual flows of a river were divided into three equal groups; the years with the highest flows of record, the years with the lowest flows of record, and the remainder. Then the annual discharges for the years following each of the grouped flows were arrayed into three groups. This quantitative evaluation of serial sequential correlation showed that the flow following a year of low runoff tended to be lower than the year following a high runoff.

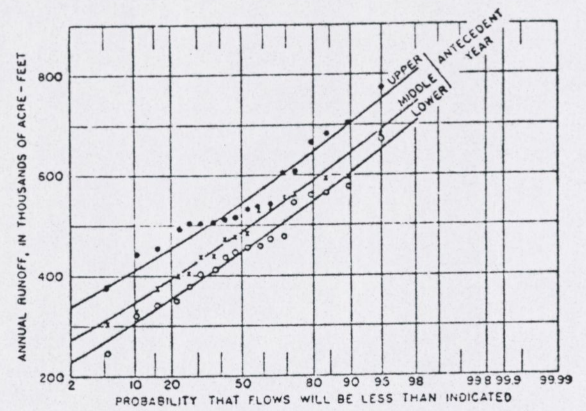

Figure 8. Variation of annual flow of Cedar River, depending on antecedent flow (from Chow, 1964).

WATER QUALITY SUBMODELS

In this section, state-of-the-art submodels are discussed for six water quality parameters: dissolved oxygen (DO), biochemical oxygen demand (BOD), algae, nitrification, temperature, and sediment transport. These parameters were selected for detailed discussion because they are probably the most important from the standpoint of fisheries, they are sensitive to low flow conditions, and sophisticated methodologies have been developed and applied for their evaluation. All of the parameters (except sediment) are linked directly to the net dissolved oxygen flux in a stream. Examples of submodels for parameters other than the six represented here can be found in the following section.

Dissolved Oxygen

Dissolved oxygen (DO) is probably the single most important water quality parameter in fisheries management. Because water contains less than one percent oxygen by volume at normal temperatures, the aquatic environment is critically sensitive to the oxygen demands of the organisms that inhabit it.

The DO concentration in a stream is the net result of oxygen fluxes into and out of the water. Fluxes into the water are primarily from atmospheric reaeration across the water surface and oxygen production by photosynthetic organisms in the water. Oxygen primarily leaves the water due to consumption by bacteria during their oxidation of organic substrates (BOD) and ammonia (nitrification), and respiration by other aquatic organisms.

Although photosynthesis may generate considerable amounts of oxygen, it is confined to the daylight hours. During the night, aquatic plants subtract oxygen and release carbon dioxide (CO_2) to the water. The result is a diurnal cycle of DO and CO_2 within water rich in vegetation. The amplitude of the cycle varies with variations in temperature, the intensity of sunlight, and the density of the plant population. Submodels for simulating the effects of photosynthesis on DO are discussed later in the report under the subheading Algae.

The reaeration process across the stream surface involves physical absorption of oxygen from the atmosphere. Adeney and Becker (1919, 1920) showed that the amount of reaeration by water can be represented as a first order process directly proportional to the saturation deficit:

$$\frac{dC}{dt} = K_2^T (C_s - C) \quad \ldots\ldots\ldots\ldots (2)$$

where C is the concentration of DO, C_s is the saturation concentration of DO, and K_2^T is the reaeration rate coefficient at temperature T. Many investigators have used common logarithms (base 10) to calculate and model K_2^T. The conversion factor from base 10 to base e is:

$$K_{(base\ e)} = 2.303\ K_{(base\ 10)} \quad \ldots\ldots\ldots (3)$$

Numerous models have been developed for the prediction of reaeration coefficients. The models most often cited in literature utilize semi-empirical and empirical types of equations.

The study by Churchill et al. (1962) is considered by many to have produced the best and most reliable set of field data on reaeration rates. Their measurements were made on stretches of rivers below dams where the water released from reservoirs was low in DO and BOD because of prolonged storage under thermally stratified conditions. They determined 509 values from 16 different reaches in 5 rivers using the dissolved-oxygen balance technique. The flow depths varied from about 2 to 11 feet, the mean velocity from 1.8 to 5 fps, and the discharge from 950 to 17,270 cfs. They ran many multiple-regression analyses in an attempt to relate their observed reaeration rates to gas and liquid parameters and various stream characteristics such as slope, friction factor, and Reynolds number. Because none of the prediction equations thus obtained proved to be statistically better than any of the others, the authors suggested the simplest one for general usage. This equation was:

$$K_2^T = 5.026\ U^{0.969}\ D^{-1.673}\ (1.0241)^{T\ -\ 20^o} \quad . . . (4)$$

where K_2 (base 10) is in reciprocal days; U, the velocity, is in feet per sec.; D, the depth, is in feet; and T, the temperature, is in degrees Celsius.

Table 7 contains a number of equations developed by other investigators for determining reaeration coefficients (base e). Figure 9 shows approximate values for K_2 at 20°C as a function of stream depth and velocity. An excellant comparitive review of the various equations used for estimating reaeration coefficients is presented by Langbein and Durum (1967). Methods for estimating values of K_2^T from measured field data are presented by Chen and Davis (1975), Langbein and Durum (1967), and by EPA (1971).

Table 7. Reaeration equations (from Texas Water Development Board, 1971).

Equation	Author	Comment
$K_2^T = K_2^{20}\ (1.047)^{20-T}$	Eckenfelder & O'Connor (1961)	Popular equation relating reaeration coef. to temperature in C°
$K_2^{20} = 5.026\ \bar{u}^{0.969} D^{-1.673} \cdot 2.31$ Definition of terms: $\bar{u}$ = Average velocity D = Average depth (ft)	Churchill, Elmore, & Buckingham (1962)	
$K_2^{20} = \dfrac{129(D_m u)^{0.5}}{D^{1.5}}$	O'Connor & Dobbins (1958)	For low velocity and isotropic
$K_2^{20} = \dfrac{480\ D_m^{0.5} S_o^{0.25}}{D^{1.25}} \times 2.31$ S_o = Slope of the streambed D_m = $1.91 \times 10^{-3}(1.037)^{T-20}$ = molecular diffusivity		For high velocity and nonisotropic
$K_2^{20} = 9.4\ \bar{u}^{0.67}/D^{1.85} \times 2.31$ $K_2^{20} = 10.9\ u^{0.73}/D^{1.75} \cdot 2.31$	Owens, Edwards, and Gibbs (1964)	For depths (0.9 - 11) ft. For velocities (0.1 - 5) ft/sec. For depths (0.4 - 11) ft. For velocities (0.1 - 1.8) ft/sec
$K_2^{20} = 10.8\ (1 + F^{0.5})\ \dfrac{u^*}{D} \times 2.31$ $F = u^*/\sqrt{gD}$ (Froude No.) Definition of terms: u^* = $\sqrt{DS_e g}$ (shear velocity ft/sec) g = accelerated gravity S_e = slope energy gradient	Thackston (1966)	Developed for rivers in the Tennessee Valley
$K_2^{20} = 3.3\ \bar{u}/D^{1.33}$	Langbien and Durum (1967)	
$K_2 = \dfrac{c\bar{u}^n}{D^2}$ c, n = constants	Streeter and Phelps (1925)	

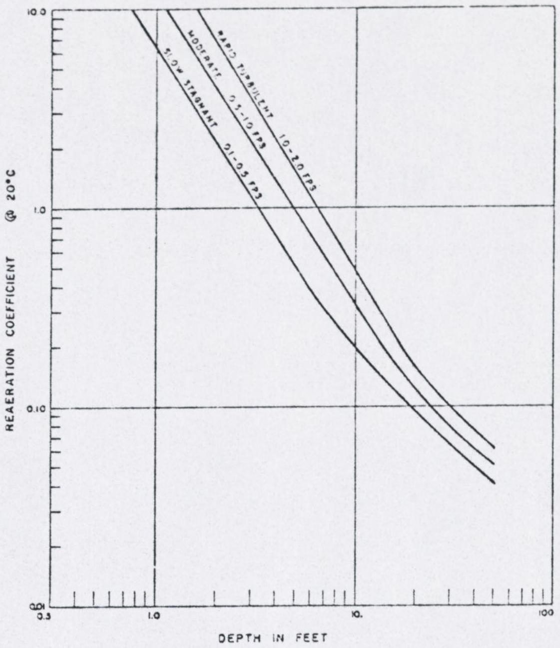

Figure 9. Reaeration coefficient (K_2) as a function of depth (from EPA, 1971).

Values for K_2^T are usually standardized to 20 °C for reporting (K^{20}). The value of K_2^T at some temperature (T) other than 20 °C is calculated as follows:

$$K_2^T = K_2^{20}\ \theta^{T-20} \quad . . . . (5)$$

where θ is an emperical coefficient. The most commonly used value for θ is 1.024 (Chen and Davis, 1975); however, 1.047 has also been used (Texas Water Development Board, 1971). Figure 10 shows the variation of K_2^T with temperature as calculated by Equation 5.

The saturation concentration of DO (C_s) is an important coefficient in Equation 2. C_s decreases significantly as temperature increases. C_s is also noticeably reduced when high TDS are present—for example, in the case of estuaries when chlorides exceed about 2,500 mg/l. Figure 11 shows C_s for various temperatures and chloride concentrations. C_s is also affected by the partial pressure of oxygen in the air above the water surface. Variations of C_s with elevation are shown in Figure 12.

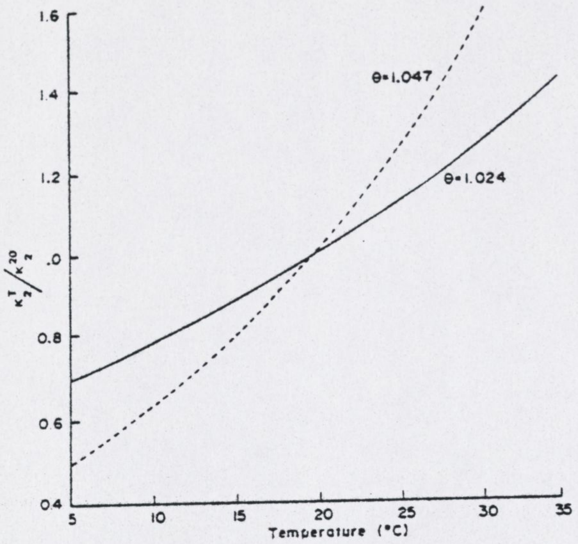

Figure 10. Variation in reaeration coefficient as a function of temperature.

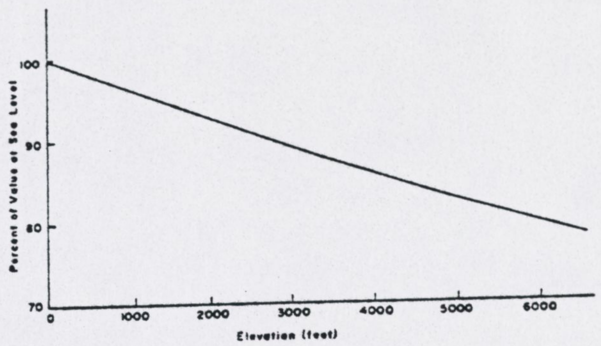

Figure 12. Decrease in dissolved oxygen saturation concentration (C_s) with increasing elevation.

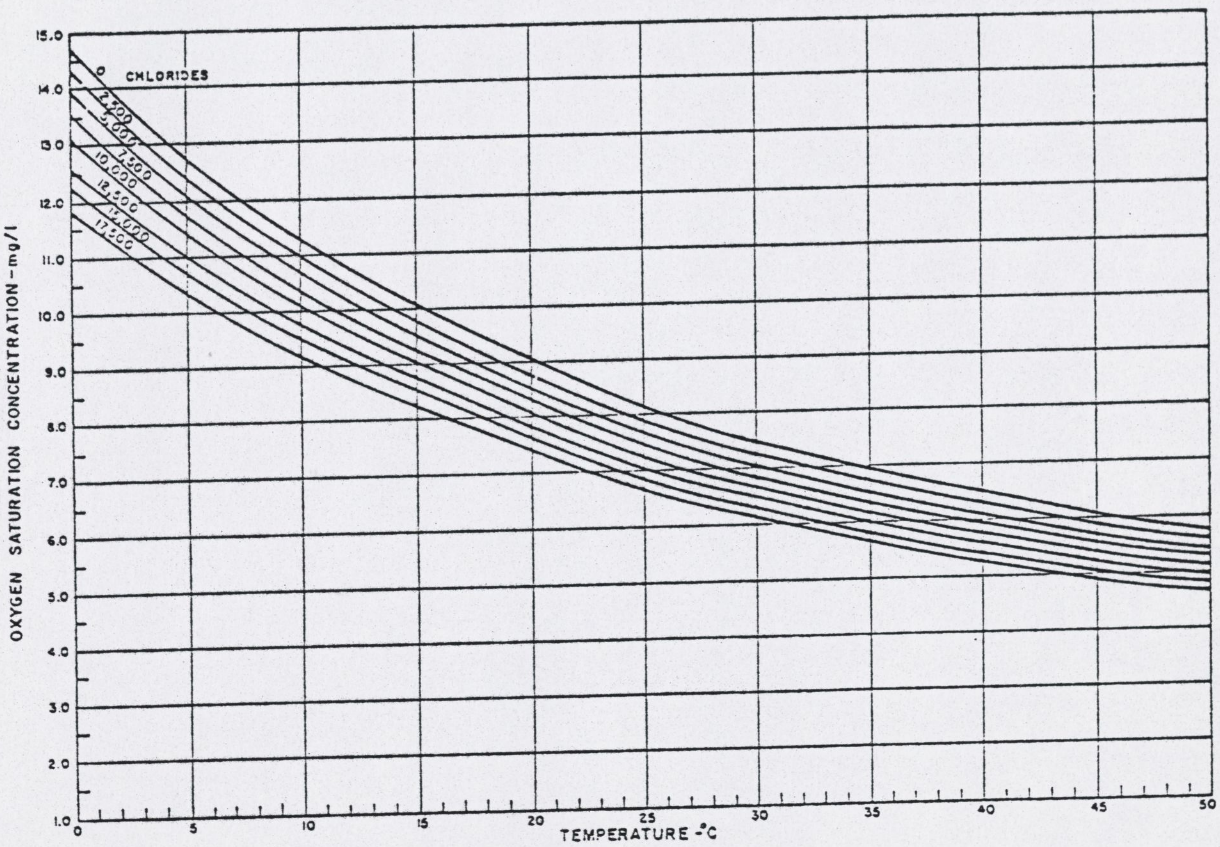

Figure 11. Saturation-temperature-chloride relationships (salinity= f (chloride) in estuarine systems) (from EPA, 1971).

Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD) is usually defined as the amount of oxygen required by bacteria as they stablize decomposable organic matter under aerobic conditions. Biological degradation of organic matter under natural conditions is brought about by a diverse group of organisms that carry the oxidation essentially to completion, i.e., almost entirely to carbon dioxide and water. The rate of biological oxidation is dependent on temperature and the characteristics of the organic substrate; however, in most cases, the oxidation takes about 20 days. The total amount of oxygen required to oxidize a given amount of organic material is called "ultimate BOD" (BOD_u). It has been found from experience that a reasonably large percentage of the BOD_u is exerted in 5 days; therefore, the 5-day BOD (BOD_5) exerted at 20°C has become the standard value reported. It should be remembered that the 5-day BOD values represent only a portion of the ultimate BOD. The exact percentage depends upon the character of the organisms and the nature of the organic matter. In the case of domestic sewage, it has been found that the BOD_5 value is about 70 to 80 percent of the BOD_u.

Although hundreds of models have been used, almost invariably in practical applications to natural waters the BOD_u oxidation process is represented as the first order reaction introduced by Streeter and Phelps in 1925. The rate of the reaction is proportional to the amount of oxidizable organic matter remaining at any time. Mathematically, the reaction is expressed as:

$$\frac{dC}{dt} = -K_d C \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where C represents the concentration of oxidizable organic matter and K_d is the reaction rate. The value of K_d varies considerably from application to application. Figure 13 shows some data seeming to suggest that K_d varies with depth; however, there is very little additional data to support such a hypothesis. The wide variation observed in BOD decay rates is probably due to K_d being an emperical coefficient that is used to lump many complex mechanisms into a single simple equation.

Because K_d represents a biological reaction rate, its value is assumed to increase with temperature in accordance with the following expression:

$$K_d^T = K_d^{20} \theta_b^{T-20} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

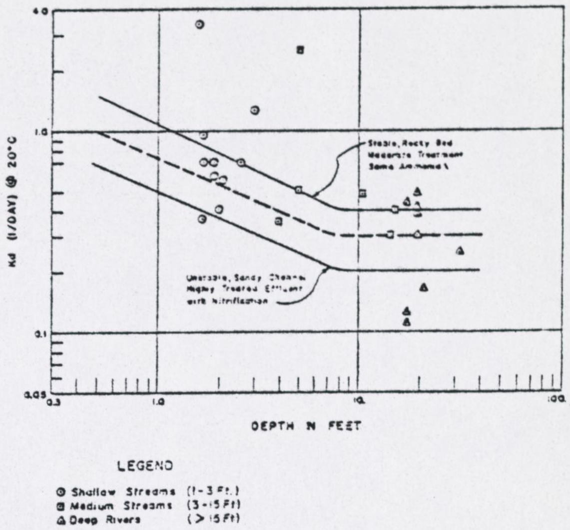

Figure 13. Deoxygenation coefficient (Kd) as a function of depth (from EPA, 1971).

where K_d^{20} and K_d^T are reaction rates at 20°C and temperature T(°C), respectively, and θ_b is an emperical coefficient. The generally accepted range of values for θ_b is about 1.05 to 1.075 for temperatures between 15° and 30°C. The value of θ_b appears to increase with decreasing temperatures and may be about 1.1 at 5°C (Fair et al., 1968). Figure 14 shows the variation in K_d with temperature as calculated by Equation 7.

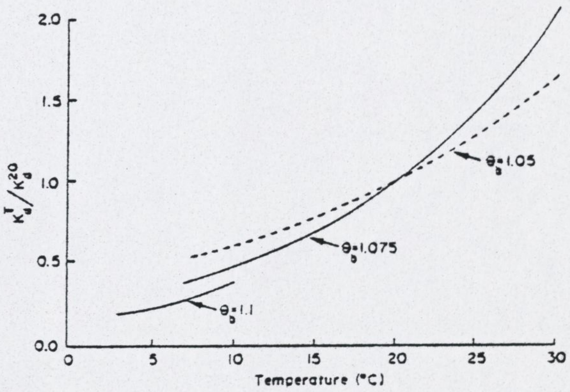

Figure 14. Variation of the BOD reaction rate coefficient (K_d) as a function of temperature: $K_d^T = K_d^{20} \theta_b^{T-20}$.

Sometimes it is convenient to characterize the assimulative capacity of a stream by the ratio of K_2 to K_d:

$$\emptyset = K_2/K_d \quad \text{. . . . .} \quad (8)$$

where $\emptyset$ is the assimilation ratio. Figure 15 shows some ranges of values that might be expected in typical circumstances.

Several equations have been proposed for estimating benthic uptake rates, as shown in Table 8. Velz (1970) classified stream bottom deposits as benthic and sludge. He defined benthic deposit as "those deposits exerting a very small oxygen demand on a stream system," and a sludge deposit as "exerting an oxygen demand as well as being able to contribute to the BOD." An example would be large organic deposits below wastewater treatment plant effluent. Nutrient leaching as well as active decomposition may exist. Resuspension of BOD due to scouring and gas production is also possible.

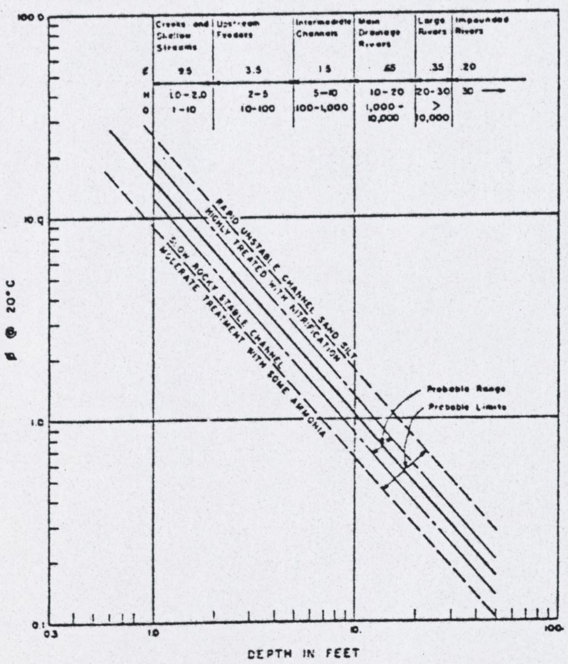

Figure 15. Assimilation ratio (ϕ) as a function of depth (from EPA, 1971).

Table 8. Benthic uptake equations.

Equations	Definition of Terms	Author
Temperature Affects		
$\log D_b' = K \log t - K_1$	D_b' = uptake rate; T = temperature; K, K_1 = constants	Hargrave (1969)
$D_b' = KT - K_1$	K = constant	Edward and Rolley (1965)
$\log D_b' = KT^{-1}$	T = degrees Kelvin	Arrhenius Equation
Uptake Rate		
$D_b' = a D^{0.485}$	a = constant; D = depth sedim.	Baity (1938)
$D_b' = aC^b$	a, b = constants	Edberg & Hofsten (1972)
$D_b' = A(1 - e^{-1.23\,D.O.})$	A = constant	Fillos & Molof (1972)

Algae

Techniques for the mathematical modeling of aquatic systems have been developed at a rapid rate over the last 30 years. Since Sverdrup et al. (1942) applied a model for productivity in the North Atlantic, numerous investigators have developed models to describe the fate of biological and chemical substances in aquatic systems and have applied the models to real systems with varying degrees of success (Riley et al., 1949; Vollenweider, 1966; Steele, 1958; Orlob et al., 1967; Fisher, 1969; Harleman et al., 1968; O'Connor et al., 1968; Callaway et al., 1969; Thomann et al., 1970; DiToro et al., 1970; Grenney and Bella, 1972). The relationship between phytoplankton growth, kinetics, and various environmental factors (light, temperature, grazing, nutrient availability, etc.) is probably the most difficult phenomenon to model.

Patten (1968) provides a good review of the mathematical models of plankton production created during the period 1932 to 1968. These models include the effects of light, temperature, and specified nutrient concentrations on growth rate. Removal of phytoplankton from the water column by sinking is considered in several of the models. The earliest models were generally restricted to linear functions that could be solved relatively easily by the methods available at the time. About 1965, digital computers became readily available to researchers, and sophisticated numerical techniques came into use. These allowed greater freedom in using nonlinear functions and feedback loops to express interactions occurring in nature and resulted in higher resolution models.

DiToro et al. (1970) developed a dynamic model of phytoplankton populations in natural waters. The model is time and one-dimensional space dependent. Phytoplankton, nutrient concentrations, and zooplankton are included in the model. The phytoplankton growth rate is represented as a function of light, temperature, and nutrient concentrations.

Chen and Orlob (1972) developed concepts and techniques for ecologic simulation of aquatic environments. They produced a time-dependent, one-dimensional (vertical) model and applied it to Lake Washington. The model contains complex expressions for modeling two phytoplankton communities, zooplankton, detritus, and sediment, benthic animal biomass and numerous other water quality parameters. In the same study, they applied a time-dependent, two-dimensional (horizontal) model to the San Francisco Bay-Delta Estuarian system.

Bella (1970) developed a time-dependent, one-dimensional model to demonstrate the effect of sinking rates and vertical mixing on algal population dynamics. He concluded that small differences in sinking velocities may significantly affect interspecific competition among phytoplankton.

Cordeiro, Echelberger, and Verhoff (in Middlebrooks et al., 1973) described a time-dependent, two-layer (epilimnion, hypolimnion) model which includes three types of algae, three types of bacteria, and a variety of organic and inorganic chemicals. The model also incorporates convective and diffusive (dispersion) transport, sedimentation, chemical reactions and biological reactions. The phytoplankton in the model have the capability for luxury uptake of nutrients.

Welch, Rock, and Krull (in Middlebrooks et al., 1973) presented a time-dependent, two-layer model that predicts long-term lake recovery related to available phosphorus. Phytoplankton and phosphorus are included in the model. Phosphorus release from the sediments is considered; however, complex cycling in the water column is ignored. Model responses were demonstrated using data from Lake Sammamish and Lake Washington.

Larsen, Mercier, and Malueg (in Middlebrooks et al., 1973) developed a model for algal growth dynamics in Shagawa Lake, Minnesota, and commented on projected restoration of the lake. The model is time-dependent for a completely mixed system. It includes phytoplankton, available phosphorus, and available nitrogen. The phytoplankton growth rate was based on Monod kinetics and is light sensitive.

The "Deep Reservoir Model" (Orlob et al., 1967) uses meteorologic and hydraulic inputs, coupled with the physical characteristics of the impoundment under construction. The model allows the temperature profile of the water column to be calculated on a daily basis. This model was modified (Anderson, 1973) to utilize the temperature profile to divide the lake into three strata: epilimnion, thermocline, and hypolimnion. He continuously modeled each stratum in time, generating $PO_4^{\equiv}$, NH_3, NO_2, NO_3, coliforms, conservative substances, and organic nitrogen as a measure of phytoplankton. The modified model utilized grazing rates, sinking rates, and bacterial development along with the incorporation of nutrients into the benthos in its materials balance. This modified model has been applied to Deer Creek Reservoir (Utah), Pyramid Lake, and Lahontan Reservoir (Nevada).

Chen (1970) and Porcella et al. (1970) proposed the following equation form for modeling phytoplankton:

$$\frac{dX}{Xdt} = \mu = \frac{\hat{\mu} S_C}{S_C + K_C} \cdot \frac{S_N}{S_N + K_N} \cdot \frac{S_P}{S_P + K_P} \cdot F_l \cdot F_T . \quad (9)$$

in which

X = mass of cells, ML^{-3}

t = time

$\hat{\mu}$ = maximum specific growth rate t^{-1}

F_l = light factor

F_T = temperature factor

S_C, S_N, S_P = concentration of available nutrients in the liquid phase (C = carbon, N = nitrogen, P = phosphorus), ML^{-3}

K_C, K_N, K_P = Saturation coefficients for C,N,P, ML^{-3}

The relationship between growth rate (μ) and levels of eutrophication is still unclear; however, an aquatic system is generally eutrophic when the measured bioassay growth rates are near maximum and oligotrophic when bioassay growth rates are low. The utility of determining growth rate lies in models that describe population changes in terms of rates such as growth, settling, and predation, and relative to hydrodynamics, lake depth, and morphology (e.g., Chen, 1970; DiToro et al., 1971; Porcella et al., 1970). Light is an important consideration when modeling phytoplankton.

The attenuation of light with depth can be approximated by an exponential function:

$$I = I_s \exp(-kZ)$$

in which I is the light intensity at depth Z and I_s is the intensity at the surface. The light extinction coefficient (k) may be a function of water turbidity at different depths.

Experimental evidence indicates that the photosynthetic rate increases with light intensity; reaches a constant, maximum rate for a particular range of intensities; and is inhibited at light intensities above this optimum range (Eppley et al., 1969; Ryther, 1956; Ryther and Yentsch, 1958; Sorokin and Krauss, 1958; Thomas, 1966a,b, 1970; and Yentsch and Lee, 1966). Some mathematical models have used linear variations of photosynthesis with light intensity (Riley, 1946; Steele, 1958); some have used a hyperbolic function (Chen, 1970, Middlebrooks and Porcella, 1971); others have used an exponential function (DiToro et al., 1970). Relative photosynthetic rates for diatoms were calculated from the average curves reported in Eppley et al. (1969), Jorgensen and Steeman-Nielsen (1966), and Ryther (1956), and are shown on Figure 16, where:

$$F_l = \frac{P}{P_{max}} \quad \ldots\ldots\ldots\ldots (10)$$

P = photosynthetic rate at light intensity l, and P_{max}=maximum photosynthetic rate. These data may be approximated by the equation:

$$F_l = 1 - \exp(-0.0224l) \quad \ldots\ldots\ldots\ldots (11)$$

as shown by the solid line on Figure 16.

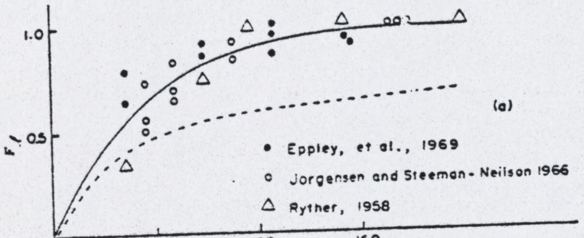

Figure 16. Relative effect of light intensity on phytoplankton growth.

DiToro et al. (1970) presented the following expression which averages the effects of light over time and depth:

$$F_l = \frac{2.718f}{K_eZ}\left[e^{-\alpha 1} - e^{\alpha o}\right] \quad \ldots\ldots\ldots\ldots (12)$$

$$\alpha_o = I_a/I_s$$

$$\alpha_1 = \alpha_o \exp - (K_eZ)$$

in which K_e is the light extinction coefficient (base e), I_s = optimum light intensity for growth (ft.-candle), I_a = average light intensity (ft.-candle) and f = photo period (fraction of a day).

The variation in growth rate with temperature has been represented in mathematical models by exponential equations of the following general form:

$$\frac{\mu_1}{\mu_2} = K_\tau^{(\tau_1 - \tau_2)} \quad \ldots\ldots\ldots\ldots (13)$$

in which μ_1 and μ_2 are specific growth rates at temperatures τ_1 and τ_2, respectively, and $K\tau$ is a constant (Middlebrooks and Porcella, 1971; Riley and Von Arx, 1949; Steele, 1958). The justification for this approach is based on the observation that enzymatic reaction rates tend to increase exponentially with temperature. A plot of saturated growth rate vs. temperature has been constructed from data from a number of sources (DiToro et al., 1970). These data were widely scattered, however, and no functional relationship was apparent.

The variation in growth rates as a function of temperature at constant light intensities has been reported for three species of tropical oceanic phytoplankton (Thomas, 1966a) and the diatom, *Nitzschia closterium* (Spencer, 1966). These data were normalized by calculating the following dimensionless variables:

$$F_\tau = \frac{\mu}{\mu_{max}} \quad \ldots\ldots\ldots\ldots (14)$$

$$\tau_r = \frac{\tau - \tau_0}{\tau_{max} - \tau_0} \quad \ldots\ldots\ldots\ldots (15)$$

in which μ = growth rate occurring at temperature τ, μ_{max} = maximum possible growth rate, τ_{max} = the temperature at which μ_{max} first occurs, and τ_0 = temperature at which zero growth occurs. In some cases, τ_0 and τ_{max} had to be extrapolated from the data. F_τ = the relative growth rate and τ_r = the fraction of the temperature range between τ_0 and τ_{max}. Values of F_τ vs. τ_r are shown in Figure 17. These data were fit by the following second order polynomial.

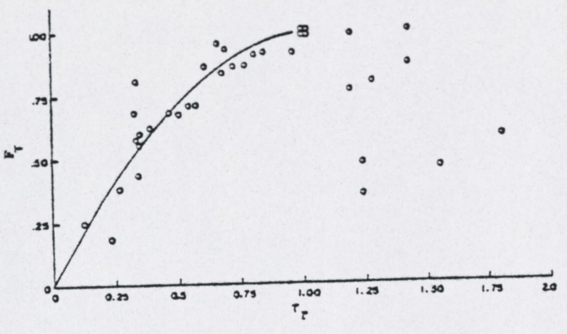

Figure 17. Relative effect of temperature on growth.

$$F_T = 1.92\tau_r - 0.92\tau_r^2, \quad 0 \leqslant \tau \leqslant \tau_{max} \quad \ldots\ldots (16)$$

Although photosynthesis is primarily a function of light, temperature and nutrient availability, all three variables are often not considered because of the difficulty involved.

Bailey (1970) represented photosynthetic oxygen production for the Sacramento-San Joaquin Estuary as:

$$P = 3.16\ C_h\ (I^{2/3})/k_e + 0.16\ T - 0.56\ H \ldots\ldots (17)$$

in which P = photosynthetic activity (gm O_2 per cubic meter), C_h = mean chlorophyll (gm per cubic meter), I = mean daily solar intensity in gm cal per square cm per day, k_e = light extinction coefficient (per meter), T = mean temperature in °C, and H = mean water depth in meters.

O'Connor and DiToro (1970) represent photosynthetic oxygen production as a periodic function of time as:

$$P = P_m \sin\ [\pi/p(t-t_s)] \text{ when } t_s \leqslant t \leqslant t_s + p$$

$$= 0 \text{ when } t_s + p \leqslant t \leqslant t_s + 1 \ldots\ldots\ldots (18)$$

in which P_m = the maximum rate of photosynthetic oxygen production (mg/1/day) and p = the fraction of the day over which the source is active (days). P_m values for several rivers ranged between 5.0 and 70.0 mg/1/day. Respiration was assumed constant with time and, for the same rivers, values ranged between 5.0 and 22.0 mg/1/day. The ratio of average daily photosynthesis to average daily respiration ranged from 0.35 to 2.0.

Pescod (1969) found photosynthetic oxygen production in a polluted tropical estuary to range between 0.5 to 1.3 mg O_2/1/day.

O'Connell and Thomas (1965) found that the net photosynthetic oxygen production by benthic algae in the Truckee River near Reno, Nevada, varied approximately sinusoidally during the day, reaching a maximum of about 36 mg O_2/1/day. Maximum respiration rate was about 17 mg O_2/1/day.

Bain (1968) utilized data from others and estimated photosynthetic oxygen production at 0.24 mg O_2/liter per day per µg/liter chlorophyll. Respiration was estimated at 10 percent of photosynthesis. Values are for 20°C and optimum light (1000-3000 ft -c.). Photosynthesis at 800 ft-c is about 75 percent of P at optimum. The ratio of oxygen produced to carbon fixed was about 2.7 by weight.

Inorganic Nitrogen

The oxidation of ammonia to nitrite and nitrate may be represented by the simplified equations:

$$NH_4^+ + \tfrac{3}{2}O_2 \xrightarrow[\text{Bacteria}]{\text{Nitrosomonas}} NO_2^- + 2H^+ + H_2O \quad (19.1)$$

$$NO_2^- + \tfrac{1}{2}O_2 \xrightarrow[\text{Bacteria}]{\text{Nitrobacter}} NO_3^- \ldots\ldots\ldots (19.2)$$

The stoichiometric oxygen requirement is 3 atoms of oxygen per atom of nitrogen (3.43 mg O_2/mg NH_4^+). Experimental observations indicate, however, that oxygen consumption during the oxidation of ammonium to nitrite may be in the range of 3.8 to 2.75 atoms O_2/atom NH_4^+-N, with an average of about 2.89 (Buswell and Pagano, 1952). Wezernak and Gannon (1968) reported a value of 2.81 (3.22 mg O_2/mg NH_4^+-N). The difference between theoretical and actual can be attributed to the organisms' ability to utilize the oxygen supplied during CO_2 fixation. The stoichiometric oxygen requirement for Equation 19.1 is 1.0 atoms O_2/atom NO_2^--N. Wezernak and Gannon (1968) report an actual value of 0.971 (1.11 mg O_2/mg NO_2-N). In summary, the theoretical oxygen demand for the biochemical oxidation of ammonium to nitrite is 4.57 mg O_2/mg NH_4-N; the observed value is about 4.33 mg O_2/mg NH_4-N.

ZERO ORDER MODELS

Zero order models are expressed as:

$$\frac{dy}{dt} = b \qquad y = NH_4^+ \text{ oxidized}$$

Stratton and McCarty (1968) were able to fit this model to a particular set of data as follows:

$$y = 0.3t \quad \text{for } t \leqslant 9.53$$
$$y = 2.86 \quad \text{for } t > 9.53$$

The authors state that this model is not suitable for the general case.

In studies on the Truckee River near Reno, Nevada, O'Connell and Thomas found nitrification rates of 0.12 to 0.5, with an average of 0.26 mg O_2/liter/hour.

FIRST-ORDER MODELS

First-order models are expressed as:

$$\frac{dN}{dt} = -KN \qquad N = NH_4^+ \text{ available for nitrification}$$

Zanoni (1969) estimated a value for K of 0.12 day $^{-1}$ at 20°C for the final effluent from a Milwaukee-activated sludge plant (initial concentrations of NH_4 were about 60 mg/1). He found that K varied with temperature as follows:

$$K_T = K_{20}(1.092)^{(T-20)} \quad 10^\circ < T < 20^\circ C \quad (20)$$

$$K_T = K_{20}(0.945)^{(T-20)} \quad 20^\circ < T < 30^\circ C \quad (21)$$

O'Conner and DiToro (1970) used a first-order term in a stream model and found values ranging from 0.1 to 2.5 day^{-1}.

Thomann et al. (1970) used a first-order term to represent ammonium oxidation in a model of the nitrogen cycle of several estuaries. Nitrate to ammonia feedback loops were incorporated in the model. To fit the model to observed data from the Delaware Estuary, K was greatly reduced for stream reaches where dissolved oxygen was less than 2 mg/1 (due to inhibition of nitrification at low DO). Decay constants of about 0.1 per day were estimated for reaches where sufficient O_2 was available. A K value of 0.28 per day (at 28° C) was estimated for the Potomac Estuary.

In a mathematical model of the Delaware River Estuary, O'Connor et al. (1968) used a K value of 0.30 per day at 20°C. K was adjusted for temperature by the relation:

$$K_T = K_{20}(1.045)^{(T-20)} \quad (22)$$

K values were set at zero for reaches of river where the carbonaticus oxygen demand reduced dissolved oxygen to low levels.

Wild et al. (1971) found ammonium decay rates ranging from 0.185 to 0.02 grams NH_3-N nitrified/day/gram MLVSS in activated sludge systems. O'Connell and Thomas (1965) found that nitrification in the Truckee River near Reno, Nevada, ranged from 0.12 to 0.5, with an average of 0.26 mg O_2/1/hr.

OTHER MODELS

The Monod model has been used extensively to represent biological reaction rates. For nitrification, the model can be written:

$$\frac{dy}{dt} = \hat{\mu} \frac{N}{K_s + N} B \quad (23)$$

$$B = B_0 + ay = B_0 + a(A-N)$$

in which

$y = NH_4^+$ oxidized
B = bacteria population (nitrifiers)
$N = NH_4^+$ concentration
A = upper limit of oxidizable NH_4^+
K_s = saturation coefficient for NH_4^+

Stratton and McCarty (1968) estimated parameters for the above equations: B_0 = 1.2 mg/1, a = 0.29, K_s = 0.2 mg/1, $\hat{\mu}$ = 0.23 per hour. Parameters have been estimated for a similar model by Stratton and McCarty (1967) as follows:

Ammonia Oxidation

$\hat{\mu} = 1.84$ to 1.68 at 20°C per day

$\hat{\mu} = 1.47\,(e)^{0.084\,(T-20)}$ per day

$K_s = 4.59$ to 2.59 mg/l

Nitrite Oxidation

$\hat{\mu} = 5.41$ to 3.98 at 20°C per day

$\hat{\mu} = 4.90\,(e)^{0.056\,(T-20)}$ per day

$K_s = 1.77$ to 0.34 per day

They found that only about 4 percent of the ammonium was assimilated by the autotrophic bacteria.

Wezernak and Gannon (1968) presented the Robertson model:

$$\frac{dy}{dt} = K(A-S)\,(S) \qquad (24)$$

in which variables have been defined above. Using certain assumptions, the equation was integrated and parameters determined for the Clinton River in Michigan.

Stratton (1968) demonstrated that nitrogen could be lost from streams by the diffusion of ammonia gas into the atmosphere. He represented the phenomenon by the following equation:

$$C = C_0 e^{-kt} \qquad (25)$$

in which $C = NH_3$ concentration and k = a rate constant which is dependent on stream depth, pH, and temperature, among other things:

$k = 0.08 \exp\,(1.57\,(\mathrm{pH}-8.5))$ at 20°C

$k = 2.3 \exp\,(1.45\,(\mathrm{pH}-8.5))$ at 41°C

Denitrification is the biochemical process of reducing nitrate to nitrogen gas and has been represented by the following formula (Siedel and Crites, 1970):

$$6H^+ + 6\,NO_3^- + 5\,CH_3OH \rightarrow 5\,CO_2 + 3N_2 + 13H_2O$$

in which methanol (CH_3OH) is the carbon source. Based on the above formula, the concentration of the carbon source required is:

$$C = 3.8\ N + 1.5\ DO$$

in which C = theoretical chemical oxygen demand of the carbon source (mg/1), N = the nitrate concentration (mg/l), and DO = the oxygen demand necessary to achieve anaerobic conditions (mg/1). Johnson (1972) has estimated a denitrification reaction rate for systems with high concentrations of bacteria as:

$$k = k_m \frac{N}{K_s + N} \qquad (26)$$

in which k = first order reaction rate (per day), k_m = maximum reaction rate (2.5 per day), K_s = half-saturation coefficient (150 mg/l), and N = nitrate concentration.

Baca (1974) developed a transport model for nitrogen supersaturated waters in river run reservoirs. The model of dissolved nitrogen gas (N_2) transport is derived from a mass balance and expressed by a one-dimensional form of the convection-diffusion equation. An empirical rate expression incorporated into the model describes the deaeration of supersaturated nitrogen.

Temperature

Numerous mathematical models of the mechanics of heat transfer in streams are now available. Current interest in stream temperature prediction stems largely from concern about the possible deleterious environmental consequences of thermally polluted surface waters. Stream temperature is an important determinant of the solubility of dissolved gases, biological reaction kinetics, the distribution of fish and lower forms of aquatic life, and the efficiency of water treatment for domestic and industrial use.

An extensive *Bibliography on Thermal Pollution* (Gerber, 1967) indicated the urgent need for a better understanding of the processes of heat transfer in streams before the processes could be more accurately modeled. The mechanics of heat transfer in streams may be divided into three components (Figure 18):

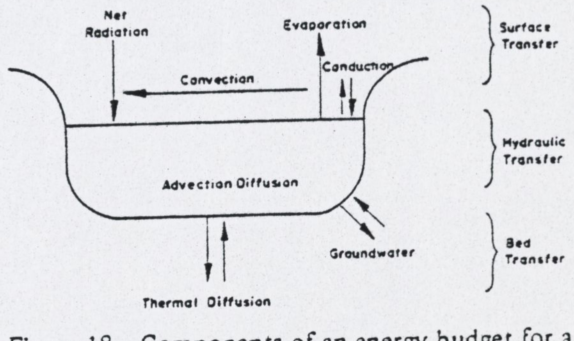

Figure 18. Components of an energy budget for a stream system.

1. Surface transfer—Heat exchange at the air-water interface due to radiation, evaporation, conduction, and advection by the evaporated water;
2. Hydraulic transfer—Transport of thermal energy within the stream due to advection and diffusion; and
3. Bed transfer—Heat transfer at the soil-water interface due to groundwater motion and thermal diffusion in solid materials.

Existing stream temperature models emphasize either the surface transfer mechanism or the hydraulic transfer mechanism. Jobson and Yotsukura (1972) attempted to integrate these two transfer mechanisms. The bed transfer mechanism has been almost entirely neglected in the literature, because soil-water heat transfer is generally considered to be small, and relevant information is scarce.

The source-sink term for temperature is typically based on the thermal energy conservation or heat balance approach. Much of the thrust of past temperature modeling has been directed toward refining or simplifying the thermal energy budget.

Assumptions and simplifications are often made in model development to facilitate ease of use and solution, and to minimize the complexity of input data required. Additional variations are sometimes made to fit local situations or specific meteorologic conditions.

A "Multi-Parametric Mathematics Model of Water Quality" by Harper (1972) was based on the basic advection-dispersion equation with the addition of a source-sink term, S(x,t), which varied for each water quality parameter considered.

For stream temperature, Harper's source-sink term was

$$S_t = \frac{\phi_T}{C_p \gamma h} \quad \text{....................} \quad (27)$$

in which ϕ is the net heat transfer across the water surface found by thermal energy budget. His net heat transfer components included incident solar radiation (ϕ_R), conductive heat transfer (ϕ_H), effective back radiation (ϕ_B), and evaporative heat transfer (ϕ_E). Equations for estimating these components were provided except for incident solar radiation. Harper suggested that solar radiation should be measured directly or calculated as a function of solar altitude, site latitude, and cloud cover as reported by Raphael (1962).

An additional source-sink term for advective sources given by Harper included point loads, tributaries, and groundwater inflow. A simple mass-balance ratio was used to define a new boundary temperature and discharge. By dividing a modeled stream into reaches of constant physical and dynamic characteristics, such as cross-sectional area, discharge, and dispersion coefficients, and inputing these variables as new boundary conditions, the simulation equation may be further simplified. Harper assumed steady flow, uniform cross-sectional area, and a constant dispersion coefficient by employing these boundary condition techniques.

Other possible sources and sinks, which were assumed negligible by Harper, are heat transfer to the ground, internal heat generated by chemical and biological reactions, and friction losses.

Dailey and Harleman (1972) divided their model into two parts: A hydraulic submodel, and a water quality submodel that includes a temperature component. Apart from a deficient derivation of terms in the temperature equation, the 1972 model failed to allow for variations in flow characteristics and variability of meteorological conditions. Because of these shortcomings, Harleman et al. (1973) modified the earlier model, stating that it was valid for temperature only when lateral inflow is zero.

In terms of the developed equation, the new model differs from the Dailey and Harleman (1972) model by only a flux term ϕ_T. Rather than using the linearized simplification of the surface heat flux, ϕ_T was calculated at each mesh point and time step by the following equation:

$$\phi_T = \phi_R - \{4 \times 10^8 (T_s + 460)^4 + f(U_a) [(e_s - e_a) + 0.255 (T_s - T_a)]\} \quad \text{....................} \quad (28)$$

Harleman et al. (1973) also used the equilibrium temperature concept developed by Edinger and Geyer (1968) that "The equilibrium temperature T_E is defined as the temperature at which, given a set of meteorological conditions, the net surface heat flux is equal to zero." Equilibrium temperature may be found by substituting T_E for T_S in Equation 28 and $\phi_T = 0$. Jobson and Yotsukura (1972) concluded that the introduction of the equilibrium temperature concept had been unnecessary and inconvenient due to its dependence on trial-and-error solution, error from the linearization effect of T_E, and inadequacy in predicting diurnal fluctuations.

Also included in this model are source terms allowing for waste heat discharge (WHD) and tributary heat discharge (THD). Development of net surface heat flux (Equation 28) was made under the assumption that radiation, convection and evaporation are of several orders of magnitude higher than other possible sources or sinks such as heat fluxes via evaporated water and direct rainfall. Of particular interest is the rationale used by Harleman et al. (1973) for neglecting streambed heat transfer:

> Heat transfer between a body of water and the environment can occur through the free surface and through the bottom and sides. In the latter case, the heat flux is limited by conduction in the adjacent soil and remains very small because of generally low thermal conductivity of earth and because the temperature gradients are limited.

A model of Novotny and Krenkel (1973) describes the dynamic nature of the air-water interface of a turbulent river. They assumed that the primary mechanism of heat transfer was turbulent motion of the water surface. Also, they stressed that the water surface temperature differs from the bulk temperature. Timofeyev and Malevisky-Malevich (1967) reported that the difference may be as great as several tenths of a °C.

Novotny and Krenkel (1973) developed a thermal energy budget under the assumption that all thermal energy acts on the air-water interface. No mention was made of heat transfer across the streambed-water interface. Paily et al. (1974) developed a closed-form solution of the unsteady one-dimensional advection-diffusion equation for temperature distributions downstream from a thermal load input. The conservation of thermal energy equation was rigorously solved by assuming complete mixing, uniformity of stream cross-section, discharge, and diffusion coefficient, and linearity of surface heat exchanges. Paily et al. (1974) stated that the surface heat exchange term ϕ_T can be expressed as a linear function of the mixed temperature of the stream with no significant loss of accuracy. The linear relation was given as:

$$\phi_T = -(eT + \eta) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

in which η = the base heat exchange rate corresponding to a stream temperature O°, T = stream temperature in °C, and e = a heat exchange coefficient. Values for e and η for various wind velocities, relative humidities, and air and stream temperatures were determined by approximate relations given by Dingman and Assur (1967).

Correlation coefficients of at least 0.999 were found between the derived linear relation and the more involved energy budget (Paily et al., 1974). Also presented were the linear relations of the equilibrium temperature model by Edinger and Geyer (1968) and excess temperature model by Jobson and Yotsukura (1972).

Paily et al. (1974) stated that heat dispersed in a receiving water is eventually transferred to the atmosphere by evaporation, radiation, or by conduction as sensible heat. "There may be some transfer of heat at the soil-water interface due to infiltration of river water into the ground. The amount of heat transferred by diffusion and dispersion in the porous media, however, is generally very small and may be neglected."

The stream temperature submodel of QUAL-I (Texas Water Development Board, 1971) was also based on the general heat budget equation. In that submodel, net solar and atmospheric radiation are found analytically from basic input such as cloud cover, latitude, sun declination, air temperature, wind speed, and relative humidity. Its minimal input requirements make QUAL-I a valuable management tool.

The dynamic character of QUAL-I is evidenced by its allowing stream cross-section and longitudinal dispersion coefficients to vary with distance downstream. The stream can thus be broken into discrete reaches of similar characteristics, allowing varying degrees of resolution. Subdivision of the stream into reaches allows more accurate handling of tributaries and inflows by redefining reach boundary conditions.

The authors of QUAL-I state that the model considers "all heat transferred across the mud-water interface. In the absence of groundwater flow, heat is transported across the mud-water interface only by molecular conduction which is relatively insignificant in comparison to surface heat exchange."

A model by Morse (1970) ignored the second-order dispersion term in the traditional conservation of energy equation and thus provided for an exact solution.

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = \frac{\phi_T}{C_p} \rho h \quad \ldots\ldots\ldots\ldots \quad (30)$$

The energy budget term $\emptyset_T$ is found by a statistical technique applied to local meteorological data. Solution of this model requires a minimal amount of input: backwater profiles, discharge, and cross-sectional areas and widths. He neglected heat exchange with the bottom and sides of the river.

Sediment Transport

Sediment particles are transported in the stream channel by one or more of the following mechanisms: 1) Suspension (suspended and supported by the surrounding fluid during its entire motion); 2) saltation (leaping into the flow and then resting on the bed); and 3) surface creep (rolling or sliding on the bed). Sediments moving as surface creep and saltation are supported by the river bed and therefore are referred to as "bed load." The sediments traveling in suspension are supported by flow and are referred to as "suspended load." These definitions are used to delimit two methods of hydraulic transport that follow different laws. Unfortunately, there is no clear division among sediments traveling as bed load and suspended load in real rivers. During a specified time in a river reach, a particular particle can move in suspension for a while, along the bed of the river for another period, and not at all for the remaining time. The summation of the bed load and the suspended load is referred to as "total sediment load."

Particles making up the total suspended load may come from: erosion of the channel bed material, tributary inflow, and surface runoff into the channel. The particles (both bed and suspended load) derived from erosion of the channel bed material make up the "bed material load." The part of the suspended load which consists of grain sizes finer than the bulk of the bed material is referred to as the "washload." The washload rate can be related to the available supply of solid particles within the watershed; it enters the watercourse by sheet wash, bank caving, etc. Because of its small size fractions, it moves readily in suspension and is merely washed through the channel. Observations indicate that average concentrations of washload are much lower at low flows than at high ones (Graf, 1971). The sum of bed material load and washload equals the total suspended load.

There are two basic types of sediment transport analysis: hydrologic and hydraulic. Hydrologic analysis is associated with gross drainage basin sediment yield and involves geomorphologic and hydrologic factors. The hydrologic analysis can be used to methodologically present an overall picture of a relatively complex system (Langbein and Schumn, 1958). In this review, only the hydraulic, or in-channel, analysis will be considered.

BED LOAD

Generally, the amount of bed load transported by a river is in the order of 5 percent to 25 percent of the suspended load (Tywoniuk, 1972). Although the amount of bed load may be small as compared with the total sediment load, it is important because it shapes the bed and influences the stability of the channel, the form of the sediment bed surface, and other factors. Imagine starting with water at constant depth over an initially flat bed of unconsolidated sediment. If the flow velocity is below some critical value, none of the bed particles will move. With increasing flow velocities, particles from the bed will be dislodged and will roll or slide short distances downstream. The mean flow velocity at which particles of the bed just begin to move is called the "critical velocity," the value of which depends largely on the size of bed material and the mean flow depth. Critical velocity cannot be defined precisely, except in a statistical sense, and its subjective definitions almost always involve qualitative judgments.

When the critical velocity is exceeded in an alluvial bed, general transport is initiated and the bed will be unstable. Ripples will form with fine sediments, while coarse sediments usually produce dunes. Ripples formed under unidirectional flows tend to be triangular in shape, with a gently sloping upstream face and a more steeply sloping downstream face that meets the horizontal at approximately the angle of repose of the bed material (Nordin, 1975). The ripples migrate downstream as material is eroded from their upstream faces and deposited on their downstream faces. Ripple sizes are largely independent of the flow depth. Their mean lengths and heights are mostly a function of particle size, but they also vary somewhat with the sediment transport rate. Ripples are not observed to form in sands with diameters greater than about 0.6 mm (Nordin, 1975).

With increasing velocities, ripple beds suddenly give way to dunes. Dunes are similar in shape to ripples and they migrate downstream in the same manner, but they are an order of magnitude larger. Dune shapes are related to flow depth, particle size and velocity. Ripples often are superimposed on the backs of dunes (Nordin, 1975).

Further increases in velocity generate a region of transition from dune bed to a stable flat bed. The flat bed is a stable configuration in the sense that any small disturbance will be damped out and the bed will return to its original flat condition (Nordin, 1975).

With increasing flow velocities, an unstable condition results in which strong interactions occur between water-surface and bed-surface waves. The bed configurations (waves) formed under these conditions generally are called antidunes because under certain flow conditions they migrate upstream, as opposed to dunes which migrate downstream. The apparent upstream migration results when the accelerated flow on the downstream face of the waves promotes erosion, while the decelerated flow on the upstream face encourages deposition of material. The initiation of antidunes takes place at Froude numbers (Fr) generally greater than 0.8 (Nordin, 1975) where:

$$(Fr) = V/(gD)^{1/2} \quad \ldots\ldots (31)$$

where V is velocity, g is the acceleration of gravity, and D is the depth. For fine sands less than 1 mm median diameters, high Froude numbers are accompanied by a highly unstable condition that is characterized by a series of steep chutes with super-critical flows separated by pools formed by hydraulic jumps. These chutes and pools and other configurations are described in considerable detail by Simons and Richardson (1966).

Large-scale formations that tend to have lengths of the same order of magnitude as the channel width are called "bars." In most natural channels bars usually do not form in any regular periodic pattern, but appear usually as point bars on the insides of bends or as middle bars that occur when the flow splits into two channels around them.

Three general types of models have been developed and modified for computation of the bed load.

The first is based on critical shear stress concept (DuBoys-type relationships). This concept was first applied by DuBoys to analysis of bed load transport in 1879. His equation was:

$$g_s = \psi \quad \tau_o [\ \tau_o - (\ \tau_o)_{cr}] \quad \ldots\ldots (32)$$

where τ_o = the bed shear stress
g_s = the bed load per unit width of channel
$(\tau_o)_{cr}$ = bed shear stress at threshold (or critical shear stress)

Straub (1936) gave ψ = 0-173/(d)$^{3/4}$ where d is the particle size diameter. Shields (1936) generalized DuBoys' relationship by including specific gravity and other hydraulic parameters and gave the relation as follows:

$$\frac{g_s \gamma_s}{q \cdot s \cdot \gamma} = 10 \left[\frac{\tau_o - (\tau_o)_{cr}}{(\gamma_s - \gamma)\, d} \right] \quad \ldots\ldots (33)$$

where q = water discharge/unit width
s = slope of channel
γ and γ_s = unit of wt. water and sediment respectively

Kalinske (1947) modified this relation to

$$\frac{g_s}{u^* d} = f \left[\frac{(\tau_o)_{cr}}{\tau_o} \right] \quad \ldots\ldots (34)$$

where u* = shear velocity

The record approach is based on critical discharge. Schoklitsch (1930) disagreed with DuBoys' theory of critical shear stress and adopted critical discharge as incipient motion criterion and gave the following equation:

$$g_s = 2500\, S^{3/2} (q - q_{cr}) \quad \ldots\ldots (35.1)$$

$$q_{cr} = 0.26 \frac{\gamma_s - \gamma^{5/3}}{\gamma} \frac{d_{40}}{S^{7/6}} \quad \ldots\ldots (35.2)$$

where S = energy slope
d_{40} = particle size at which 40% is finer in mix
q_{cr} = critical discharge/width at which sediment motion begins

Gilbert, MacDougall and Casey proposed Schoklitsch type equations (in Graf, 1971).

Einstein (1950) departed from above relationship and suggested that a particle of a given size moves in series of steps rather than moving continuously, and developed the following equation based on statistical consideration:

$$\phi = \frac{g_s}{\gamma_s}\left(\frac{\gamma}{\gamma_s - \gamma}\right)^{1/2}\left(\frac{1}{gd^3}\right)^{1/2} \quad \ldots\ldots\ldots\ldots (36)$$

$$\psi = \frac{\gamma_s - \gamma}{\gamma}\,\frac{d}{R_b^1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (37)$$

and based on experiments, ϕ and ψ were related as $0.465\ \phi = \exp(-0.391\,\psi)$.

R_b^1 = hydraulic radius of sediment grain on bed. Future developments led to the partial differential equation:

$$\frac{\partial^2 q_B}{\partial x \partial t} + \frac{1}{K_1}\frac{\partial q_B}{\partial x} + \frac{1}{K_2}\frac{\partial q_B}{\partial t} = 0 \quad \ldots\ldots\ldots\ldots (38)$$

DeVries (1965), Pemberton (1971) and others modified Einstein's studies, and many hydrodynamic models for nonsteady transport condition were evolved.

SUSPENDED LOAD

The sediment concentration distribution over the depth of flow is given by Rouse's equation (1937).

$$\frac{C_{xy}}{C_a} = \left(\frac{D-y}{y} \cdot \frac{a}{D-a}\right)^Z \quad \ldots\ldots\ldots\ldots (39)$$

where: C_{xy} = concentrations at a distance "y" above bed
C_a = concentrations at a level "a" above bed (reference)
D = total depth of flow
$Z \doteq w/(k \cdot u^*)$

where w = fall velocity, k = Karman's constant = 0.4, and u* = shear velocity

The vertical distribution of concentration, provided a reference concentration is known for a level y = a, is described by:

$$\frac{uy}{u^*} = 8.5 + 5.75 \log_{10}\left(\frac{y}{K_s}\right) \quad \ldots\ldots\ldots\ldots (40)$$

The combination of above two led to a new equation and its integration resulted in the form:

$$Q_s = \gamma Q \overline{C} \quad \ldots\ldots\ldots\ldots\ldots\ldots (41)$$

where Q_s = suspended sediment rate over entire cross section, Q = water discharge, and $\overline{C}$ = velocity-weighted average of sediment concentration. Lane and Kalinske performed integration by a different approach.

Bagnold (1966) and Velikanov (Kon Drat'ev, 1962) made recent studies by energy approach and Bagnold's equation is as follows:

$$g_{ss} = 0.01\,\tau\,U_m^2/w \quad \ldots\ldots\ldots\ldots\ldots\ldots (42)$$

where g_{ss} = suspended load per unit width
τ = shear stress
U_m = mean flow velocity

Computer simulation of unsteady flow has been undertaken by Tywoniuk (1972) and others based on momentum and continuity equations. Owens and Odd (1970) put out a two-layer hydrodynamic model for flow and sediment transport.

TOTAL LOAD

Two approaches have been adopted for computation of total load: 1) Computation of bed load and suspended load by previous models and summation; and 2) direct computation.

Einstein modified his approach for bed load and developed new concepts for bed load and suspended load. Taking his lead, a number of investigators came up with models based on field and laboratory experimentation. For example, Toffaleti (1969) proposed a method adaptable to computer programming.

Empirical approaches have been adopted by Colby and Hembree (1955), Colby and Hubbell (1961), and Colby (1964). More recently, Shen and Hung (in Tywoniuk, 1972) used a nonlinear multiple regression technique and a computer to perform analysis and, based on 1411 sets of data, came up with the equation:

$$\log_e C = -204922.607 + 409317.743\,x - 204384.464\,x^2$$

$$\text{where } x = \left(\frac{VS^{0.833}}{w}\right)^{0.009793} \quad \ldots\ldots\ldots\ldots (43)$$

where V = mean flow velocity
S = energy slope
w = fall velocity
C = total sediment concentration

A similar model was proposed by Chih (1973), based on unit stream power and 1093 sets of data.

$$\log C = 5.435 - 0.286 \log\left(\frac{wd}{\gamma}\right) - 0.457 \log\left(\frac{u^*}{w}\right) +$$
$$1.799 - 0.409 \log\left(\frac{wd}{\gamma}\right) - 0.314 \log\left(\frac{u^*}{w}\right)$$
$$\log\left(\frac{VS}{w} - \frac{V_{cr}S}{w}\right) \quad \text{(44)}$$

V_{cr} = critical velocity
γ = kinematic viscosity

The Bureau of Reclamation (Denver office) has developed a computer program for total transport, based on a modification of Einstein's procedure and adjustment in mean flow velocity. Rosgen (1975a,b) has developed a methodology for characterizing baseline sediment transport in a watershed and then predicting variations in loads due to forest management activities. The analysis has been used to detect landslides, road washouts, and other events affecting sediment concentrations. Briefly, the method involves measuring suspended loads and flows in a stream over a wide range of discharges. A sediment rating curve is constructed by plotting suspended load vs. discharge on semi-log graph paper. An empirical relationship is estimated by fitting a line to these data. Bed load is also field measured and analyzed in terms of sediment transport rate (bed load) versus stream power. The results of the suspended load and bed load analyses are added to determine total sediment load. Once the baseline characteristics of the stream are established, increases in sediment production due to channel erosion of water yield increase can be estimated from the sediment rating curves. Sediment predictions associated with logging and silvicultural systems are described in detail by Rosgen (1975b).

Grenney and Mandavia (1975) have developed a mathematical model for simulating total sediment load in a stream network. The model includes bed material load and washload. Sediment transport is related to stream power by an empirical function. Techniques for estimating model coefficients for specific applications are provided. The model has been applied to the Green River, Utah.

Some two-dimensional models for watershed flow have been developed recently (Chow and Zvi, 1973; Sakhan et al., 1971) for computer simulation of sediment transport. As yet, these models have not been widely applied.

LINKING TECHNIQUES AND MODEL EXAMPLES

Hydraulic submodels and models for the six water quality parameters: 1) Dissolved oxygen; 2) biochemical oxygen demand; 3) algae; 4) nitrification; 5) temperature; and 6) sediment transport have been discussed. The other water quality factors will be considered in this section as part of the models in which they occur. We describe techniques for linking the hydraulic and the water quality submodels, and include nomograph and computer methods. The computer methods can be categorized as linear or nonlinear systems. Linear systems are relatively simple to solve, and frequently exact solutions can be obtained. Nonlinear systems require numerical solution techniques.

Nomograph Solutions

EPA (1971, 1972) provided a simplified mathematical modeling methodology for analysis of water quality. Utilization of the nomographs included in the 1971 and 1972 publications could provide a basis for rapid qualitative, predictive judgments of the effects of low flows on water quality. The technique is summarized in Tables 9 and 10.

The data for these techniques are based on initial concentrations of the following parameters:

- Streams and Rivers
  - Chlorides, TDS
  - Coliform Bacteria
  - Nutrients, BOD
- Streams and Rivers
  - Dissolved Oxygen
  - Single Source
  - Multiple Source
- Estuaries and Tidal Rivers
  - Chlorides, TDS
  - Coliform Bacteria
  - Nutrients, BOD
- Estuaries and Tidal Rivers
  - Dissolved Oxygen
  - Single Source
  - Multiple Source

Applying these techniques produces only trend indications. They are designed to supplement knowledgeable judgment and not to substitute for it.

Table 9. Low resolution models for water quality in estuaries.

Technique	Water Quality Constituents	Linked Constituents	Output	Input Hydraulics	Input Water Quality	Comments
EPA 71 EPA 72	Total dissolved solids: TDS (107)	None	Total dissolved solids concentration resulting from numerous point loads.	1. Steady-state flows for all significant inflows and representative points in the estuary. 2. Dispersion coefficient (E) for the estuary.	1. Flows, concentrations and locations of point loads. 2. Background concentration of TDS in the estuary.	1. This technique applies for any conservative substance. 2. Maximum concentrations will always occur just downstream from point sources. 3. Tables of average coefficients for dispersion (66, E38).
	Coliform bacteria: COLI (108)	None	Coliform bacteria concentration distributions resulting from numerous point loads.	1. Steady-state flows for all significant inflows and at representative points in the estuary. 2. Dispersion coefficient (E) for the estuary. 3. Estuary travel times for all reaches.	1. Flows, concentrations and locations of point loads. 2. Background concentration of coliforms in the estuary. 3. First-order die-off rate.	1. Maximum concentrations will always occur just downstream from point sources. 2. Tables of average coefficients: a) Die-off rates (111) b) Background concentrations (56) c) Temperature adjustment (70) d) Waste loading estimates (50) e) Dispersion (66, E38)
	Nutrients NUT (108)	None	Nutrient concentration distributions resulting from numerous point loads.	1. Steady-state flows for all significant inflows and at representative points in the estuary.	1. Flows, concentrations and locations of point loads.	1. First order nutrient removal rates are assumed. 2. Maximum concentration will always occur just downstream from point source. 3. Tables of average coefficients: a) Removal rates (111) b) Temperature adjustment (70) c) Water loading estimates (50, 54)
	Bio-chemical oxygen demand: BOD (108)	Dissolved oxygen	BOD concentration distributions resulting from numerous point loads.	1. Steady-state flows for all significant inflows and at representative points in the estuary.	1. Flows, concentrations and locations of point loads.	1. Ultimate oxygen demand for the combined effects of carbonaceous and nitrogenous BOD. 2. Tables of average coefficients: a) Decay rates (111, Appendix C) b) Temperature adjustments (70, E35) c) Waste loading estimates (50, 53, E6, E8) 3. Maximum concentrations will always occur just downstream from point sources.
	Dissolved oxygen: DO (112)	Biochemical oxygen demand *	Dissolved oxygen concentration distributions resulting from numerous point loads.	1. Steady-state flows for all significant inflows and at representative points in the estuary.	1. Flows, concentrations and locations of point loads. 2. Background concentrations of DO in the estuary. 3. DO saturation concentration for the existing temperature, elevation, and salinity. 4. Reaeration coefficient.	1. Modeled as dissolved oxygen deficit. 2. Maximum DO deficit as a function of dispersion, velocity, deoxygenation rate, and ultimate BOD loading (45). 3. Maximum deficit occurs at some point a distance x_c from waste load (44). 4. Average values for some coefficients: a) Reaeration rates (111, 113, 117, Appendix C) b) Temperature effects on reaeration rates (E35). c) Assimilation ratios (114, Chart D, Appendix D). d) Saturation concentration as a function of temperature and salinity (57). 5. Background concentrations (56)
	Critical dissolved oxygen deficit (45)	Biochemical oxygen demand *	Magnitude of the maximum dissolved oxygen deficit for a given point load.	1. Steady-state flows for all significant inflows and at representative points in the estuary.	1. Flows, concentrations and locations of point loads.	1. Modeled as dissolved oxygen deficit. 2. Solution graph: Critical depth as a function of BOD loading, deoxygenation and reoxygenation rates.
	Photo-synthesis and respiration					Requires a more sophisticated model.
	Tempera-ture					Requires a more sophisticated model.

Notes: 1) Numbers enclosed in parentheses are page numbers.
2) * indicates that the constituent in column 2 is effected by this linked constituent.

Table 10. Low resolution models for water quality in rivers.

Technique	Water Quality Constituents	Linked Constituents	Output	Input Hydraulics	Input Water Quality	Comments
EPA 71 EPA 72	Total dissolved solids: TDS (67)	None	Total dissolved solids concentration distributions resulting from numerous point loads.	1. Steady-state river flows for all significant tributaries and at representative points along the river.	1. Flows, concentrations and locations of point loads. 2. Background concentration of TDS in the river system.	1. This technique applies for any conservative substance. 2. Maximum concentrations will always occur just downstream from point sources.
	Coliform bacteria: COLI (69)	None	Coliform bacteria concentration distributions resulting from numerous point loads.	1. Steady-state river flows for all significant tributaries and at representative points along the river. 2. River travel times for all reaches.	1. Flows, concentrations and locations of point loads. 2. Background concentrations of coliform in the river system. 3. First-order die-off rate.	1. Maximum concentration will always occur just downstream from point sources. 2. Tables of average coefficients: a) Die-off rates (70) b) Background concentrations (56) c) Temperature adjustment (70) d) Waste loading estimates (50)
	Nutrients: NUT (69)	None	Nutrient concentration distributions resulting from numerous point loads.	1. Steady-state river flows for all significant tributaries and at representative points along the river.	1. Flows, concentrations and locations of point loads.	1. First order nutrient removal rates are assumed. 2. Maximum concentration will always occur just downstream from a point source. 3. Tables of average coefficients: a) Removal rates (70) b) Temperature adjustment (70) c) Waste loading estimates (50, 54)
	Biochemical oxygen demand: BOD (69)	Dissolved oxygen	BOD concentration distributions resulting from numerous point loads.	1. Steady-state river flows for all significant tributaries and at representative points along the river.	1. Flows, concentrations and locations of point loads.	1. Ultimate oxygen demand for the combined effects of carbonaceous and nitrogenous BOD. 2. Tables of average coefficients: a) Decay rates (70, A3, Appendix C) b) Temperature adjustment (70, E35) c) Waste loading estimates (50, 53, E6, E8) 3. Maximum concentrations will always occur just downstream from a point source.
	Dissolved oxygen: DO (71)	Biochemical oxygen demand *	Dissolved oxygen concentration distributions resulting from numerous point loads.	1. Steady-state river flows for all significant tributaries and at representative points along the river.	1. Flows, concentrations and locations of point loads. 2. Background concentrations of DO in the river system. 3. DO saturation concentration for the existing temperature, elevation, and salinity. 4. Reaeration coefficient.	1. Modeled as dissolved oxygen deficit. 2. Maximum deficit occurs at some point a distance x_c downstream from waste load (73). 3. Average values for some coefficients: a) Reaeration rates (A3, E18, Appendix C) b) Temperature effects on reaeration rates (E35) c) Assimilation ratios (A5) d) Saturation concentration as a function of temperature and salinity. 4. Background concentrations (56)
	Critical dissolved deficit (73)	Biochemical oxygen demand *	Magnitude of the maximum dissolved oxygen deficit for a given point load.	1. Steady-state river flows for all significant tributaries and at representative points along the river.	1. Flows, concentrations and locations of point loads.	1. Modeled as dissolved oxygen deficit. 2. Solution graph: Critical depth as a function of BOD loading, deoxygenation and reoxygenation rates.
	Reaeration over small dam (E25)	Biochemical oxygen demand *	Decrease in oxygen deficit over a dam.	1. Steady-state river flows for all significant tributaries and at representative points along the river. 2. Height through which the water falls.	1. Flows, concentrations and locations of point loads.	1. Modeled as dissolved oxygen deficit. 2. Solution graphs: a) Decrease in deficit as a function of height b) Effect of a small dam on the dissolved oxygen profile in a river reach.
	Photosynthesis and respiration					Requires a more sophisticated model.
	Temperature					Requires a more sophisticated model.

Notes: 1) Numbers enclosed in parentheses are page numbers.
2) * indicates that the constituent in column 2 is affected by this linked constituent.

Linear Systems of Equations with Exact Solutions

A model (SSAM) developed at Utah Water Research Laboratory (Grenney and Porcella, 1975) can be applied to a river system with any reasonable number of tributaries, point loads, and point diversions. The river channels must be divided into "reaches" which are lengths of river that can be assumed to have uniform physical characteristics.

Basically, the SSAM model simulates the reactions and interactions of constituents of a slug of water (Figure 19) as it travels downstream at a given velocity, $\overline{V}$. Mass can be added to the slug by lateral inflow and by leaching from the stream bottom. Oxygen can enter the slug by diffusion across the air-water interface and by the photosynthetic oxygen production of benthic and planktonic algae.

The model starts at the first headwater, where water quality constituent concentrations are known. These concentrations provide the initial conditions for the differential equations describing the system and are used in conjunction with the river characteristics for the downstream reaches to obtain a closed-form solution to the differential equations. Concentrations can then be calcualted for any point of interest in the downstream reach. The concentrations at the end of one reach become the initial conditions for the next.

The SSAM model assumes steady flow (invariant with time). The model water quality equations represent two phenomena occurring in a slug of water as it travels downstream (Figure 19):

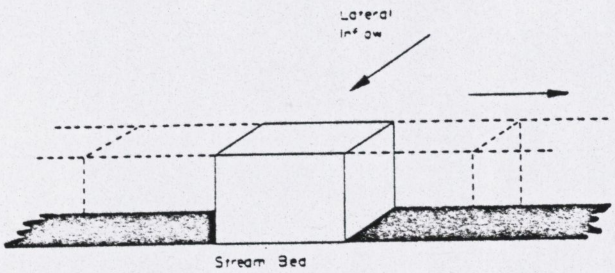

Figure 19. Model conceptualization of a slug of water moving downstream.

1. Mass being added to or removed from the water due to sources or sinks distributed along the stream channel.
2. Biochemical reactions and interactions among constituents.

Descriptions of the symbols used in the equation are shown in Table 11.

The expression for rate change in constituent concentration due to lateral surface and subsurface flow can be expressed as follows:

$$S_i = \frac{dC_i}{dt} = \begin{cases} -C_i(Q_S + Q_G)/\overline{A} + (Q_S C_{Si} + Q_G C_{Gi})/\overline{A} & \text{when subsurface flow is into the stream} \\ -C_i Q_S/\overline{A} + Q_S C_{Si}/\overline{A} & \text{when subsurface flow is out of the stream} \end{cases} \quad (45)$$

Table 11. Description of symbols used in the water quality equations.

$\overline{A}$ = average cross-sectional area (sq m)

B_A	Benthic load for NH4N	(mg/sq m/sec)
B_B	Benthic load for CBOD	(mg/sq m/sec)
B_N	Benthic load for NO3N	(mg/sq m/sec)
B_O	Oxygen production from the benthic algae for DOXY	(mg/sq m/sec)
B_P	Benthic load for PHOS	(mg/sq m/sec)
B_u	Oxygen uptake by the benthic BOD for DOXY	(mg/sq m/sec mg/l oxygen)
CBOD	Carbonaceous biochemical oxygen demand	(mg/l)
C_{Gi}	Concentration of i[th] constituent in the lateral groundwater inflow (Q_G)	(mg/l)
C_i	Concentration of the i[th] constituent	(mg/l)
COLI	Coliform bacteria	(MPN/100 ml)
CON1	Conservative constituent	(mg/l)
CON2	Conservative constituent	(mg/l)
C_{Si}	Concentration of i[th] constituent in the lateral surface inflow (Q_S)	(mg/l)
DOXY	Dissolved oxygen	(mg/l)
D_{sat}	Dissolved oxygen saturation concentration	(mg/l)
E_L	Elevation of element	(m)
K_2	Reaeration rate of 20°C for DOXY	(per sec)
K_3	First-order decay coefficient for NCON	(per sec)
K_4	Removal rate at 20°C for COLI	(per sec)
K_5	Removal rate for PHOS	(per sec)

K_6	Decay rate at 20°C for NH4N	(per sec)
K_{A6}	Removal rate (other than biochemical decay) for NH4N	(per sec)
K_{A7}	Removal rate for NO3N	(per sec)
K_8	Decay rate at 20°C for CBOD	(per sec)
K_{A8}	Removal rate (other than biochemical decay) for CBOD	(per sec)
NCON	Nonconservative constituent	(mg/l)
NH4N	Ammonium	(mg/l)
NO3N	Nitrate	(mg/l)
PHOS	Available phosphorus	(mg/l)
P_r	Net photosynthetic oxygen production by phytoplankton	(mg/l/sec)
Q_G	Lateral groundwater inflow inflow	(cu m/s/m)
Q_S	Lateral surface inflow	(cu m/s/m)
$\bar{R}$	Hydraulic radius	(m)
S_i	Source (or sink) for i^{th} constituent due to lateral inflow	(mg/l/sec)
t	Time	(sec)
T	Temperature	(°C)
T_f	Temperature	(°F)
TDS	Total dissolved solids	(mg/l)

The total rate changes in the various constituent concentrations in the main channel are expressed by the following system of equations.

CONSTITUENTS 1 and 2. CONSERVATIVE CONSTITUENTS (CON1 AND CON2)

The rate change in concentration is influenced only by mass input from lateral inflow.

$$\frac{dC_i}{dt} = S_i, \; i = 1, 2 \qquad (46)$$

CONSTITUENT 3. NONCONSERVATIVE CONSTITUENT (NCON)

The rate change in concentration is influenced by first-order decay and by mass input from lateral inflow.

$$\frac{dC_3}{dt} = -K_3 C_3 + S_3 \qquad (47)$$

CONSTITUTENT 4. COLIFORM BACTERIA (COLI)

The rate change in concentration, MPN (most probable number per 100 ml), is influenced by first-order decay (death) and by mass input from lateral inflow. The decay rate (K_{4a}) increases with temperature.

$$\frac{dC_4}{dt} = -K_{4a} C_4 + S_4 \qquad (48.1)$$

$$K_{4a} = K_4 \, 1.047^{(T-20)} \qquad (48.2)$$

CONSTITUTENT 5. AVAILABLE PHOSPHORUS (PHOS)

The rate change in concentration is influenced by first-order removal (algal uptake, precipitation, etc.), leaching from bottom deposits, and mass input from lateral inflow.

$$\frac{dC_6}{dt} = -K_5 C_5 + \frac{B_P}{1000\,\bar{R}} + S_5 \qquad (49)$$

CONSTITUENT 6. AMMONIUM (NH4N)

The rate change in concentration is influenced by first-order decay (biochemical oxidation to nitrate), first-order removal (uptake by algae, etc.), leaching from bottom deposits, and mass input from lateral inflow.

$$\frac{dC_6}{dt} = -K_{6a} C_6 - K_{A6} C_6 + \frac{B_A}{1000\,\bar{R}} + S_6 \qquad (50.1)$$

$$K_{6a} = K_6 \, 1.047^{(T-20)} \qquad (50.2)$$

CONSTITUENT 7. NITRATE (NO3N)

The rate change in concentration is influenced by the accumulation of oxidized ammonia, first-order removal (uptake by algae, etc.), leaching from bottom deposits, and mass input from lateral inflow.

$$\frac{dC_7}{dt} = K_{6a} C_6 - K_{A7} C_7 + \frac{B_N}{1000\,\bar{R}} + S_7 \qquad (51)$$

CONSTITUENT 8. CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND (CBOD)

The rate change in concentration is influenced by first-order decay (biochemical oxidation), first-order removal (absorption, settling), leaching from bottom deposits, and mass input from lateral inflow. CBOD is modeled as the ultimate demand. Five-day BOD can be input to the model and is converted to ultimate BOD by a user-supplied conversion factor (BODCON) as follows: $BOD_U = BOD_5 * BODCON$. Output is converted back to five-day BOD to be consistent with the input.

$$\frac{dC_8}{dt} = -K_{8a} C_8 - K_{A8} C_8 + \frac{B_B}{1000 \overline{R}} + S_8 \quad \ldots\ldots (52)$$

$$K_{8a} = K_8 \, 1.047^{(T-20)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (53)$$

CONSTITUENT 9. DISSOLVED OXYGEN (DOXY)

The rate change in concentration is influenced by reaeration across the surface, carbonaceous oxygen demand, nitrogenous oxygen demand, photosynthetic production by benthic algae, photosynthetic production by phytoplankton, uptake by bottom deposits, and mass input from lateral inflow.

$$\frac{dC_9}{dt} = K_{2a} (D_{sat} - C_9) - K_{8a} - 4.22 K_{6a} C_6$$

$$+ \frac{B_O}{1000 \overline{R}} + P_r - \frac{B_U}{1000 \overline{R}} C_9 + S_9 \quad \ldots\ldots (54.1)$$

$$K_{2a} = K_2 \, 1.0159^{(T-20)} \quad \ldots\ldots\ldots\ldots\ldots (54.2)$$

$$T_f = \frac{T}{0.556} + 32.0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (54.3)$$

$$D'_{sat} = 24.8 - 0.4259\, T_f + 0.003734\, T_f^2 - 0.0001328\, T_f^3 \quad (54.4)$$

$$D_{sat} = D'_{sat} \left\{ \exp \left[- \frac{0.03418\, E_L}{288.0 - 0.006496\, E_L} \right] \right\} \quad \ldots (54.5)$$

Stream temperature values may be input to the model as data for each reach. If stream temperatures are not input, then stream temperature is held constant at 20°C. The reaeration coefficient K_2 may be estimated from one of the equations in Table 7.

The solution algorithm for this model is one that constructs the closed-form solution for a system of constant coefficient linear ordinary differential equations which can be solved in sequence.

Nonlinear Systems of Equations Requiring Numerical Solutions

A Hydrologic Engineering Center (1974) publication describes the most comprehensive water quality model available to date. The model can be used to simulate water in both rivers and reservoirs in a system. The hydraulics are modeled as steady nonuniform flow for streams.

Reservoirs are modeled as one-dimensional vertically and may become thermally stratified. The water quality constituents considered in the HEC model are shown in Table 12. The expressions for the commonly modeled constituents BOD, DO, coliforms, ammonia, and nitrate are similar to those in the linear system except that they are linked to the nonlinear biological terms. Three equations are available to represent fish (three types of fish can be included, depending on the coefficients in the equations). The growth rate of fish is a hyperbolic function of the quantity of the zooplankton or benthic animals available for grazing. The mortality and respiration rates of the fish are constants. The net growth rate (growth rate less respiration rate and mortality rate) is adjusted for temperature by a biota activity rate coefficient at the local temperature. The rate change in fish

Table 12. Interdependence of constituents (from Hydrologic Engineering Center, 1974).

CONSTITUENT DEPENDENT ON	Temperature	BOD	Fish	Benthic Animals	Zooplankton	Algae	Detritus	Organic Sediment	Phosphate	Total Carbon	Ammonia	Nitrite	Nitrate	Oxygen	Coliforms	Alkalinity & TDS	Light Penetration	Carbon Dioxide	pH
Temperature																	F		
BOD	R													L					
Fish	R.⊥			F				F						L					
Benthic Animals	R.⊥		C					F						L					
Zooplankton	R.⊥		C			F								L					
Algae	R.⊥				C				F		F		F				L	F	
Detritus	R		B		B														
Organic Sediment	R		B	F.B		B	B												
Phosphate			B	B	B	B.C	B	B											
Total Carbon		B	B	B	B	B	B	B						L					
Ammonia	R		B	B	B	B.C	B	B											
Nitrite	R										B			L					
Oxygen						C						B		L					
Oxygen	R.S.A	C	C	C	C	B.C	C	C			C	C							
Coliforms	R																		
Alkalinity & TDS																			
Light Penetration					D	D	D												
Carbon Dioxide	A.S.I					C				I						I.S			I
pH	I									I						I			

population according to the HEC model is equal to the net growth rate less a harvesting factor.

$$\frac{\partial F}{\partial t} = F^*K^*{}_b{}^* \frac{F_{max}{}^*Z_b}{K_2 + Z_b} - F_m - F_r - H \quad \ldots\ldots\ldots (55)$$

in which F = concentration of fish, K_b = temperature adjustment coefficient, F_{max} = maximum specific growth rate of fish, Z_b = quantity of benthic animals or zooplankton available for grazing, K_2 = coefficient, F_m = fish mortality rate, F_r = fish respiration rate, and H = rate of fish removal by fishing.

The benthic animal growth rate is a hyperbolic function of the quantity of organic sediments per unit area. The net growth rate is equal to the growth rate less the mortality and respiration rate and is adjusted for temperature. The rate change in population is related to the net growth rate less the rate of grazing by fish.

The zooplankton growth rate is a function of the effective phytoplankton population because three types of algae are modeled. This effective population is a function of a grazing preference factor. The net growth rate is equal to the growth rate less the mortality and respiration rates and is adjusted for temperature. The rate change in population is related to the net growth rate less the rate of grazing by fish.

Three types of phytoplankton can be covered in the HEC model. The growth rates are represented by the following expression:

$$\frac{dX}{Xdt} = \mu \frac{\hat{\mu} S_C}{S_C + K_C} \cdot \frac{S_N}{S_N + K_N} \cdot \frac{S_N}{S_P + K_P} \cdot F_l \cdot F_T \quad \ldots\ldots\ldots (56)$$

in which X = mass of cells, ML^{-3}

t = time
$\hat{\mu}$ = maximum specific growth rate, t^{-1}
F_l = light factor
F_T = temperature factor
S_C, S_N, S_P = concentration of available nutrients in the liquid phase (C = carbon, N = nitrogen, P = phosphorus), ML^{-3}.

In this model:

$$F_l = \frac{l}{K_l + l} \quad \ldots\ldots\ldots (51.1)$$

$$F_T = K_{20}\ \theta^{(T-20)} \quad \ldots\ldots\ldots (56.2)$$

in which K_{20} = rate at 20°C, θ = coefficient, and T = temperature in °C.

MODELING TECHNIQUES BEING DEVELOPED FOR DETERMINATION OF INSTREAM FLOW NEEDS TO MAINTAIN WATER QUALITY

Orsborn et al. (1973) discuss four separate models that can be applied, dependent on the intensity of the study proposed. The first model gives the required low-flow as a function of population and is to be used when a data base does not exist. All data on wastes discharged into the stream must be converted to population equivalents before being utilized in that model. The other three models estimate low-flow requirements as a function of the stream's assimilation and dilution capacity. They range from the second model, which is fairly simple, to the fourth, which is extremely complex.

Data Needs and Sources

Data requirements for the Orsborn models may be obtained or estimated from the literature. Water quantity data are available from USGS Surface Water Records, and water quality data are available on STORET. Both types of data may be available from other specialized Federal, state, or university research projects.

The first model requires flow data and waste loading data that are available from the literature; these can be converted to the population equivalents. The remaining models are summarized in Table 13.

Table 13. Specific data requirements for models.

		WEATHER				PHYSICAL					BIOLOGICAL					CHEM.		INPUTS	
MODEL	LEVEL OF ANALYSIS	Net Solar Radiation	Air Temperature	Vapor Pressure	Wind Speed	Mean Width	Mean Depth	Average Velocity	Flowrate	Temperature	Half-saturation Constants	Uptake Rate Coefficients	Phyto. Ext. Coefficients	Phytoplankton	Benthic Algae	Nutrient Concentrations	Total Phosphorus, Carbon	Wastewater Discharge	Concentrations of W.Q. Parameters in Discharge
2	Simplified	W	W	W	W				X									W	W
3	Intermediate	T	T	T	T	X	X	X	X	S								W	W
4	Complex	T	T	T	T	X	X	X	X	B	X	X	X	B	S	B	B	T	T

W = worst conditions, i.e., lowest streamflow estimates, highest production of waste, warmest day average weather conditions
S = spatial variations
T = temporal variations
B = both spatial and temporal variations
X = single value necessary

Value of the Prediction

The first model yields a maximum estimate of low flow, which can be ten times too large. The second model provides single estimates of the worst DO and BOD concentrations. The third model estimates bulk water temperature, DO, and BOD from a slug of water as it travels downstream. To model a conservative pollutant, the reaeration and deoxygenation rate coefficients are set at zero. The fourth model includes spatial and temporal variations of BOD, temperature, phytoplankton, carbon dioxide, DO, phosphate, nitrate, pH, and benthic algae. In all cases, the value of the prediction is weighed against the amount of time and resources available for the study.

Trumbull and Loomis (1973) discuss a stream allocation model (SAM) being developed to estimate streamflow needs. The ecologic model incorporated within the stream allocation model is to be based on work done on the Boise River utilizing the previously discussed HEC (1974) model.

Data Needs and Sources

Historical water quality data will be utilized wherever possible. In-field measurements will also be available for parameters, such as DO, BOD, temperature, pH, solids, and chemical nutrients.

Value of the Prediction

Various river reaches on which this will be applied have been designated. The hydrologic model will be adjusted for each river reach by the Idaho Water Resource Board, Hydraulic Branch. Water quality needs and standards will be taken into consideration in weighting the value of various diversions.

A DISCUSSION OF APPLICATIONS OF MODELS TO FLOW REDUCTION OR AUGMENTATION

Models are powerful tools for relating extremely complex phenonema in aquatic ecosystems and thereby allowing flow to be managed or the effects of flow changes on aquatic communities to be determined. The complexity of models makes it difficult to obtain an intuitive understanding of the overall system or of the interrelationships between parts of the system, even though a specific function by itself can be easily understood. To obtain such sophistication, a simple solution would be to utilize a selection of computerized models at a central facility to which input data and appropriate management questions could be directed.

Table 14 lists the properties of a number of models which have been applied to practical problems. The listing is not comprehensive, but is intended to provide examples of the wide variety of models currently in use.

The use of nomograms seems appropriate as a supplement to knowledgeable judgments and not as a substitute for it. In addition, considerable understanding of the equations relating water quality parameters and flow are needed before the nomograms are usable. For example, flow changes affect the depth of streams and depth affects the reaeration coefficient (Figure 9), the deoxygenation coefficient (Figure 13), and thus the assimilation ratio (Figure 15), the ratio of critical DO deficit (DC), and initial loading rate (L_0). Thus, for a given temperature as stream depth increases, the ability of a stream to be restored to optimum conditions after waste loading decreases (Figure 15). However, temperature is affected by stream depth also and the interaction cannot easily be determined from given nomographic solutions. Development of "easy access" computer solutions or appropriate nomographs appears to be a most important methodology needed for assessing flow change effects on water quality.

The following models represent the state-of-the-art at various levels of resolution. They were selected because they show a wide variety of modeling techniques, they have all been applied to rivers, and they are available from state and Federal agencies.

Hydraulic Model–Low Resolution

Standard hydrologic techniques (Chow, 1964) are used to estimate flow regimes from USGS gaging station records. Flows in ungaged basins may have to be estimated from flows in gaged basins or from precipitation data. Flow-duration analysis can be applied.

Table 14. Summary of certain stream and estuary models.

Author	Applications	Hydraulics	Mass Transport	DO	Ammonium (Nitrification)	BOD	Temperature	Remarks
Grenney and Porcella 1975	Water Quality for Systems of Rivers. Applied to the Bear, Virgin, Sevier, Jordan, Weber, and Green Rivers in Utah.	RIVER. Type One-dimensional simulation, steady-nonuniform flow. Input Boundary conditions (upstream, lateral, tributary) Channel geometry, slope and roughness coefficient. Output Flow distributions	Advection	Reaeration = $K_2(C_s-C)$. Temperature dependent and linked to: BOD, nitrification, Photosynthesis	First order oxidation, uptake by algae. Temperature dependent.	First order oxidation. Temperature dependent.	Air-water surface, radiation.	Moderate resolution. User option for exact or numerical solution depending on parameters being modeled.
Battelle, 1974b	Water Quality for Systems of Rivers and Estuaries. Applied to the Willamette River Basin.	Simulation model, river and estuary Type Two-dimensional (horizontal), unsteady flow. Includes tides and river flows. Input Estuary and/or river configurations and characteristics. Boundary flows. Output Flows, velocities and depths with space and time.	Advection and dispersion	Reaeration = $K_2(C_s-C)$. K_2 is temperature dependent. Linked to BOD, nitrification, detritus decomposition algae (photo/resp.)	First order oxidation uptake by algae. Temperature dependent.	First order decay Temperature dependent.	Air-water surface, radiation. Steady state or daily variations.	Modification and expansion of EPA's Storm Water Management Model and Dynamic Estuary Model (Feigner and Harris, 1970). High resolution, large data requirement. Solution scheme based on Orlob's link-node technique (WRE 1972).
Penumalli, et al., 1975	Estuary: Optimization (non linear)-water quality simulation model. Minimizes treatment costs subject to constraints: a) physical constraints, b) socio-economic, c) political/administrative, d) engineering, e) water quality goals. Applied to Corpus Christi Bay on the Gulf Coast of Texas.	Simulation model - estuary. Type Two-dimensional (horizontal), unsteady flow. Includes wind, coriolis acceleration, tides, and river inflow. Input Estuary configuration and characteristics. Output Flows, velocities, and depths with space and time.	Two-dimensional (Horizontal) advection and dispersion					Hydraulics: Explicit finite difference solutions technique. Mass Transport: Implicit, explicit. Model run for phosphorus only. High resolution, large amounts of detailed data.
Hann and Young, 1972	Estuary: Two-dimensional simulation. Applied to Huston Ship Cannel.	Type Two-dimension, unsteady flow, includes tides and river flows. Input Estuary configurations and characteristics. Output Flows, velocities and depths with space and time.	Two-dimensional (horizontal) advection and dispersion	a) first order deficit, b) first order BOD decay		First order decay	Constant	Explicit and implicit solution techniques are used. High resolution, large amounts of detailed data.
Rutherford and O'Sullivan, 1974	River: One-dimensional simulation. Applied to Taraw-era River, New Zealand.	Steady - nonuniform as data input.	Dispersion and advection. Dispersion calculated as a function of hydraulic radius and shear velocity.	a) First order deficit; reaeration calculated as a function of hydraulic radius and velocity, b) Linked to: Bacteria biomass Protozoal biomass		Models bacteria biomass, where growth rate is a hyperbolic function of organic substrate availability.	Constant	Decomposition of organics is a function of bacteria biomass which is modeled by saturation kinetics. Explicit and implicit finite difference solution techniques. High resolution, large detailed data requirement.
Huck and Farquhar, 1974	River: One-dimensional stochastic simulation, Saint Clair River near Corunna, Canada.							Moderate resolution model. The Box-Jenkins method for time series analysis was used. Water quality parameters not linked or associated explicitely with hydraulics. Long term records of quality data.
Bayer, 1974	Optimization nonlinear objective function, linear constraints: minimum cost of BOD treatment to meet specified stream standards for BOD and DO.	Steady flow input data. Average travel times in specific reaches.	Advection	First order deficit; reaeration constant.		First order decay		Moderate resolution. Moderate data requirements.
Hwang, et al., 1973	Optimization, nonlinear objective function, nonlinear constraints: minimum cost of BOD treatment and cooling to meet stream BOD, DO, and temperature standards. Applied to the Chattahoochee River Basin below Atlanta, Georgia.	Steady flow input data. Average travel times in specific reaches.	Advection	First order deficit; reaeration adjusted for temperature. Net photosynthesis adjusted for temperature.		First order decay.	Surface conduction water temperature. Radiation, wind, evaporation.	Moderate resolution. Moderate data requirements.
Texas Water Development Board, 1974	River: One-dimensional simulation. Applied to the San Antonio River, Texas.	Type Steady flow by water balance. Input Constant boundary flows (upstream boundary and lateral); and channel characteristics. Output Steady flow, velocity and hydraulic radius along the river. Note: Flows may be augmented from reservoirs to meet target DO values.	Advection and dispersion. Dispersion coefficient calculated as a function of velocity, roughness, and depth.	Steady state or daily variations. First order deficit, reaeration may be calculated by one of five options.		First order decay. Temperature adjusted.	Steady state or daily variations. Surface conduction, radiation, evaporation.	High resolution, large detailed data requirements.
Jeppson, 1974	River hydraulics. Applied Temple Fork Creek, Logan, Utah.	Type One-dimensional simulation, unsteady flow. Input Time varying boundary conditions (upstream, downstream, lateral). Channel geometry, slope and roughness coefficient. Output Hydraulic properties (flow, velocity, depth) at desired downstream locations.						Linear implicit finite difference solution technique. High resolution. Large amounts of detailed data.
Hydrologic Engineering Center, 1974	Water Quality for Systems of Rivers and Impoundments. Applied to California River including Smith Reservoir.	RIVER: Type One-dimensional simulation, steady nonuniform flow. Input Boundary conditions (upstream, lateral); Channel geometry, slope and roughness coefficient. RESERVOIR: Type One-dimensional (vertical) simulation, steady flow linked to temperature and density. Input Tributary inflow, dam releases, reservoir properties. Output Flow distributions, reservoir level.	Advection and dispersion	Reaeration = $K_2(C_s-C)$. K_2 is temperature dependent. Linked to: BOD, nitrification, detritus decomposition, algae photo/resp. zooplankton respiration, fish respiration, benthic animal respiration.	First order decay; detritus recycle: uptake or decomposition of algae, zooplankton, fish, and benthic animals.	First order decay, temperature dependent.	Air-water surface, radiation, evaporation.	Linear implicit finite difference solution technique. High resolution. Large amounts of detailed data. Note: WRE 1972 includes two-dimensional mass transport based on Orlob's link-node technique.
Shearman and Swissheim, 1975	River Flow Simulation and low-flow analysis for systems of rivers and reservoirs. Applied to the Kentucky River.	Type One-dimensional simulation, unsteady flow, based on flow routing equations. Flow may be routed downstream, upstream, and through reservoirs. Input Long-term flow and reservoir storage records. Output Average daily flows at desired locations for specified boundary condt.						Moderate resolution. Long term flow and storage records.
Bovee, 1974	River: One-dimensional simulation.	Steady flow, input data.	Advection and dispersion	First order deficit. Reaeration coefficient calculated as a function of temperature, velocity, and depth.		First order decay.	Surface condition, radiation, evaporation.	High resolution. Large detailed data requirements.
Stochastics, Inc. 1971	River/estuary: One-dimensional stochastic.	Steady average net seaward flow.	Advection and dispersion	First order deficit.		First order decay.	Constant	High resolution. Large detailed data requirements.

Hydraulic Model–Moderate Resolution

Steady flow is assumed and a water budget for the river system must be conducted. Headwater flows, surface and subsurface runoff, point loads and diversions should be considered. Data from USGS gaging stations and topographical maps must be augmented by field surveys to identify flow conditions as well as hydraulic and physical characteristics (such as channel geometry and stage-discharge relationships) at various points in the system.

Hydraulic Model–High Resolution

This is a model such as the one developed by Jeppson (1974) for one-dimensional unsteady flow. Model application requires extensive field monitoring of unsteady flow conditions in order to calibrate the model. Field surveys are necessary to provide detailed information on the physical and hydraulic characteristics of the channels. Model responses give hydraulic properties (i.e., velocities, flows, hydraulic radii, etc.) as a function of space and time.

Water Quality Model–Low Resolution

A system of nomographs such as the ones developed by EPA (1971) is used. This technique provides good estimates for instream concentrations of BOD, ammonia and DO resulting from various loading conditions. Charts and tables are available to assist in estimating the hydraulic characteristics for a wide range of flow regimes, including estuaries.

Water Quality Model–Moderate Resolution

This approach uses a steady-state one-dimensional model such as the one developed by Grenney (1975) for conservative substances, coliform bacteria, available phosphorus, ammonia, nitrate, BOD, DO, and algae. Pollution loadings in surface and subsurface runoff are included as well as point loads. User options are available to provide exact solutions for systems of linear equations or numerical solutions for nonlinear equations. Field surveys should be conducted during low-flow periods to obtain data for model calibration.

To account for temperature, a one-dimensional model such as QUAL II (Environmental Dynamics, 1971) can be used. Diurnal variations in temperature can be modeled. Field sampling for 24-hour periods should be conducted during times of significant fluctuations in water temperature.

For sediment transport, use graphical techniques such as those discussed by Rosgen (1975b); Colby's method (1964) may be used for rivers with flow depths less than about 10 feet. For a stream network computer model, techniques similar to Grenney and Mandavia (1975) are appropriate.

Water Quality–High Resolution

The Hydrologic Engineering Center (1974) publication describes the most comprehensive river water quality model available to date. The model represents one-dimensional steady flow. The following water quality constituents can be modeled: 1) Temperature; 2) BOD; 3) fish; 4) benthic animals; 5) zooplankton; 6) algae; 7) detritus; 8) organic sediment; 9) phosphate; 10) total carbon; 11) ammonia; 12) nitrite; 13) nitrate; 14) dissolved oxygen; 15) coliforms; 16) alkalinity and total dissolved solids; 17) carbon dioxide; and 18) pH. Functional relationships are nonlinear and are based on saturation kinetics. Extensive input data are required. Intensive field surveys should be conducted to provide sufficient data for model calibration.

For sediment transport when measured data are available, separate the material bed load from the washload for individual analysis. The modified Einstein method can be used to estimate the unmeasured suspended load and bed load based on measured data. A system of available sediment transport equations that best agrees with the observed data should be defined, and used to estimate the sediment transport load for the design flow where actual measurements are not available.

NEEDED METHODOLOGY DEVELOPMENT-RECOMMENDATIONS

The previous sections provide examples of the complexities of water quality relationships and the difficulties of accurately assessing flow change effects. Other problems with computer models require development of methodologies. Benthic oxygen uptake, benthic photosynthesis, the effects of mixing, phytoplankton settling rates, scour (velocity) effects on benthic communities, nutrient concentration relationships with productivity, mass flow nutrient effects on plant productivity, sediment transport modeling, temperature modeling, and coupling of models to flow management approaches seem to be, in order, the most important areas of water quality parameter modeling which need to be developed. Approaches for developing the methodologies appropriate to these phenomena include laboratory stream studies and field studies of stream and estuary DO dynamics under controlled conditions. In addition, field verification of the models generated are an absolute requirement. Cooperative studies with reservoir managers (SBR, Corps of Engineers) using controlled releases would be necessary for such verification.

All of these questions were dealt with in the FWS, IFW workshop where a draft of the present document was considered, and in discussions about the feasibility of developing a "manual" of methodologies. The workshop participants on the water quality phases (listed in Appendix 1) reviewed this report and their input helped to substantially improve several recommendations for further development. The most significant recommendation was the need for a "manual" on assessing water quality impacts of flow changes in streams and estuaries.

Recommendation I

Development of a "manual" including user guides for selection of models. The included guide would have a format using criteria to describe and evaluate the data requirements, availability, useability and areas of applicability.

Project time–(6 months)–personnel	\$21,500
Task force	2,500
Publication, distribution	3,000
	\$29,000

The general approach for the "manual" would be as shown in the flow chart (Figure 20). The development of the "manual" would allow models to be taken off the shelf and placed into use. There is a critical need for tools to analyze and recommend streamflow requirements.

Recommendation II

The following studies (short term is less than three years duration and long term is greater

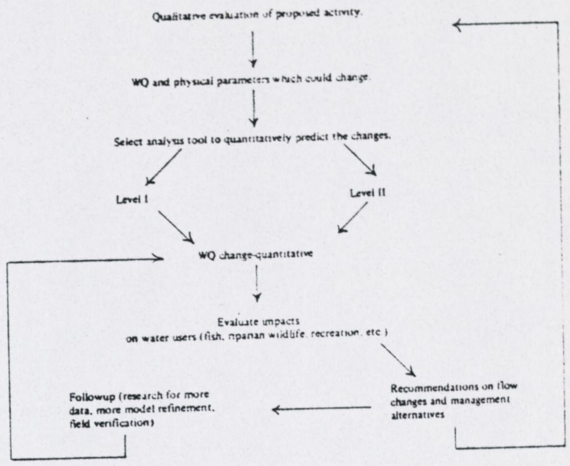

Figure 20. State-of-the-art method of problem solving with respect to water quality.

than three years duration) should be initiated as soon as possible to insure that in-stream-flow requirements are accurately and precisely determined and maintained.

PRIORITY 1 STUDIES

1. Evaluation of how water quality changes affect aquatic and riparian communities and water uses such as recreation. How are aquatic communities affected by the frequency, duration, and magnitude of water quality change? What are the synergistic/antagonistic relationships among water quality parameters and related communities? (Long-term study.)
2. Application of existing models to test sensitivity to flow. This will include "post factor" analysis to judge efficacy (not a substitute for verification) of analysis; training of users for application of models, data collection and analysis. (Short-term study.)
3. Development of data collection methods and techniques to evaluate and analyze geomorphological impacts on streamflow, estuary inflow linkages with water quality – aquatic community relationships. (Short-term study.)

PRIORITY 2 STUDIES

1. Union of modelers and users so that data collection, model formulation, and model verification is consistent and efficient in

terms of instream flow management objectives. (Short-term study.)

2. Refinement of models to predict temporal and spatial distribution. Involvement of stochastic modeling techniques is very important here. (Long-term study.)
3. Evaluation of diffuse (non-point) sources of specific water quality factors in terms of loading is needed; this involves a better understanding and conceptualization of natural events. (Short-term study.)

REFERENCES CITED

ADENEY, W. E., and H. G. BECKER.
1919. The determination of the rate of solution of atmospheric nitrogen and oxygen by water. Phil. Mag. 38:317-338.

ADENEY, W. E., and H. G. BECKER.
1920. Determination of the rate of solution of atmospheric nitrogen and oxygen by water. Phil. Mag. 39:385-404.

ALEXANDER, V., D. C. BURRELL, J. CHANG, T. R. COONEY, C. COULON, J. J. CRANCE, J. A. DYGAS, G. E. HALL, P. J. KINNEY, D. KOGL, T. C. MOWATT, A. S. NAIDU, T. E. OSTERKAMP, D. M. SCHELL, R. D. SEIFERT and R. W. TUCKER.
1974. Environmental studies of an arctic estuarine system. Final Rep. Inst. of Marine Science, Univ. of Alaska, Fairbanks, Alas., 539 p.

ANDERSON, D. R. (ed.)
1973. Truckee-Carson River Basin modeling project data report. Environmental Dynamics Inc. for EPA, Washington, D. C., 150 p.

APHA.
1971. Standard methods for examination of water and wastewater. 13th ed. Amer. Pub. Health Assn. Washington, D.C., 874 p.

ARMSTRONG, N., M. HINSON, Jr., J. COLLINS and E. G. FRUH.
1975. Biogeochemical cycling of carbon, nitrogen and phosphorus in saltwater marshes of Lavaca Bay, Texas. Univ. of Texas, Austin, Tex., 46 p.

ASANO, T.
1967. Distribution of pollutional loadings in Suisun Bay. National Symposium on Estuarine Pollution. Stanford Univ., Stanford, Calif., pp. 441-461.

BACA, R. G.
1974. A transport model for nitrogen supersaturated waters in river-run reservoirs. Battelle Pacific Northwest Lab., Richland, Wash., 66 p.

BAGNOLD, R. A.
1966. An approach to the sediment transport problem from general physics. USGS Professional Paper. 442-J, Washington, D.C.

BAILEY, T. E.
1970. Estuary oxygen resources–photosynthesis and reaeration. J. San. Eng. Div. ASCE 96:279.

BAIN, R. C.
1968. Predicting DO variations caused by algae. J. San. Eng. Div. ASCE 94:867-881.

BAITY, H. G.
1938. Some factors affecting the aerobic decomposition of sewage sludge deposits. J. Sewage and Water Works, pp. 539-568.

BATTELLE, PACIFIC NORTHWEST LABORATORIES.
1974a. Pioneer, a water quality simulation model. Rep. to the EPA, 40 p.

BATTELLE, PACIFIC NORTHWEST LABORATORIES.
1974 b. Explorer, a water quality simulation model. Rep. to the EPA, 52 p.

BAYER, M. B.
1974. Nonlinear programming in river basin modeling. Water Resour. Bull. 10(2):311-317.

BELLA, D. A.
1968. Discussion of "Solution of estuary problems and network programs" by J. V. Leeds and H. H. Bybee, J. San. Eng. Div. ASCE 94:180-181.

BELLA, D. A.
1970. Simulating the effect of sinking and vertical mixing on algal population dynamics. J. Water Pol. Con. Fed. 42:R140-R152.

BELLA, D. A., and W. DOBBINS.
1968. Difference modeling of stream pollution. J. San. Eng. Div. ASCE 94:995-1016.

BIOLOGY DEPARTMENT, HEIDELBERG COLLEGE.
1971. Water quality control through flow augmentation. EPA 16080DF001/71. EPA, Office of Water Quality, Tiffin, OH, 58 p.

BISWAS, A. K.
1974. Modelling of water resources systems. Vol. 1, 2, and 3. Harvest House LTD, Montreal, Can., pp. 1-292 pp. 296-645 pp. 483-776.

BOVEE, K.
1974. The determination, assessment, and design of "In-stream value" studies for the Northern Great Plains Region. Final Rep. Univ. of Montana, Missoula, Mont., pp. 55-204

BROWN, G.
1969. Predicting temperature in small streams. Water Resour. Res. 5(1):68-75.

BROWN, G.
1972. An improved temperature prediction model for small streams. Oregon State Univ., Water Resources Research Inst., Corvallis, Ore., 20 p.

BUREAU OF FISHERIES, NACOTE CREEK RESEARCH STATION.
1975. Studies of the Great Egg Harbor River and Bay. Misc. Rep. No. 8M. New Jersey Dept. of Environmental Protection, Div. of Fish, Game and Shellfish, Trenton, N. J., 156 p.

BUSWELL, A. M., and J. F. PAGANO.
1952. Reduction and oxidation of nitrogen compounds in polluted streams. Sewage and Ind. Wastes 24:897.

CALLAWAY, R. J., K. V. BYRAN and G. R. DITSWORTH.
1969. Mathematical model of the Columbia River from the Pacific Ocean to Bonnivelle Dam. Part I. Fed. Water Pol. Con. Admin., Northwest Reg., Corvallis, Ore., 155 p.

CHABRECK, R. H.
1972. Vegetation, water and soil characteristics of the Louisiana Coastal Region. Bull. No. 664, Louisiana State Univ., Agricultural Experiment Station, Baton Rouge, La., 71 p.

CHANDLER, P. B., W. L. DOWDY and D. T. HODDEN.
1970. Study to evaluate the utility of aerial surveillance methods in water quality monitoring. Final Rep. Pub. 41. California State Water Resources Control Board, Sacramento, Calif., 100+p.

CHEN, C. L., and K. D. DAVIS.
1975. Process studies and modeling of self-cleaning capacity of mountain creeks for recreation planning and management. PRWG 13-1, Utah Water Research Lab. Logan, Ut., 79 p.

CHEN, C. W.
1970. Concepts and utilities of ecological models. J. San. Eng. Div. ASCE 96:1085-1097.

CHEN, C. W., and G. T. ORLOB.
1972. Ecologic simulation of aquatic environments. Water Resour. Engineers, Inc., Walnut Creek, Calif., 155 p.

CHEN, C. W., and R. E. SELLECK.
1969. A kinetic model of fish toxicity threshold. J. Water Pol. Con. Fed. 41:8(2) R294-R308.

CHEN, C. W., and J. WELLS.
1974. Boise River water quality ecologic model for urban planning study. Tetra Tech No. TC-348 and TC-409. Tetra Tech, Inc., Lafayette, Calif., 110 p.

CHESAPEAKE BAY CENTER FOR ENVIRONMENTAL STUDIES.
1973. Collection and analysis of remotely sensed data from the Rhode River estuary watershed. NASA, Cr-62094. NASA, Wallop Island, Va., 72 p.

CHESAPEAKE BAY CENTER FOR ENVIRONMENTAL STUDIES.
1974. Investigation on classification categories for wetlands of Chesapeake Bay using remotely sensed data. NASA, Cr-137479, NASA, Wallop Island, Va., 99 p.

CHESAPEAKE BAY CENTER FOR ENVIRONMENTAL STUDIES.
1975. Classification of wetlands vegetation using small scale color infrared imagery. NASA Cr-62091, NASA, Wallop Island, Va., 25 p.

CHIH, T. Y.
1973. Incipient motion and sediment transport. J. Hyd. Div. ASCE 99(HY 10): 1679-1704.

CHOW, V. T.
1964. Handbook of Applied Hydrology. McGraw-Hill Book, Co., New York., 1000 p.

CHOW, V. T., and B. A. ZVI.
1973. Hydrodynamic modeling of two dimensional watershed flow. J. Hyd. Div. ASCE 99 (Hy 11): 2023-2040.

CHURCHILL, M. A., H. L. ELMORE and R. A. BUCKINGHAM.
1962. The prediction of stream reaeration rates. J. San. Eng. Div. ASCE 89:1-46.

CLARK, S. M., and G. R. SNYDER.
1969. Timing and extent of a flow reversal in the Lower Columbia River. Lim. and Ocean. 14:960-965.

COLBY, B. R.
1964. Discharge of sands and mean-velocity relationships in sand-bed streams. USGS Professional Paper 462-A, 47 p.

COLBY, B. R., and C. H. HEMBREE.
1955. Computation of total sediment discharge, Niobrara River near Cody, Nebraska. U.S.G.S. Water Supply Paper, 1357, 187 p.

COLBY, B. R., and D. W. HUBBELL.
1961. Simplified method for computing total sediment discharge with the Modified Einstein Procedure. U.S.G.S. Water Supply Paper, 1593, 17 p.

COMER, L., and W. J. GRENNEY.
1975. Temperature modeling of a high mountain stream (In press)

COWAN, P., and D. B. PORCELLA.
1971. Water quality analysis laboratory procedures syllabus. Utah Water Res. Lab., Logan, Ut., 150 p. 150 p.

CREVENSTEN D., A. STODDARD and G. VAJDA.
1973. Water quality model of the Lower Fox River, Wisconsin. EPA-905-73-001. EPA Enforcement Div., Washington, D.C., 45 p.

DAILEY, J. E., and D. R. F. HARLEMAN.
1972. Numerical model for the prediction of transient water quality in estuary networks. Ralph M. Parsons Lab. for Water Resources and Hydrodynamics, Rep. No. 158, Dept. of Civil Engineering, MIT, Cambridge, Mass.

DEMARCO, J., J. KURBIEL, J. M. SYMONS and G. ROBECK.
1967. Influence of environmental factors on the nitrogen cycle in water. J. Amer. Water Works Assn. 59:580.

DE VRIES, M.
1965. Considerations about nonsteady bed-load transport in open channels. Delft Hydraulics Lab. Pub. No. 36.

DINGMAN, S. L., and A. ASSUR.
1967. The effect of thermal pollution on river ice conditions, Part I. U. S. Army Cold Regions Research and Engineering Lab., Hanover, N. H.

DITORO, D. M., D. J. O'CONNOR and R. V. THOMANN.
1970. A dynamic model of phytoplankton populations in natural waters. Manhattan College, Bronx, N. Y., 62+ p.

DITORO, D. M., D. J. O'CONNOR and R. V. THOMANN.
1971. A dynamic model of the phytoplankton population in the Sacramento-San Joaquin Delta. Nonequilibrium Systems in Natural Waters, ACS, Washington, D. C., pp. 131-180.

DOOLEY, J. M.
1975. Application of U. S. Bureau of Reclamations Water Surface Profile Program (WSP). Upper Missouri Regional Office, U. S. Bur. of Reclam., Billings, Mont., 8 p.

DORNHELM, R. B., and D. A. WOOLHISER.
1968. Digital simulation of estuarine water quality. Water Resour. Res. 4:1317-1328.

DRESNACK, R. and W. E. DOBBINS.
1968. Numerical analysis of BOD and DO profiles. J. San. Eng. Div. ASCE 94:789-807.

DUBOYS, M. P.
1879. Le Rhône et les Rivières a Lit affouillable. Mem. Doc. Ann. Pont et Chaussées. Ser. 5. Vol. XVIII.

ECKENFELDER, W. W., and D. J. O'CONNOR.
1961. Biological waste treatment. Pergarmon Press, New York, 299 p.

EDBERG, N., and B. HOFSTEN.
1972. Uptake of bottom sediments studied *in situ* and in the laboratory. J. Water Resour., Vol. 7, No. 9.

EDINGER, J. E., and J. C. GEYER.
1968. Heat exchange in the environment. EEI Pub. No. 65-902. Edison Electric Ins., New York, N. Y. 259 p.

EDWARDS, R. W., and H. L. J. ROLLEY.
1965. Oxygen consumption of river muds. J. of Ecol. 53:1-19.

EINSTEIN, H. A.
1950. The bed load function for sediment transportation in open-channel flows. Soil Conser. Ser., Tech. Bull. No. 1026.

ELDER, R. A., P. A. KRENKEL and E. L. THACKSTON (EDS.).
1968. Proceedings of the Specialty Conference on Current Research into the Effects of Reservoirs on Water Quality. Tech. Rep. No. 17. Dept. of Environmental and Water Resources Engineering, Vanderbilt Univ., Nashville, Tenn., 389 p.

ENVIRO CONTROL, INC.
1971. Systems analysis for water quality management. Survey and Abstracts for Water Quality Office. EPA. Contract No. 68-01-0096. Washington, D. C., 55+ p.

ENVIRONMENTAL DYNAMICS, INC.
1971. Utah Lake-Jordan River Basin modeling project documentation and sensitivity analysis report. Submitted to EPA, Office of Water Quality, Washington, D. C.

EPA.
1971. Simplified mathematical modeling of water quality. Hydroscience, Inc., Washington, D. C., 123 p.

EPA.
1972. Addendum to simplified mathematical modeling of water quality. Hydroscience, Inc., Washington, D. C., 33 p.

EPPLEY, R. W., J. L. COATSWORTH and L. SALARZANO.
1969. Studies of nitrate reductase in marine phytoplankton. Lim. and Ocean. 14:194-204.

EPPLEY, R. W., J. N. ROGERS and J. J. MCCARTHY.
1969. Half-saturation constants for uptake of nitrate and ammonium by marine phytoplankton. Lim. and Ocean. 14:912.

EUSTIS, A. B., and R. H. HILLEN.
1954. Stream sediment removal by controlled reservoir releases. The Progressive Fish Culturist.

FAIR, G. M., J. C. GEYER, and D. A. OKUN.
1968. Water and Wastewater Eng. Vol. 2. John Wiley and Sons, 659 p.

FEIGNER, K. D., and H. S. HARRIS.
1970. Documentation report, FWQA dynamic estuary model. Federal Water Quality Admin., U. S. Dept. of the Int.

FILLOS, J., and A. H. MOLOF.
1972. Effect of benthal deposits on oxygen and nutrient economy of flowing waters. J. Water Pol. Con. Fed. 44:644-662.

FISHER , H. B.
1969. A lagrangian method for predicting dispersion in Bolinas Lagoon, Menlo Park, Calif., USGS, Water Resour. Div., Open File Rep.

FISCHER, H. B.
1970. A method for predicting pollutant transport in tidal waters. No. 132. Hydraulic Laboratory, Univ. of California, Berkeley, 143 p.

FREAD, D. L.
1973. Technique for implicit dynamic routing in rivers with tributaries. Water Resour. Res. 9:4.

FREAD, D. L.
1974. Implicit dynamic routing of floods and surges in the Lower Mississippi. Presented at the American Geophysical Union Spring National Meeting in Washington, D. C.

GERBER, M. B.
1967. Bibliography on thermal pollution. J. San. Eng. Div. ASCE 93(SA3):85-113.

GRAF, W.
1971. Hydraulics of sediment transport. McGraw-Hill, N. Y., 513 p.

GRENNEY, W. J.
1975. Modeling phytoplankton blooms in a stratified embayment. Occasional Paper 8. Utah Water Res. Lab. Logan, Ut., 24 p.

GRENNEY, W. J., and D. A. BELLA.
1970. Finite-difference convection errors. J. San. Eng. Div. ASCE 96:1361.

GRENNEY, W. J., and D. A. BELLA.
1972. Field study and mathematical model of the slack water buildup of a pollutant in an estuary. Lim. and Ocean. 17:229.

GRENNEY, W. J., D. S., BOWLES, M. D. CHAMBERS and J. P. RILEY.
1974. Development and preliminary application of mathematical models to the Weber River Basin. Report PRWA 20-1. Utah Water Res. Lab., Logan, Ut., 99 p.

GRENNEY, W. J., and M. MANDAVIA.
1975. Development and application of a sediment transport model to the Green River, Utah. Utah Water Res. Lab., Logan, Ut. (In press)

GRENNEY, W. J., and D. B. PORCELLA.
1975. SS AM model application to the Green River, Utah. Proceedings from the Seminar on the Colo. River Basin Study. Utah State Univ., Logan, Ut. July 16-18.

HANN, R., Jr., and P. YOUNG.
1972. Mathematical models of water quality parameters for rivers and estuaries. Tech. Rep. No. 45. Water Resources Inst., Texas A and M Univ. College Station, Tex., 424 p.

HARGRAVE, B. G.
1969. Similarity of oxygen uptake by benthic communities. Lim. and Ocean. 14:801-805.

HARLEMAN, D. R. F., D. N. BORCARD and T. O. NAJARIAN.
1973. A predictive model for transient temperature distributions in unsteady flows. Ralph M. Parsons Lab. for Water Resources and Hydrodynamics, Rep. No. 175, Dept. of Civil Engineering, MIT.

HARLEMAN, D. R. F., C. LEE and L. C. HALL.
1968. Numerical studies of unsteady dispersion in estuaries. J. San. Eng. Div. ASCE 94:897-911.

HARPER, M. E.
1972. Development and application of a multi-parametric mathematical model of water quality. Ph.D. Dissertation, Univ. of Washington, Seattle, Wash.

HICKMAN, G. L.
1974. Principles and standards requirement for the measurement of effects of water and related land resource plans on environmental quality. Water Resour. Coun., Washington, D. C., 220 p.

HOLLEY, E. R.
1969. Discussion of "Difference modeling of stream pollution" by D. A. Bella and W. E. Dobbins. J. San. Eng. ~~Div.~~ ASCE 95:968-972.

HOOPER, D.
1973. Evaluation of the effects of flows on trout stream ecology. Dept. of Engineering Research, Pacific Gas and Electric Co., Emeryville, Calif., 97 p.

HOPPE, D.
1975. USFWS memorandum to Region 3 Office, Twin Cities, Minnesota with accompanying slide-tape material on minimum fishery flows.

HUTCHINSON, G. E.
1973. Eutrophication. Amer. Sci. 61:269.

HUCK, P. M., and G. J. FARQUHAR.
1974. Water quality models using the Box-Jenkins Method. J. Envir. Eng. Div. ASCE 100(EE3):733-752.

HWANG, C. L., J. L. WILLIAMS, R. SHOJALASHKARI and L. T. FAN.
1973. Regional water quality management of the generalized reduced gradient method. Water Resour. Bull. 9(6):1159-1181.

HYDROLOGIC ENGINEERING CENTER.
1974. Water quality for river-reservoir systems. No. 401-100 and 401-100A. U. S. Army Corps of Engineers. Davis, Calif., 208 p.

IDAHO STATE STUDY TEAM.
1973. Procedure for determining instream flow needs for water quality. Idaho Water Resource Board. Boise, Idaho. 6 p.

IPPEN, A. T.
1966. Estuary and coastline hydrodynamics. McGraw-Hill Book Co., New York, 744 p.

JEPPSON, R. W.
1974. Simulation of steady and unsteady flows in channels and rivers. PRYNE-070-1. Utah Coop. Fish. Unit, Logan, Ut., 77 p.

JEPPSON, R. W.
1975. Graphical solutions to frequently encountered fluid flow problems. Utah Water Res. Lab., Logan, Ut., 8+ p.

JOBSON, H. E., and N. YOTSUKURA.
1972. Mechanics of heat transfer in nonstratified open-channel flows. Chapter 8 in Institute of River Mechanics Paper, Colorado State Univ., Fort Collins, Colo.

JOHNSON, P. L.
1974. Hydraulics of stratified flow. Final Rep. Selective Withdrawal from Reservoirs. REC-ERC-74-1. Engineering and Research Center, U. S. Bur. of Reclam., Denver, Colo., 41 p.

JOHNSON, W. K.
1972. Process kinetics for denitrification. J. San. Eng. Div. ASCE 98:623.

JORGENSEN, E. G., and E. STEEMAN-NIELSEN.
1966. Adaptation in plankton algae. In: Goldman, C. Primary Productivity in Aquatic Environments. Univ. of California Press, Berkeley, Calif., 464 p.

KADLEC, J. A.
1971. A partial annotated biography of mathematical models in ecology. Analysis of Ecosystems. IBP, Univ. of Michigan, Ann Arbor, Mich., 150 p.

KALINSKE, A. A.
1947. Movement of sediment as bed-load in rivers. Trans. Am. Geophys. Union Vol. 28, No. 4.

KAWAHARA, M., N. YOSHIMURA, K. NAKAGAWA and H. OHSAKA.
1975. Steady and unsteady finite element analysis of incompressible viscous fluid. Unpub., 19 p.

KING, D. L.
1970. Reaeration of streams and reservoirs, analysis and bibliography Eng. and Res. Center, U. S. Bur. of Reclam., Denver, Colo., 313 p.

KING, D. L., and J. J. SARTORIS.
1973. Mathematical simulation of temperatures in deep impoundments. Eng. and Res. Center, REC-ERC-73-20, U. S. Bur. of Reclam., Denver, Colo., 27 p.

KING, H. W., and E. F. BRATER.
1963. Handbook of Hydraulics. McGraw-Hill Book Co., New York, 450 p.

KONDRAT'EV, N.
1962. River flow and river channel formation. Translation from Russian. 1959. NSF and USDI. Washington, D. C.

LANGBEIN, W. B., and W. H. DURUM.
1967. The aeration capacity of streams. USGS Circular 542, Washington, D. C., 6 p.

LANGBEIN, W. B., and S. A. SCHUMN.
1958. Yield of sediment in relation to mean annual precipitation. Trans. Am. Geophy. Union 39:1076-1084.

LASSITER, R.
1975. Modeling dynamics of biological and chemical components of aquatic ecosystems. EPA 660/3-75-012. EPA, Corvallis, Ore., 54 p.

LEEDS, J. V., and H. H. BYBEE.
1967. Solution of estuary problems and network programs. J. San. Eng. Div. ASCE 93:29-36.

LEHMANN, E. J.
1974. Water quality modeling – A bibliography with abstracts. Rep. No. NTIS-WIN-74-036. National Technical Information Service, Springfield, Va., 157 p.

LINSLEY, R. K., and J. B. FRANZINI.
1972. Water Resources Engineering. 2nd Ed. McGraw-Hill Book Co., New York, 690 p.

LOMBARDO, P. S.
1973. Critical review of currently available water quality models. Hydrocomp. Inc., Palo Alto, Calif., 97 p.

LORENZEN, M., C. CHEN, E. NODA and L. HWANG.
1974. Final Rep. Lake Erie wastewater management study. Tetra Tech Rep. No. TC-413. Tetra Tech, Inc., Lafayette, Calif., 183 p.

LOUISIANA COOPERATIVE FISHERY RESEARCH UNIT.
1974. Use of ERTS data to relate water depth to observed area of inundation in coastal marshes. Proposal to the U. S. Fish and Wildlife Ser., Louisiana State Univ., Baton Rouge, La., 5 p.

MAHLOCH, J. L.
1974. A comparative analysis of modeling techniques for coliform organisms in streams. Applied Micro. 27(2) 340-345.

MASCH, F., and ASSOCIATES.
1971. Simulation of water quality in streams and canals. Rep. 128. Texas Water Development Board, Austin, Tex.

MCCLELLAND, N. I.
1974. Water quality index application in the Kansas River Basin. EPA-907/9-74-001. EPA Region VII, Kansas City, Mo., 226 p.

MEYER, R. L.
1974. Biochrome analysis as a method for assessing phytoplankton dynamics – Phase I. Arkansas Water Resour. Res. Center, Pub. No. 27. Univ. of Arkansas, Fayetteville, Ark., 62 p.

MIDDLEBROOKS, E. J., D. H. FALKENBORG and T. E. MALONEY, (EDS).
1973. Modeling the eutrophication process. PRWG 136-1, Utah Water Res. Lab., Logan, Ut., 227 p.

MIDDLEBROOKS, E. J., and D. B. PORCELLA.
1971. Rational multi-variant algal growth kinetics. J. San. Eng. Div. ASCE 97:135-140.

MORSE, W. L. L.
1970. Stream temperature prediction model. Water Resour. Res. 6(1):290-302.

NEMEROW, N.
1974. Scientific stream pollution analysis. Scripta Book Co., Washington, D. C., 358 p.

NORDIN, C.
1975. Alluvial channel bedforms. Lecture notes from the Institute on Application of Stochastic Methods to Water Resource Problems. Colorado State Univ., Fort Collins, Colo. June 30-July 11.

NOVOTNY, V., and P. A. KRENKEL.
1973. Simplified mathematical model of temperature changes in rivers. J. Water Pol. Con. Fed. 45(2):240-248.

O'CONNELL, R. L., and N. A. THOMAS.
1965. Effect of benthic algae on stream dissolved oxygen. J. San. Eng. Div. ASCE 91:1.

O'CONNOR, D. J.
1960. Oxygen balance of an estuary. J. San. Eng. Div. ASCE 86:35-55.

O'CONNOR, D. J.
1965. Estuarine distribution of non-conservative substances. J. San. Eng. Div. ASCE 91:23-24.

O'CONNOR, D. J., and D. M. DITORO.
1970. Photosynthesis and oxygen balance in streams. J. San. Eng. Div. ASCE 96:541.

O'CONNOR, D. J., and W. E. DOBBINS.
1958. Mechanisms of reaeration in natural streams. Trans. ASCE 123:641-684.

O'CONNOR, D. J., J. ST. JOHN and D. M. DITORO.
1968. Water quality analysis of the Delaware River Estuary. J. San. Eng. Div. ASCE 94:1225-1252.

ODUM, H., W. SILER, R. BEYERS and N. ARMSTRONG.
1963. Experiments with engineering of marine ecosystems. Inst. of Marine Science, Port Arkansas, Tex. 9:373-403.

OLUFEAGBA, B. J. and R. H. FLAKE.
1975. Modelling and control of dissolved oxygen in an estuary. Preprint, Sixth Triennial World Congress International Federation of Automatic Control. Boston/Cambridge, Mass., 12 p.

O'NEILL, R. V., J. M. HETT and N. F. SOLLINS.
1970. A preliminary bibliography of mathematical modeling in ecology. IBP, Oak Ridge National Lab., Oak Ridge, Tenn., 87 p.

ORLOB, G. T., R. P. SHUBINSKI and K. D. FEIGNER.
1967. Mathematical modeling of water quality. National Symposium on Estuarine Pollution. Stanford Univ., Stanford, Calif., 9:646-675.

ORSBORN, J. F., B. W. MAR, J. W. CROSBY III and J. CRUTCHFIELD.
1973. A summary of the quantity, quality and economic methodology for establishing minimum flows. Rep. No. 13. Vol. I and Vol. II (in press). State of Washington Water Res. Center, Pullman, Wash., 85 p.

OWENS, M. V., R. W. EDWARDS and J. W. GIBBS.
1964. Some reaeration studies in streams. Inter. J. Air Water Pol. 8:469-486.

OWEN, M. V., and N. V. M. ODD.
1970. A mathematical model of the effect of a tidal barrier on siltation in an estuary. Proceedings International Conference on the Utilization of Tidal Power. Halifax, Nova Scotia, May 24-29, 36 p.

PAILY, P., E. MACAGNO, and J. KENNEDY.
1974. Winter-regime thermal response of heated streams. J. Hyd. Div. ASCE 100(HY4):531-550.

PARSONS, T. R., K. STEPHENS and J. D. H. STRICKLAND.
1961. On the chemical composition of eleven species of marine phytoplankters. Fish. Res. Board of Canada 18:1001.

PATTEN, B. C.
1968. Mathematical models of plankton production. Internationale Revue Der Gesamten Hydrobiologie 53:357.

PEMBERTON, E. L.
1971. Einstein's bed load function applied to channel design and degradation. Sedimentation Symposium. Fort Collins, Colo., 28 p.

PENCE, G. D., J. JEGLIC and R. THOMANN.
1968. Time-varying dissolved oxygen model. J. San. Eng. Div. ASCE 94:381-401.

PENUMALLI, B. R., R. H. FLAKE and E. G. FRUH.
1975. Establishment of operational guidelines for Texas Coastal zone management studies for Corpus Christi Bay: A large systems approach. Univ. of Texas, Austin, Tex., 223 p.

PESCOD, M. B.
1969. Photosynthetic oxygen production in a polluted tropical estuary. J. Water Pol. Con. Fed. 41:R309.

PFANKUCH, D. J.
1973. Stream reach inventory and channel stability evaluation. R-1, USFS Watershed Manag. Procedure. Missoula, Mont.

PORCELLA, D. B., P. GRAU, C. H. HUANG, J. RADIMSKY, D. F. TOERIFN and E. A. PEARSON.
1970. Provisional algal assay procedures. First Annual Report. Sanitary Engineering Research Lab., College of Engineering, Berkeley, Calif., 176 p.

RAPHAEL, J. M.
1962. Prediction of temperature in rivers and reservoirs. J. Power Div., Proc. ASCE 88(PO2):157-181.

REAERATION RESEARCH PROGRAM MANAGEMENT TEAM.
1975. Reaeration and control of dissolved cases. A progress report. REC-ERC-75-1. Eng. and Res. Center, U. S. Bur. of Reclam., Denver, Colo., 22 p.

RIGGS, H. C.
1972. Low-flow investigations. USGS, Techniques of Water-Resources Investigations, Book 4, Chapter 81, USGS, Washington, D. C., 18 p.

RILEY, G. A.
1946. Factors controlling phytoplankton populations on George Bank. J. Mar. Res. 6:54.

RILEY, G. A., H. STOMMEL and D. F. BUMPAS.
1949. Quantitative ecology of the plankton of the Western North Atlantic. Bul. Bingham Oceanography College 12(3):1-169.

RILEY, G. A., and R. VON ARX.
1949. Theoretical analysis of seasonal changes in the phytoplankton of Husan Harbor, Korea. J. Mar. Res. 8:60-72.

ROSGEN, D. L.
1973. The use of color infrared photography for the determination of sediment production. Proceedings of Hydrology Sumposium. Univ. of Alberta, Edmonton, Can., pp. 381-402.

ROSGEN, D. L.
1975a. Sedimentation. Paper presented at Forest Service – EPA Water Quality Session – Portland, Oregon. U. S. For. Ser., Sandpoint, Id.

ROSGEN, D. L.
1975b. Procedure for quantifying sediment production. Preliminary Rep. North Zone Planning, Sandpoint, Id., 12 p.

ROUSE, H.
1937. Modern conceptions of the mechanics of turbulence. Trans. ASCE. Vol. 10.

ROWELL, J. H.
1975. Truckee River temperature prediction study. U. S. Bur. of Reclam., Sacramento, Calif., 56 p.

RUTHERFORD, J. C., and M. J. O'SULLIVAN.
1974. Simulation of water quality in Tarawera River. J. Envir. Eng. Div. ASCE 100(EE2):360-390.

RYTHER, J.
1956. Photosynthesis in the sea as a function of light intensity. Lim. and Ocean. 1:61-70.

RYTHER, J. H., and C. S. YENTSCH.
1958. The estimation of phytoplankton production in the ocean from chlorophyll and light data. Lim. and Ocean. 3:281-285.

SAKHAN, K. S., J. P. RILEY, and K. G. RENARD.
1971. Hybrid computer simulation of sediment transport with stochastic transfer at the stream bed. Sedimentation Symposium. Fort Collins, Colo., 44 p.

SCHOFIELD, W. R., and R. G. KRUTCHKOFF.
1974. Stochastic model for a dynamic ecosystem. Bull. 60. Virginia Polytechnical Institute and State Univ., Blacksburg, Va., 149 p.

SCHOKLITSCH, A.
1930. Handbuch des Wasserbauch Springer, Vienna. 2nd Ed. 1950. English Trans., 1937, by S. Shulits.

SHEARMAN, J., and R. SWISSHELM, JR.
1975. Derivation of homogeneous stream flow records in the Upper Kentucky River Basin, Southeastern Kentucky. USGS, Water Resour. Div., Louisville, Ken., 32 p.

SHEN, H. W.
1971. Sedimentation Symposium. Fort Collins, Colo., 28 p.

SHIELDS, A.
1936. An wendung der Ahnlichkeits mechanik und Turbulenzforschung auf die Geschiebebewegung. Mitteic. Preuss. Versuchsans Wasser, Ero, Schiffsbau, Berlin. No. 26.

SHUBINSKI, R. P., J. C. MCCARTY and M. R. LINDORF.
1974. Computer simulation of estuarial networks. J. Hyd. Div. ASCE 91(HY5):33-49.

SIEDEL, D. F., and R. W. CRITES.
1970. Evaluation of anaerobic denitrification process. J. San. Eng. Div. ASCE 96:267.

SIMONS, D. B., and E. V. RICHARDSON.
1966. Resistance to flow in alluvial channels. USGS Professional Paper 422-J, 61 p.

SOIL CONSERVATION SERVICE.
1964. Sedimentation. Section 3, Chapter 4-10. SCS National Engineering Handbook. U. S. Dept. of Agri., Washington, D. C., 50 p.

SOROKIN, C., and R. W. KRAUSS.
1958. The effects of light intensity on the growth rates of green algae. Plant Phys. 33:109-113.

SPENCER, C. P.
1966. Studies on the culture of a marine diatom. In: Harvey, H. W., The Chemistry and Fertility of Sea Waters. Cambridge Univ. Press.

STEELE, J. H.
1958. The quantitative ecology of marine phytoplankton. Biological Reviews of Cambridge Philosophical Society 34:129-158.

STOCHASTICS, Inc.
1971. Stochastic modeling for water quality management. EPA, Office of Water Quality. Washington, D. C., 396 p.

STRATTON, F. E.
1968. Ammonia nitrogen losses from streams. J. San. Eng. Div. ASCE 94:1085.

STRATTON, F. E., and P. L. MCCARTY.
1967. Prediction of nitrification effects on the dissolved oxygen balance of streams. Envir. Sci. and Tech. 1:405.

STRATTON, F. E., and P. L. MCCARTY.
1968. Discussion on evaluation of nitrification in streams. J. San. Eng. Div. ASCE 95:952.

STRAUB, L. G.
1936. Transportation of sediment in suspension. Civil Eng. ASCE Vol 6. No. 3.

STREETER, H. W., and E. B. PHELPS.
1925. A study of the pollution and natural purification of the Ohio River. U. S. Pub. Health Ser. Bul. FS2(3):146.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING.
1942. The oceans; their physics, chemistry and general biology. Prentice-Hall. New York.

TEXAS WATER DEVELOPMENT BOARD.
1970. Systems simulation for management of a total water resource. Rep. 118. Texas Water Development Board, Austin, Tex., 83 p.

TEXAS WATER DEVELOPMENT BOARD.
1971. Simulation of water quality in streams and canals. Rep. 128. Texas Water Development Board, Austin, Tex.

TEXAS WATER DEVELOPMENT BOARD.
1974. Analytical techniques for planning complex water resource systems. Rep. 183. Texas Water Development Board, Austin, Tex., 59 p.

THACKSTON, E. L.
1966. Longitudinal mixing and reaeration in natural streams. T. Rep. No. 7. Sanitary and Water Resources Engineering, Vanderbilt Univ., Nashville, Tenn.

THAYER, R. P., and R. G. KRUTCHKOFF.
1967. Stochastic model for BOD and DO in streams. J. San. Eng. Div. ASCE 93:59-72.

THOMANN, R. V.
1963. Mathematical model for dissolved oxygen. J. San. Eng. Div. ASCE 89:1-30.

THOMANN, R. V.
1967. Time-series analysis of water quality data. J. San. Eng. Div. ASCE 93:1-23.

THOMANN, R. V.
1972. Systems analysis and water quality management. McGraw-Hill Co., New York, 286 p.

THOMANN, R. V., D. J. O'CONNOR and D. M. DITORO.
1970. Modeling of the nitrogen and the algal cycles in estuaries. Presented at the Fifth International Association of Water Pollution Research Conference, 14 p.

THOMANN, R. V., D. M. DITORO, R. WINFIELD and D. J. O'CONNOR.
1975. Mathematical modeling of phytoplankton in Lake Ontario. Model Development and Verification. EPA 660/3-75-005. EPA, Corvallis, Ore., 178 p.

THOMAS, W. H.
1966a. Effects of temperature and illuminance on cell division rates of three species of tropical oceanic phytoplankton. J. of Phy. 2:17-22.

THOMAS, W. H.
1966b. Surface nitrogenous nutrients and phytoplankton in the Northeastern Tropical Pacific Ocean. Lim. and Ocean. 11:393-400.

THOMAS, W. H.
1970. Effect of ammonium and nitrate concentration on chlorophyll increases in natural tropical Pacific phytoplankton populations. Lim. and Ocean. 15:386.

TIMOFEYEV, M. P., and S. P. MALEVSKY-MALEVICH.
1967. Patterns of thermal regime of the surface layer of water. In: Soviet Hydrology: Selected Papers No. 1, 102 p.

TOFFALETI, F. B.
1969. Definitive computations of sand discharge in rivers. J. Hyd. Div. ASCE 95(HY1):225-248.

TRIMBLE, S. W.
1972. Denudation Studies: Can we assume stream steady state? Science 188(4194):1207-1208.

TRUMBULL, L. E., and D. LOOMIS.
1973. Instream flow needs for Idaho. Stream Development of Determinative Methodology. Idaho Water Resource Board, Boise, Id., 77 p.

TSIVOGLOU, E., and J. WALLACE.
1972. Characterization of stream reaeration capacity. EPA-R3-72-012. EPA, Washington, D. C., 317 p.

TYWONIUK, N.
1972. Sediment discharge computation procedures. J. Hyd. Div., Proc. ASCE 98(HY3):521-540.

USDA.
1974. A sag-type method of channel cross-section measurement for use with minimum instream flow determinations. R-2 Cross Program. USFS, Region 2. Denver, Colo., 17 p.

USDI.
1968. Guide for application of water surface profile computer program. Office of the Chief Engineer, Hydrology Branch, U. S. Bur. of Reclam., Denver, Colo., 17 p.

U. S. FOREST SERVICE.
1973. A methodology for determining instream water flows required for National Forest purposes. Idaho Panhandle National Forests, 5 p.

VELZ, C. J.
1970. Applied stream sanitation. Wiley-Interscience, New York, 619 p.

VOLLENWEIDER, R. A.
1966. Calculation models of photosynthesis – depth curves and some implications regarding day rate estimates in primary production measurement. In: Goldman C. Primary Productivity in Aquatic Environments, 646 p.

WANG, J. D., and J. J. CONNOR.
1974. Finite element model of two layer coastal circulation. Preprint: 14th Coastal Engineering Conference. Copenhagen, Denmark, 20 p.

WANG, J. D., and J. J. CONNOR.
1975. Mathematical modeling of near coastal circulation. Rep. No. 200. School of Eng. MIT, Cambridge, Mass., 272 p.

WANG, J. D., J. J. CONNOR, D. A. BRIGGS and O. S. MADSEN.
1973. Mathematical models of the Massachusetts Bay. Part I and II. Report No. 172. Ralph M. Parson's Lab. for Water Resources and Hydrodynamics. MIT, Cambridge, Mass., 57 p.

WASTLER, T. A., and C. M. WALTER.
1968. Statistical approach to estuarine behavior. J. San. Eng. Div. ASCE 94:1175-1193.

WATER RESOURCES ENGINEERS INC.
1965. A water quality model of the Sacramento-San Joaquin Delta. Rep. of an Investigation of U. S. Pub. Health Ser., Lafayette, Calif.

WATER RESOURCES ENGINEERS INC.
1966. A hydraulic-water quality model of Suisan and San Pablo Bays. Rep. of an Investigation for the Fed. Water Pol. Con. Admin. Lafayette, Calif.

WATER RESOURCES ENGINEERS INC.
1969. The thermal simulation of Applegate Reservoir to evaluate the effect of outlet placement and discharge on downstream temperature. Rep. of U. S. Army Corps of Eng., Portland District.

WEZERNAK, C. T., and J. J. GANNON.
1968. Evaluation of nitrification in streams. J. San. Eng. Div. ASCE 94:883.

WICKS, G.
1975. A study to evaluate potential physical, biological, and water use impacts of water withdrawals and water development on the middle and lower portions of the Yellowstone River drainage in Montana. Old West Regional Commission Quarterly Report. Montana Dept. of Natural Resources and Conservation, Helena, Mont., 61 p.

WILD, H. E., Jr., C. N. SAWYER and T. C. MCMAHON.
1971. Factors affecting nitrification kinetics. J. Water Pol. Con. Fed. 43:1845.

WOFFINDEN, D. S., and C. G. CLYDE.
1971. A portable direct reading open channel flow measurement device. Paper No. 2-6-190. Utah Water Res. Lab., Logan, Ut., Unpublished paper, 17 p.

YENTSCH, C. S., and R. W. LEE.
1966. A study of photosynthetic light reactions, a new interpretation of sun and shade phytoplankton. J. Mar. Res. 319-337.

ZANONI, A. E.
1969. Secondary effluent deoxygenation at different temperature. J. Water Pol. Con. Fed. 41:640.

APPENDIX I.

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4. METHODOLOGIES FOR DETERMINING INSTREAM FLOWS FOR FISH AND OTHER AQUATIC LIFE

C. B. STALNAKER AND J. L. ARNETTE

CONTENTS

METHODOLOGIES FOR DETERMINING INSTREAM FLOW REGIMES FOR PRESERVATION OF THE AQUATIC HABITAT AND ASSOCIATED ENVIRONMENTAL RESOURCES

Annual Flow Analyses

During the course of the development of methodologies for establishing instream flow needs for fish, wildlife, and recreation, the initial concepts were naturally centered on correlations between records of flow and preservation or maintenance of aquatic habitat and associated riparian vegetation. Most of these methods are directed toward the biological components of the aquatic ecosystem. However, an assumption, stated or implied, is that flows satisfactory for the needs of fish, aquatic insects and riparian vegetation are sufficient for maintaining the recreational and aesthetic qualities of the streams examined (e.g., Tennant, 1975). Recommended flow methodologies based upon historic records of flow have been described by Robinson (1969) for the Connecticut River basin; by Tennant (1975) as applied to warm and cold water streams in the Midwest, Great Plains, and intermountain west; and by Collings (1974) for application to West Coast salmon streams (Colling's approach is discussed under the section on spawning).

Based upon flow studies and numerous observations, Tennant (1975) suggests the following semiannual discharge regimens: A minimum instantaneous flow of 30 percent of the average annual flow (20 percent October-March and 40 percent April-September) and 50 percent of average annual flow (40 percent October-March and 60 percent April-September). A 10 percent average flow is said to sustain short-term survival of aquatic life; 20-40 percent average is considered a satisfactory range for fishery flows, while 40-60 percent and 60-100 percent are considered excellent and optimum ranges, respectively. Table 1 summarizes Tennant's approach to recommendations for stream classes and operating conditions.

Tennant (1975) recommends the following steps to quantify on-site project feasibility studies: 1) Determine the average annual flow at the appropriate location; 2) if the discharge can be controlled, arrange to observe, photograph, and measure the flow regimes at 10 percent, 30 percent, and 60 percent of the average annual flow. If the stream flow is uncontrolled, use USGS records and gage checks to observe natural flows of approximately 10 percent, 30 percent, and 60 percent; 3) photographs and transect measurements of depth, velocity, etc. should be made for comparison of substrate, bank exposure, wetted perimeter and other hydraulic parameters.

Table 1. Instream flow regimes for fish, wildlife, recreation, and related environmental resources (from Tennant, 1975).

Narrative Description of Flows	Fisheries Classification[a]	Recommended Base Flow Regimens: Oct.-Mar.	Recommended Base Flow Regimens: Apr.-Sept.
Flushing Flow	---	200% of the Average Flow	
Optimum Range	---	60%-100% of the Average Flow	
Outstanding	I	40%	60%
Excellent	II	30%	50%
Good	III	20%	40%
Fair	IV	10%	30%
Poor or Minimum	---	10%	10%
Severe Degradation	---	10% of Average Flow to Zero Flow	

[a]Montana Fish and Game Department, fisheries classification system.

U.S. Fish and Wildlife Service (FWS) personnel (Billings, Montana Area Office),[1] developed a flow recommendation scheme for application to streams in the Northern Great Plains area. This procedure was based first upon estimates of stream flow needs related to average hydrologic conditions for each specific month, and secondly, on estimating flow needs for extremely dry periods. Four successive steps were involved in determining instream flows. These procedures are detailed in a report by the Instream Needs Subgroup, Work Group (C) Water, for the Northern Great Plain Resource Program (Anonymous, 1974). The first step in this method assembled all available flow data for the streams under consideration and segregated the information by calendar month. Mean discharge for each month was computed. When a normal distribution for flow data (over years) was evident, the "t" statistic was used in establishing an upper and lower limit for the mean monthly values. From initial testing on several stream reaches (relatively stable over years), it was found that 70 percent of the yearly flows for a given month clustered about the mean and are considered as representative of average hydrologic conditions. The 30 percent of recorded flows lying outside the range were eliminated and assumed to represent abnormally high and low flows. When a normal distribution of flow data was not evident, abnormally high and/or low values were arbitrarily eliminated. The second step arrays, from the highest to the lowest, the remaining daily values for a particular month for all the years of record. This results in a flow duration curve for the month in question. This process is repeated for each month of the year. The recommended instream flow was set at that flow exceeded 90 percent of the time as determined from the flow duration curves for each month of the year. This flow is referred to as the 10 percentile flow. This technique resulted in a series of monthly flow estimations. The third step divided the stream into sections based upon tributaries entering, or diversions leaving, the reach being examined, and additions or subtractions from the 10 percentile flow were made according to the volume of flow

[1]Personal communication. 1975. William Jones. FWS. Billings, Montana.

in the tributaries and/or diversions. Lastly, adjustments were made upwards for spawning times, for the period of spring runoff (May, June and July when the mean annual flow of record was recommended), and for ease of operation (e.g., 105, 95, and 100 would be adjusted to 100 for three months).

This method, using the "t" statistic, was not used for those stream reaches which exhibited extremely erratic mean daily flows of record for the months examined. In those cases, judgments were used to eliminate certain extremely low and/or high daily records.

A procedure for determining instream flows for fisheries has been developed by Robinson (1969) and applied to streams in the Connecticut River basin. This method is based on the following premises:

> (a) that flows in June are about optimum for fisheries (in some sections of the country optimum flows may occur earlier or later); (b) that desirable flows for the rest of the year are determined in relation to the June flows and follow natural patterns on the basis that fish are acclimated to natural patterns; (c) that flows in adjacent or nearby watersheds exhibit similar flow patterns; and (d) that the results are directly applicable to streams having about the same flow magnitudes as the stream used to determine the values and applicable with judgement to streams having significantly different flow magnitudes. (Robinson, 1969:1)

To calculate a flow for fisheries purposes, at a specific stream location, the following steps are given: 1) Select those stream gaging points (USGS gages etc.) within the same basin which are as close to the specific stream reach to be examined as is possible. Also preferable are gaging stations which are affected slightly or not at all by regulation from upstream dams and diversions; 2) from the historical records at the chosen gaging stations, determine the average monthly median and lowest flows (cfs) and the drainage area in square miles at the gage; 3) convert the flow data to cubic feet per second per square mile (cfsm); 4) combine the flows from all gages and tabulate the combined average median and low flows; 5) select the historic median flow for June and set at 100%, i.e., the flow representing maximum fishery values. The flows for each of the other 11 months are selected as a percentage of the June flow as follows: (a) July through September-90%; (b) October through February-110%; (c) March through May-180%.

This results in a flow pattern which reflects the natural flow, but differs in magnitude and stability. This regime theoretically produces maximum fishery values and is referred to as the "optimum flow."

A low (minimum desirable in *their* words) fishery flow was also tabulated in a similar manner by setting 30 percent of the median June flow as the reference and continuing as above with percentages for the other 11 months.

The final steps in determining the fishery flow recommendations then follow: 6) determine the drainage area for the specific point or if for a stream reach the average among the drainage areas at the upstream, the downstream ends and the midpoint of the reach; 7) determine the optimum and lower (minimum) fishery flows (cfs) by multiplying the drainage area by the appropriate values in cfsm from step 3.

Recommended flows are then selected within the range of tabulated flows by selecting a flow which is "desirable and reasonable" under local conditions. Through the use of this procedure on a number of streams in the New England area, Robinson has developed the following "rule of thumb" formulae for calculating fishery flows most applicable to very early stages of planning (or reconnaisance studies as used here):

Q_1 (for maximum fishery values)=1.24 cfsm x A . . . (1)

Q_2 (for moderate fishery values)=0.36 cfsm x A. . . . (2)

where Q is discharge in cfs and A is drainage area in square miles.

The State of Washington Department of Ecology, in cooperation with the Departments of Fisheries and Game, is presently using a "base flow" concept for reservation or retention of water for the preservation of environmental values in Washington streams.[2,3] The state is divided into 62 water resource inventory river areas. Each of these areas is divided into stream sections (the number is variable among the areas) which are generally located above USGS stream gaging stations. The present base flow program grants water for instream requirements according to the importance of each stream considered.

The stream sections are rated by personnel of involved state agencies (Ecology, Fisheries, Game, Parks and Recreation, Natural Resources, Highways, and the Interagency Committee for Outdoor

[2]Personal communication. 1975. John Hunter, Washington Department of Game, Olympia, Washington.

[3]Personal communication. 1975. Robert Milhous. Washington Department of Ecology, Olympia, Washington.

Recreation). Six parameters (wildlife, fisheries, scenic and aesthetic, water quality, navigational and other environmental values) are evaluated for their relationship to each agency's area of concern. These evaluations are used to arrive at a numerical importance rating. Each agency places rating values from 0 (no value) to 4 (highest) on each of the 6 parameters for the stream in question—e.g., the highest rating one agency could give a stream is 24. Agency ratings for each parameter are averaged and the total for all parameters is entered on a conversion "curve" (nomograph) to directly read a flow duration percentile (Figure 1). The flow duration obtained from the conversion curve is translated by use of a flow duration curve for the site to an actual base flow in cfs (Figure 2).

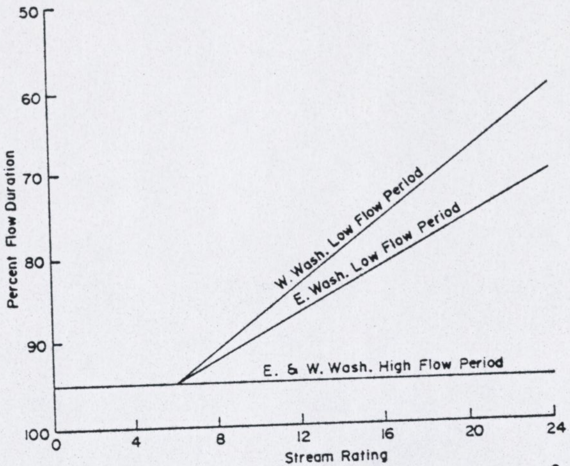

Figure 1. Representative conversion curve.[3]

Summer (low-flow period) flows are determined on the importance rating of each stream. However, desirable flows, depending on the region (eastern or western Washington) are usually those equalled or exceeded 60-70 percent of the time. The desired flow levels were approximated on the basis of prior work. It has been determined that lower summer flows dramatically reduce wetted area resulting in reduced area for aquatic insect production and trout fry habitat.

Winter (high-flow period) flows recommended have been those equaled or exceeded 95 percent of the time. This is a relatively fixed percentage agreed upon by interagency personnel. This flow level is considered adequate for spawning, rearing and aquatic insect production in Washington streams, during the low water demand, high availability winter period.

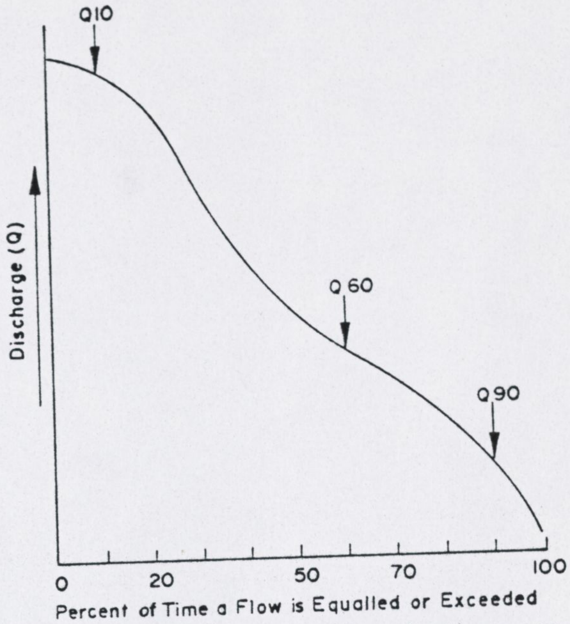

Figure 2. Representative flow duration curve.

Although the base flow approach is presently the focus of the Washington Department of Game's recommendation program, additional data are sometimes necessary. Information for the establishment and defense of positions and priorities has been provided by use of methodologies that are described in the section on spawning flows (USGS and Washington Department of Fisheries) and by wetted area—discharge curves (loss of wetted area is considered critical).

USFS, Region 2 (Anonymous, 1973) personnel have synthesized preservation stream flows based on discharge percentile levels from flow duration curves. By constructing flow duration curves for mountain streams, percentiles were recommended for fish food production (80 percentile), spawning (40 percentile), and spawning area flushing (15 percentile). The latter is necessary for removal of fines from the gravel beds and intragravel water movement.

Data (biological and physical) from studies conducted on the Frying Pan River, Colorado (Hoppe and Finnell, 1970) were compared with average annual flow records and discharge percentile recommendations made for application to Rocky Mountain trout streams. Average annual flows of record are ranked from high to low and a flow duration curve drawn with discharge on the ordinate (Y axis) and percent of time a flow is equaled or exceeded is drawn on the abscissa (X axis) (Figure 2).

Flushing flows for a 48-hour period were found to be adequate at the 17 percentile level, spawning flows adequate at the 40 percentile level, and food production and cover flows adequate at the 80 percentile level, as measured on the Frying Pan River, Colorado.[4] These 40 and 80 percentile discharges can be approximated for specific points between gaging stations by developing a log-log plot of drainage area vs Q_{80} (taken at gaged points), and interpolation from the resulting graph, or mathematically from the following equations:

$$Q_{80} = \text{antilog}\ [\cosh^{-1} (\log A - 0.60)\ 1.43] \quad \ldots\ldots (3)$$

$$Q_{40} = \text{antilog}\ [\cosh^{-1} (\log A - 0.55)\ 1.53] \quad \ldots\ldots (4)$$

when Q_{80} is the 80 percentile discharge level, Q_{40} is the 40 percentile level, and A is the drainage area in square miles.[5]

Simons has developed two computer programs "CURVE FIT" and "EVALUATE" based upon the Q_{80}, Q_{40} equations. The curve fit routine inputs the drainage area and flow rate determined for two points along the study reach and outputs the appropriate constants for the equations. The evaluate routine inputs the constants and outputs the 40 and 80 percentile discharge values.[6]

Critique

Methodologies utilizing average flow records (annual, monthly, etc.) are primarily of value for reconnaissance or limited field studies for recommending instream flows early in the planning stages. These methodologies, because they use primarily synthesized data, have the advantage of allowing evaluation of needed flows from existing records with either limited or no field studies. For an appraisal of an extensive area, this type of method provides a relatively quick, inexpensive information base for flow recommendations. The 30/60 percentage average annual flow (Tennant, 1975) and the monthly 10 percentile figure of the USFWS (Anonymous, 1974) are usually satisfactory preservation flows (in some cases, these flows exceed the norm for the period in question).

Because Tennant's (1975) method is based on mean annual flow percentages, the reliability of recommendations may be less valid when applied to streams with more stable flows (i.e., a spring creek with uniform flow might suffer severe discharge reduction during particular times of the year). The approach seems valid for streams that have fluctuating flow regimes.

The FWS method developed in the Great Plains region (streams usually exhibit highly variable seasonal flow patterns) uses monthly flows to arrive at the 10 percentile figure to cope with this variability. However, development of this value must be considered highly subjective.

Robinson's formulae were developed in the Connecticut River basin and would need to be recalculated for each major basin or geographic area. The hydrologic pattern must be similar throughout each basin or area. When applying this procedure to a new situation, the critical steps, and those which are entirely dependent upon the judgement of the professional biologist, are the choice of the reference month (and reference flow) and the apportionment from that flow to other seasons of the year. Once a formula is established and varified for a particular hydrologic province, this method is very easy to apply.

A major constraint of methods using flow records is the availability of records and the suitability of their duration. When working below impoundments or on streams that are gaged, the provision of accurate flow data does not present a problem. However, when the stream is not gaged, as is often the case, flow data must be computed from records other than on the stream in question and become less accurate, and/or some field measurements and additional time commitments are necessary. In Tennant's (1975) approach, observations of the stream at varying percentages of the average annual flow are necessary for documentation. This is an expedient technique where discharge can be controlled, but involves a greater expenditure of time and effort when the appropriate natural flow regimes must be observed.

Flow record analysis, developed in a particular region and based on a local hydrologic cycle, may be limited in its usefulness in other dissimilar regions. Theoretically, percentage criteria could be used on any stream system, but in many cases the criteria would have to be altered or developed for

[4]Personal communication. 1975. Richard Hoppe, FWS, Green Bay, Wisconsin.

[5]USFWS memorandum from Richard Hoppe to Region 3 Office, Twin Cities, Minnesota, with accompanying slide-tape material on minimum fishery flows, March 1975.

[6]A description of the program is available from Roger Simons, University of Wisconsin, Green Bay, Wisconsin.

the particular area. The division into seasonal regimes should be adjusted to the climatic conditions of the region in which a particular stream is located. Flow regimes can also be modified to satisfy specific life cycle requirements of a given species, e.g., satisfactory flows for fall spawning brown trout.

Studies have been conducted using the "flow record" approach (Elser, 1972; Wesche and Rechard, 1973). The results of these studies indicate that below approximately 30 percent mean annual flow (M.A.F.) or 25 percent average daily flow (A.D.F.) there is a significant reduction in hydraulic parameter values, e.g., velocity, and available habitat. This work tends to increase the credibility of Tennant's 10 percent (M.A.F.) survival flow and 30 percent (M.A.F.) preservation flow. Under proper conditions, in the locales where they were developed, approaches using records of flow seem to provide an adequate assessment of instream preservation flows for the level of study for which they were intended.

Techniques using recorded discharge and flow duration curves can serve as a good "rule of thumb" and for correlation with other methods. The 40 percentile (spawning) and the 15 to 17 percentile (flushing) flows represent short-term needs and, as a result, can usually be obtained in a flow program. The 80 percentile (food production) figure generally represents an adequate flow for maintaining critical wetted perimeter, but in areas (e.g., intermountain west) of high water demand and low availability, this quantity may not be available over the long term.

The use of flow duration curves, rather than mean annual flow percentiles, appears to be gaining support. As a means of standardizing recommendations based upon flow records, we recommend that percentile expressions from flow duration curves be adopted for discharge determination.

The base flow concept of flow recommendation presently in use in the State of Washington is a nontechnical approach to evaluating stream discharge requirements. The rating system used is subjective and must be considered highly variable between individuals and agencies. The fact that subjectivity exists in the ratings means that flow recommendations are also judgmental. However, communication with the Department of Game[2, 3] indicates that the base flow approach is, at least initially, a workable program and water requests have been granted. This concept is apparently functional in a "water-rich" state; however, in arid regions, a more technical, less subjective approach may be needed.

Transect Analyses

USFS personnel (Region 4) have developed a methodology which relates stream habitat loss to reductions in stream discharge. This methodology is based on the assumption that suitable aquatic habitat would meet the requirements of the biological components of the ecosystem, including riparian vegetation. Since any flow reduction or manipulation affects the aquatic habitat, the basic approach is to determine discharge-habitat relationships and establish a reference from which further flow reductions could be related to retention or loss of aquatic habitat (Dunham and Collotzi, 1975).

Transect measurements of hydraulic parameters and subjective cover evaluations are used in a technique to "quantify" the general habitat. Sample stations (determined on a stratified random basis) are established and a cross-sectional profile is drawn to scale, using field-measured data (at a reference flow) from a representative transect. Hydraulic parameters and habitat features measured at the reference flow include velocity, width, depth, pool-riffle area, and streambank and bottom composition. Discharge, wetted perimeter, surface area, etc. are determined from the field-measured data and the profile. Additional lines representing different water stage levels are drawn on the profile. Hydraulic parameters of the cross sections are determined for each water level (stage). Calculations can be performed manually or by computer.

The habitat evaluation technique determines a reference habitat value representing the habitat existing at the reference flow (Herrington and Dunham, 1967; Dunham and Collotzi, 1975). The rating approach groups "priority habitat components" in four categories and provides a numerical rating for each.[7]

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[7]The Utah State Office Bureau of Land Management also uses this procedure. Mimeo draft copy BLM, Manual Supplement, 6671, June 1975.

1. Pool measure - a ratio of the total sample width as pool and riffle habitat (the percentage of total stream width which contained pools).
2. Pool structure - a rating of the percentage of the total pool width which contained good quality pools. Pool ratings are based on pool size and depth as related to stream width. (Specific pool rating criteria are presented in the USFS Habitat Inventory Techniques.)
3. Stream bottom - a ratio of the total sample width containing boulder, rubble, gravel and silt. (The percentage of total stream width containing boulder, rubble, gravel, and silt.)
4. Stream environment - a rating of the streambank vegetative cover in descending order of trees, brush, and exposed banks.

Reference Habitat Value[8] $= \dfrac{1 + 2 + 3 + 4}{400} \quad . . . . \quad (5)$

The ratings for all categories are added and divided by the maximum possible sum according to the above formula to arrive at a reference habitat value.[9] This value can indicate the relative habitat quality of each sample station or of the stream as a whole when all sample stations are summed. Habitat values are calculated for each of the additional water stages drawn on the cross-sectional profile. These are determined by measurements taken from the profile and observations made in the field. Region 4 (USFS) personnel graphically relate reference flow data to the habitat value which existed in the stream when field measurements were taken. Since flow reductions, from the reference measurements, would affect the aquatic habitat to varying degrees, flow reductions are related to the existing physical parameters on a percentage basis.

Utilizing the calculated discharge and habitat values, a graph is drawn for each sample station, or representative transect. This is done by plotting the habitat values, expressed as percentages of the reference habitat value, on the ordinate, and discharge, expressed as percentage reduction from the reference flow, on the abscissa (Figure 3).

Discharges and habitat ratings both range from 0 to 100 percent, with 100 percent set as the value determined from actual field measurements. The additional calculated discharges and habitat values for the added water stages are expressed as percentages of the respective reference values.

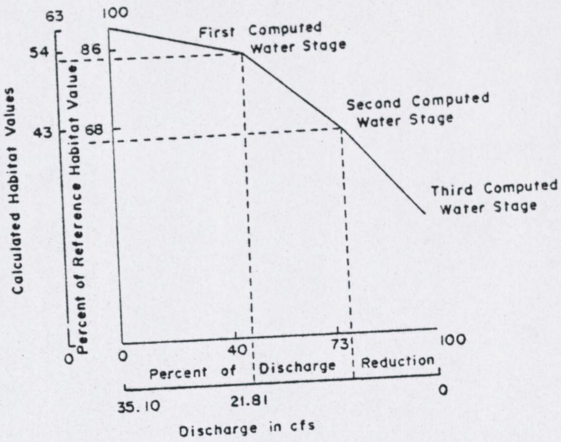

Figure 3. Representative discharge habitat curve for a mountain trout stream. On the Y axis, 63 is the reference habitat value. Fifty-four is the habitat value at the first water stage and represents a retention of 86 percent of the reference habitat value. On the X axis, 35.1 is the reference flow; 21.8 is the computed discharge at the first water stage and represents approximately a 40 percent discharge reduction (from Chrostowski, 1972).

Analysis of habitat data from a number of field studies indicates a general rate of reduction in quality of habitat with decreasing discharge. However, a distinct change in this rate of habitat quality reduction is found to occur within the 0-50 percentile range of reduction (see inflection point at first computed water stage, Figure 3) from the reference flow. Further reduction in discharge beyond this point results in an accelerated rate of habitat quality loss.

Analysis of several streams in USFS Region 4 has shown that this inflection point is evident only for those streams with rectangular-shaped cross sections (see Figure 1-B Section 2). On those streams with generally trapezoidal cross sections, the discharge-habitat relationship is very nearly linear, representing a constant high rate of loss with

[8] Referred to by Dunham and Collotzi (1975) as percent optimum habitat rating.

[9] USFS, R-1 Wildlife Surveys Handbook, Amend. No. 15, April 1973.

decreasing discharge.[10] The distinct sharp breaks have been found to occur along the habitat axis above the 80 percentile values. Habitat values below these sharp changes along the discharge-habitat curve are interpreted as habitat significantly degraded from field measure values. Chrostowski (1972) states "habitat preservation requires a minimum flow equal to no less than 80 percent retention of low flow habitat value." The necessity of retaining 80 percent of the reference habitat value is a primary assumption of the Region 4 methodology. Recommended preservation flows for habitat maintenance are set at or above the inflection point of the discharge-habitat curve for higher quality, steep-sided streams. Generally, for sloping banked streams, the recommended preservation flow is set at or above the 80 percentile habitat value. Flow recommendations from analysis of habitat data along shallow-sloping curves requires some judgment to be exercised by the biologist.

The Region 4 methodology has been used to determine the amount of water (preservation flow) necessary to maintain aquatic habitat in streams that will be affected by the Central Utah Project, a major Bureau of Reclamation multipurpose water transfer project. Specific cross-sectional and graphic presentations of field data are available in Chrostowski (1972).

USFS (Region 2), FWS, and Colorado Division of Wildlife personnel utilize a technique developed by Mulvaney and Russel (Anonymous, 1973).[11] This is termed the "Critical Area Method" and is an interdisciplinary approach utilizing a field team (biologist, limnologist, hydrologist and someone trained in aesthetic considerations). Based upon records and a field examination, each team member determines certain areas on the stream which are considered critical. These areas would contain the limiting factors for stream flow in that particular stream reach or study section. Considerations are: Spawning areas; cover; aquatic insect production; fishability; and the concept of measurements for aesthetics based on the "change in character." Critical areas are marked on the ground and photographed, and identified as either fisheries and/or aesthetics and marked if high flow should be investigated. A transect is established and the cross section and profile measured. Manning's equation [Equation (8), Section 2] is used to compute flows at various levels of water depth. The flow needed to maintain fish life or meet minimum aesthetic needs would be judgmentally determined. An optimum flow is established in a similar fashion. Flows would not necessarily be the same for fish and aesthetic considerations.

Field techniques developed in Colorado and New Mexico are summarized by Hoppe[5], who recommends first determining the limiting factors of the study stream. A transect is established at a point representing the type of habitat considered limiting. For example, if cover is limiting, a point is located where a typical pool is too shallow or an undercut bank is partially exposed. The transect is positioned to pass directly over the critical point. At the transects, velocity, cross-sectional area and gradient are measured for actual stream discharge computations. To determine a minimum spawning discharge, a velocity of 2 fps (fixed velocity determined from other work) is "plugged" into the flow equation [Equation (8), Section 4] and discharge (cfs) computed. Where cover is limiting, a water stage is visualized that satisfies cover needs and an average depth is estimated or measured [for use as R in Equation (10) in Section 2]. Manning's equation is then used to calculate n. With this input, the flow equation is used to compute discharge.

Critique

The USFS Region 4 technique should be viewed as an intensive on-site field approach, as it does consider the total aquatic habitat for each stream evaluated. The method generally provides a satisfactory index to aquatic habitat. Hydraulic parameters correlate well in determining flows necessary to retain a percentage of habitat. The 80 percent habitat retention value has been determined by evaluating a considerable number of stream situations. The assumption that this value is necessary for aquatic habitat preservation in small wadable trout streams appears to be valid for seasons of lowest stream flow. However, at the present level of refinement, this technique is of use mainly on smaller streams; therefore, a different habitat rating system should be developed and tested for large rivers.

The habitat rating approach does have limitations. Stream environment ratings are subjective and may vary among field personnel. The development of the discharge-habitat curve is somewhat

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[10] Personal communication. 1975. Donald Dunham, USFS, Ogden, Utah.

[11] Personal communication. 1975. Richard Moore, USFS, Lakewood, Colorado.

complex and should be evaluated for simplification. Some judgment is necessary to interpret flows from the curve for certain types of stream configurations. Since this method is quite intensive, it requires a considerable expenditure of time and manpower, from the field measurement stage to developing the discharge-habitat curve. Although velocity is considered as a standard measurement, it is not included in the habitat values or in the discharge-habitat relationship. In streams, especially those with lower gradients, intragravel water movement is directly dependent upon the velocity component of flow; therefore, the habitat retention alone may not give an adequate assessment of the substrate environment. If spawning habitat is suspected as being limiting to the fish population, appropriate techniques for its assessment must supplement the habitat rating technique.

The "Critical Area" method combines field investigation with synthetic flow data and should be considered for reconnaissance studies only. The limited field work approach considering only critical areas makes the time commitment much shorter. The team approach to evaluating stream system needs and recommending flows can be considered an asset. The primary limitation of this technique is the ability of the observer to identify the specific critical or limiting areas. However, this effect is lessened by use of an experienced team.

The limiting factor transect approach uses limited field data in combination with a previously established velocity figure or occular estimates of stage to arrive at an appropriate minimum discharge. A very limited time investment is necessary with this method and the computations involved in determining discharge are minimal and can be performed in the field. However, use of a fixed velocity value and visual estimates of stage (also average depth is not always comparable with R in Manning's equation) make this a subjective approach and necessitates considerable field experience.

METHODOLOGIES FOR ASSESSING THE EFFECTS OF CHANGED STREAMFLOWS UPON AQUATIC FAUNA

Since flow, at various levels, is directly related to virtually all stream parameters of significance to the life of aquatic organisms, it becomes the major determinant of the activities of many species of stream-dwelling organisms. Discharge determines stream phusical dimensions, such as width, depth, and velocity characteristics, thereby controlling the amount and suitability of spawning areas, microhabitat, riffle areas (for insect production) and insect drift. Flow-percolation-intragravel water movement relationships can determine the success or failure of egg incubation (in redds). Flowing water serves as a dilutant and transporter of natural and man-generated pollutants. These range from chemical and thermal pollution to sedimentation, all of which, undiluted or deposited, have dramatic effects on aquatic life. Temperature regimes critical to fish production (from initiating spawning behavior to egg survival) are often the direct result of particular flows.

It is generally agreed that, of all of the stream flow parameters, water depth and velocity are most important as potential limiting factors during the various life stages of aquatic organisms. However, of the two, velocity is considered to be of greater significance in the aquatic system. Hynes (1970) recognized velocity as the major factor controlling the structure of animal communities in streams. Velocity is a primary agent in maintaining desirable insect species composition, influencing stream-carrying capacity, reducing effects of predation on young fish, and determining spawning site preference. Fraser (1972) considers depth as the second most important streamflow parameter after velocity. Depth is significant in maintaining pool quality and other types of microhabitat, in allowing passage (critical for anadromous salmonids) and in supplying the necessary wetted area for spawning and food-producing riffes. Because of the significance depth and velocity have to aquatic fauna, it is of paramount importance to define species criteria for the two parameters. The depth-velocity requirements for passage and spawning are known for some of the major salmonid species. Incubation depth-velocity needs are poorly understood and methods usually consider spawning flows or a high percentage of this flow as adequate. Rearing, as a life stage, generally encompasses those times of the year when fish are not engaged in the other three major activities. Rearing flows are those that will maintain the habitat (including food production) necessary for the sustenance of the fish species present. Specific depth and velocity criteria for a variety of species rearing requirements are poorly understood.

Methods are available that relate depth and velocity requirements of fish to stream discharge.

The general approach is to translate knowledge of the depth-velocity requirements for the major life stages (passage, spawning, incubation, and rearing) of species into actual discharges necessary for these life stages.

Passage Flows

The Oregon Department of Fish and Wildlife personnel utilize depth-velocity criteria as a basis for flow recommendation. Passage flows are established by locating shallow bars, in a given stream, that are most critical for movement of adult fish. A transect is established on the selected bars along the shallowest bank-to-bank course and transect-length and depth-velocity data are measured once at a flow that covers all or most of the bar. Depth measurements are taken approximately every two feet on small streams, four feet on medium streams, and eight feet on large streams and rivers. Velocity is measured at 0.6 of the total depth from the flow surface (Oregon State Game Commission, 1972). The total width and longest continuous portion of the transect that meet necessary minimum depth and maximum velocity criteria are determined for several discharges (usually six flows). These are expressed as the percent total width usable and percent of longest continuous portion usable and are plotted against discharge to arrive at a flow recommendation (Figure 4).

Recommended passage discharge is that which meets the depth velocity criteria on at least 25 percent of the total transect width and along a continuous portion of at least 10 percent of the total transect width (Figure 4). The results from all transects on the examined stream are averaged and recommended as the minimum (lowest) flow for passage (Thompson, 1972).

Bovee (1974) has proposed the use of this technique for determination of passage flows in the rivers of the Northern Great Plains (see section on *Methodology Development*). Rather than using the method to arrive at needed flows for one species, the author advocates the determination of flows for an *indicator* species on the premise that:

> . . . If environmental conditions are not unfavorable for the species with the narrowest ranges of discharge requirements, they will likely be suitable for all other organisms as well. An indicator species is defined as the species which demonstrates the narrowest range of tolerance or requirements for any particular biological function. Therefore, the same indicator species is not used for every phase of the life history. (Bovee, 1974: 119)

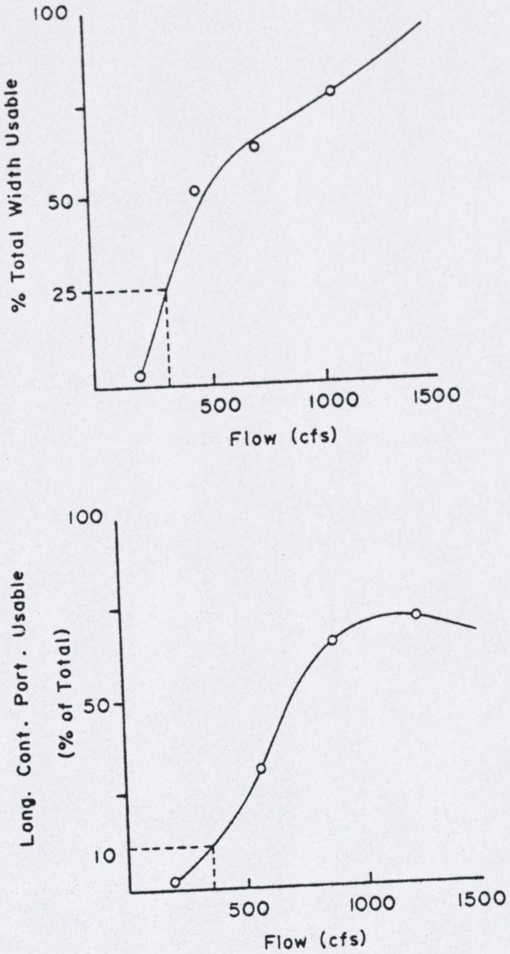

Figure 4. Representative data plot for passage flow recommendations (from Thompson, 1972).

The passage flow indicator species proposed for large rivers in the Missouri basin is the paddlefish *Polyodon spathula*. Although the depth velocity (clearance) requirements for adult paddlefish have yet to be intensively investigated, Bovee (1974) proposes the usable width approach described above. Minimum passage flow recommendations (using indicator species) for the larger rivers are suggested as those that meet depth velocity criteria over 50 percent of the total transect width and over a continuous portion of at least 30 percent of the total width.

White (1975) proposes a conceptually similar approach with the white sturgeon as the key (indicator) species for the middle Snake River. Passage flow criteria for adult white sturgeon are poorly understood. Until their requirements become clarified, White (1975) recommends a minimum continuous depth of 1.5 m (5 ft) be maintained over 25 percent of the shallowest bank-to-bank course.

As noted above, specific information on the passage requirements (and flow levels necessary to stimulate migration) of a number of fish species are not well known. This is particularly the case for the warm water fishes. Table 2 gives reported depth velocity passage criteria for certain salmonids.

Table 2. Reported passage depth velocity criteria (from Thompson, 1972).

Species	Minimum Depth (ft)	Maximum Velocity (ft/sec)
Chinook	0.8	8.0
Coho	0.6	8.0
Chum	0.6	8.0
Steelhead	0.6	8.0
Large Trout	0.6	8.0
Other Trout	0.4	4.0

Critique

The methods (presently in use or proposed) discussed under passage flow are all conceptually similar, generate basically the same type of information and fall into the limited on-site field study category. The techniques all consider areas critical for passage of adult fish by ascertaining a usable and continuous portion along the shallowest bank-to-bank course of a potential passage block. These portions along the critical area transect line are evaluated by depth velocity criteria for the particular migrating fish species. However, with the exception of certain salmonids, depth velocity criteria for fishes are generally unknown. When these criteria are known for the target species, this approach can provide a valid base for passage flow recommendations.

The indicator species approach (Bovee, 1974), after selection of valid species and refinement and broadening of the data base, should have merit as a method to evaluate flows for warm water species.

The methods, as they presently exist, are adequate; however, the lack of sufficient depth velocity data results in a major limitation in the quality of flow recommendations. Emphasis, therefore, should be placed on study of movement, swimming speeds and behavior of all important stream fishes (especially migration stimuli), rather than on further development of passage methodologies. The major field limitation of existing techniques is the measurement of the cross-section depths and velocities in large swift rivers. However, the use of echo-sounding gear and the recently perfected probe-type electronic current (velocity) meters should greatly reduce this problem.

Spawning Flows

Flow parameters, depth, velocity and, in some cases, wetted width, have been used as the determinants of preferred spawning areas and the success of reproductive activities.

Hooper (1973) states that the available spawning area for salmonids is determined by the physical dimensions of the stream reach having suitable substrate and velocities at different flows. Smith (1973) also emphasizes the importance of incorporating depth velocity criteria for species into spawning flow determinations. A quote by D. H. Fry (in Hooper, 1973) summarizes the general effects of flow on the spawning capacity of a stream.

> As flows increase, more and more gravel is covered and becomes suitable for spawning. As flows continue to increase, velocities in some places become too high for spawning, thus cancelling out the benefit of increases in usable spawning area near the edges of the stream. Eventually, as flows increase, the losses begin to outweigh the gains, and the actual spawning capacity of the stream starts to decrease. If spawning area is plotted against streamflow, the curve will usually show a rise to a relatively wide plateau followed by a gradual decline. Often there are secondary rises as subsidiary channels become usable as spawning area. (Hooper, 1973:26)

The significance of velocity to spawning is indicated by the following quotes:

> Water depth and velocity in spawning areas, both appear to be of significance not only for successful spawning, but for maximum egg survival. Velocity appears to be the most important with depth of secondary importance in that suitable velocities are generally available only with a certain depth range. [Andrew and Geen, 1960 (in Sams and Pearson, 1963:20)]

> . . . depth of water is believed to be of less

importance than velocity. . . . in general where velocity is acceptable to spawning fish the depth will be suitable. (Sams and Pearson, 1963:47)

CORRELATION OF SPAWNING FLOWS WITH BASIN AND STREAM CHANNEL PARAMETERS

Considerable work has been done by the USGS in modeling the minimum discharge that will provide for the maximum suitable spawning riffles in Pacific Northwest streams. Regression equations have been developed for relating watershed characteristics to spawning discharges, for several Pacific salmon species; starting with the work of Rantz (1964) for chinook salmon spawning sites in northern California Coast Range streams, and for five additional species in the major streams of western Washington (Collings et al., 1972a, 1972b; Collings and Hill, 1973; Collings, 1974). Rantz (1964) studied nine salmon spawning sites in the Eel and Mad River basins. These spawning sites were selected in the vicinity of stream gaging stations where the streamflow characteristics were known and suitable spawning criteria (determined by Westgate, 1958) of depth, velocity, and stream bed composition existed. Three to five transects were established perpendicular to the direction of flow and appropriate hydraulic measurements were made at various controlled discharges. The suitable spawning areas were determined at each discharge by planimetering the potentially usable area on maps drawn to scale. Steps in establishing the discharge assumed to provide the maximum spawning area for chinook salmon were: 1) Determine the average annual flow from gaging station records or make 5-6 discharge measurements at the spawning reach and correlate to the nearest comparable gaging station; 2) from topographic maps, measure the drainage area at the spawning reach; 3) determine the average stream width when the discharge is at the average annual flow; 4) determine spawning discharge by use of the following regression equation:

$$Q_0 = 0.89(Q_m)^{1.09} (R)^{1.44} \quad R = \frac{W}{A} \quad \ldots\ldots\ldots \text{(6)}$$

in which Q_0 is the minimum computed discharge that will provide the maximum spawning area, Q_m is the average annual discharge in cubic feet per second, and R is the ratio of stream width (W), in feet, to drainage area (A), in square miles.

Collings (1974) has developed models from which spawning discharges for five salmon species in western Washington streams may be computed. These are multiple regression models utilizing drainage area, altitude, gravel size, and reach parameters as independent variables.

Spawning discharges for the five salmon species were found to be significantly different when tested as random variables, but were not significant when tested as nonrandom variables (0.95 testing level). The following general equation and the coefficients in Table 3, from Collings (1974), were used for computing preferred (optimal) spawning discharges and spawning-sustaining (minimal) discharge.

$$Y = a(A)^{b1} (MA)^{b2} (RA)^{b3} (W)^{b4} (GS)^{b5} (RS)^{b6} (SF)^{b7} (HR)^{b8} \ldots\ldots\ldots\ldots \text{(7)}$$

in which Y is the computed spawning discharge, a is the regression constant, (A) is drainage area in square miles, (MA) is the mean altitude of the basin above the study reach, (RA) is reach altitude in feet, (W) is reach width in feet, (GS) is percentage of 1 to 3-inch diameter gravel, (RS) is reach slope in feet per mile, (SF) is shape factor (shape of the channel as indexed by averaging the depths at 25 and 75 percent of the stream width and dividing the larger by the smaller value), (HR) is hydraulic radius, in feet, and b's are the regression coefficients. Collings (1974) defines preferred spawning discharge as "the discharge that will provide the maximum area for spawning" (same as Q_0 in Rantz, 1964), and spawning-sustaining discharge as the point at which the percentage reduction in spawnable area becomes greater than the percentage reduction in discharge, but not less than 75 percent of the preferred spawning discharge. Means of determining preferred and spawning-sustaining discharges from field measurements are discussed in the section on hydraulic parameters and mapping. Collings (1974) also has developed simple regression models for each of the five salmon species, using spawning-sustaining discharge as the dependent variable and preferred spawning discharge as the independent variable.

Table 3. Results of multiple-regression analysis for generalizing preferred and spawning-sustaining discharges and rearing discharges (from Collings, 1974).

Model equation: $Y = a(A)^{b_1}(MA)^{b_2}(RA)^{b_3}(W)^{b_4}(GS)^{b_5}(RS)^{b_6}(SF)^{b_7}(HR)^{b_8}$

Discharge, Y, in cubic feet per second for:	Regression constant a	Drainage area (sq mi) A	Mean basin altitude (ft, msl) MA	Reach altitude (ft, msl) RA	Reach width (ft) W	Percentage of 1-3-inch gravel size GS	Reach slope (ft/mi) RS	Shape factor SF	Hydraulic radius (ft) HR	Standard error (percent)	Correlation coefficient	Number of reaches used for model
Preferred spawning:												
Fall chinook, PFC_1[a]	11.8	0.629	--	--	--	--	--	--	--	44.5	0.87	50
PFC_2	3.39	.412	--	--	0.464	--	--	--	--	41.5	.89	50
PFC_3	4.19	.426	--	-0.061	.476	--	--	--	--	41.5	.89	50
PFC_4	2.09	.436	--	-.112	.544	--	0.187	--	--	40.6	.90	50
Spring chinook, PSC_1	22.6	.572	--	--	--	--	--	--	--	43.7	.69	26
PSC_2	21.7	.625	--	--	--	--	--	-0.549	--	41.9	.73	26
PSC_3	111	.670	-0.242	--	--	--	--	-.483	--	41.1	.76	26
PSC_4	30.4	.595	-.263	--	.359	--	--	-.444	--	40.3	.78	26
PSC_5	91.9	.597	-.243	--	.340	-0.354	--	-.482	--	39.9	.80	26
Coho, PC_1	8.25	.692	--	--	--	--	--	--	--	44.3	.88	53
PC_2	3.27	.532	--	--	.345	--	--	--	--	43.0	.89	53
PC_3	1.75	.528	--	--	.390	--	.132	--	--	42.6	.90	53
PC_4	1.73	.544	--	-.101	.438	--	.209	--	--	41.9	.90	53
PC_5	.754	.528	--	-.093	.484	.167	.233	--	--	41.8	.90	53
Sockeye, PS_1	5.85	.805	--	--	--	--	--	--	--	58.1	.86	18
PS_2	24.0	.801	--	-.264	--	--	--	--	--	54.7	.88	18
PS_3	6.24	.524	--	-.238	.520	--	--	--	--	52.0	.90	18
PS_4	4.72	.735	--	-.267	.571	--	--	--	-0.703	49.0	.92	18
PS_5	1.31	.645	--	-.249	.721	.290	--	--	-.800	49.7	.92	18
Pink and chum, PPC_1	16.5	.606	--	--	--	--	--	--	--	27.8	.93	33
PPC_2	5.54	.439	--	--	.375	--	--	--	--	25.3	.94	33
PPC_3	1.57	.425	--	--	.462	.266	--	--	--	25.0	.94	33
PPC_4	1.27	.446	--	--	.501	.329	--	--	-.282	24.2	.95	33
PPC_5	.781	.403	.089	--	.486	.344	--	--	0.260	24.2	.95	33
Mean of species, PM_1	12.0	.654	--	--	--	--	--	--	--	37.9	.90	53
PM_2	3.11	.420	--	--	.504	--	--	--	--	33.9	.92	53
PM_3	4.09	.435	--	-.080	.521	--	--	--	--	33.1	.93	53
PM_4	4.02	.433	--	-.078	.539	--	--	-.104	--	32.9	.93	53
PM_5	2.49	.435	--	-.108	.592	--	.122	-.233	--	32.6	.93	53
PM_6	1.17	.419	--	-.100	.632	.153	.143	-.224	--	32.4	.93	53
Spawning sustaining:												
Fall chinook, OFC_1	8.38	.667	--	--	--	--	--	--	--	47.9	.86	50
OFC_2	2.40	.450	--	--	.467	--	--	--	--	45.2	.88	50
OFC_3	1.40	.449	--	--	.503	--	.116	--	--	45.1	.89	50
OFC_4	1.33	.475	--	-.120	.557	--	.216	--	--	44.1	.89	50
Spring chinook, OSC_1	18.1	.592	--	--	--	--	--	--	--	43.9	.70	26
OSC_2	3.00	.498	--	--	.449	--	--	--	--	42.4	.74	26
OSC_3	3.29	.550	--	--	.417	--	--	-.470	--	41.2	.77	26
OSC_4	14.7	.556	--	--	.399	-.430	--	-.508	--	40.3	.79	26
OSC_5	45.0	.587	-.201	--	.427	-.393	--	-.448	--	40.0	.80	26
Coho, OC_1	6.03	.730	--	--	--	--	--	--	--	44.7	.89	53
OC_2	2.38	.570	--	--	.346	--	--	--	--	43.3	.90	53
OC_3	1.09	.564	--	--	.402	--	.165	--	--	42.5	.91	53
OC_4	.382	.545	--	--	.465	.212	.204	--	--	42.2	.91	53
OC_5	.507	.592	-.153	--	.545	.228	.268	--	--	42.2	.91	53
Sockeye, OS_1	4.88	.806	--	--	--	--	--	--	--	50.3	.89	18
OS_2	18.6	.801	--	-.250	--	--	--	--	--	46.6	.91	18
OS_3	16.8	.969	--	-.272	--	--	--	--	-.491	46.2	.92	18
OS_4	7.20	.814	--	-.258	.323	--	--	--	-.543	45.9	.92	18
Pink and chum, OPC_1	11.5	.631	--	--	--	--	--	--	--	30.1	.92	33
OPC_2	3.75	.461	--	--	.385	--	--	--	--	27.8	.93	33
OPC_3	.941	.445	--	--	.480	.291	--	--	--	27.4	.94	33
OPC_4	.771	.464	--	--	.517	.350	--	--	-.263	26.9	.94	33
OPC_5	.425	.411	.110	--	.498	.369	--	--	-.236	26.7	.95	33
Mean of species, OM_1	9.32	.675	--	--	--	--	--	--	--	36.8	.91	53
OM_2	2.64	.457	--	--	.470	--	--	--	--	33.2	.93	53
OM_3	3.30	.469	--	-.065	.484	--	--	--	--	32.8	.93	53
OM_4	2.24	.470	--	-.091	.524	--	.101	--	--	32.6	.93	53
OM_5	2.00	.469	--	-.094	.552	--	.125	-.206	--	32.4	.94	53
OM_6	1.05	.456	--	-.087	.587	.131	.143	-.199	--	32.3	.94	53
Rearing:												
All species, R_1	2.53	.867	--	--	--	--	--	--	--	62.1	.87	53
R_2	.084	.543	.649	--	--	--	--	--	--	53.4	.90	53
R_3	.032	.327	.533	--	.591	--	--	--	--	49.6	.92	53
R_4	.026	.301	.683	-.124	.564	--	--	--	--	48.7	.92	53

[a] Subscripts denote number of independent variables.

SPAWNING FLOW CRITERIA

Techniques used to obtain spawning criteria differ somewhat, at least conceptually. Depth velocity measures can be collected from known suitable spawning areas or directly from active redds. One of the major problems with determining criteria is taking measurements that reflect the true hydraulic conditions of spawning reaches. Subtle velocity and/or substrate differences may occur between the macroenvironment of a spawning reach and the microenvironment of the actual area selected for the redd. If this is the case conditions measured over the reach may not provide accurate species spawning criteria. The converse is also true that construction of the redd may alter conditions in the immediate area resulting in velocity measurements not truly representative of the reach.

To develop accurate spawning criteria, measurements must be taken over a wide range of hydraulic conditions. If this is not undertaken, criteria will not be representative of species preference, but only of reactions to the specific stream conditions sampled. This is a valid consideration for measurement of both actual redd conditions or of spawning reaches. This is not to say that, at the present level of criteria development, any and all data are not useful, but that criteria determined from a narrow or restricted set of conditions must be considered in that context. Measurements from streams with limited ranges of hydraulic conditions may account for actual spawning site similarities between species known to have different velocity preferences. Most species of fish will spawn with some degree of success, where hydraulic, substrate and temperature conditions fall within a suitable set of limits. However, the conditions at the actual spawning site may be quite different from those the fish would select if presented with a wide range of choices.

When establishing spawning flow criteria (depth and velocity), it is advisable (although often unfeasible) to obtain data from fish of the same species, of similar size and under similar hydraulic and hydrologic conditions. The level of criteria precision drops when data are extrapolated across a range of species, fish sizes and basin or watershed conditions. Hunter (1973), speaking of salmonids, states that:

> most species have a fairly wide range of acceptable conditions with minimum water depth and maximum water velocity being governed largely by the size of the fish. Variations in preferences are greater between fish of one species when they are of different size (ex. an 8-inch vs. an 18-inch kokanee) than between fish of different species the same size (ex. 10 to 12-inch rainbow, cutthroat, brook and kokanee). (Hunter, 1973:23)

That fish size is an important consideration for determining spawning requirements cannot be disputed. However, inherent differences in the stamina levels of fishes (especially evident in anadromous salmonids) have also been shown by Paulik (1959). This variation could be thought of as an adaptive response to differing flows, therefore velocity, and must be considered in establishing species requirements.

Sams and Pearson (1963) established, for the Oregon Fish Commission, spawning flow criteria for four anadromous salmonids by measuring depth and average velocity in the water column over active redds in four streams in the Willamette River basin. During this study, a single measurement of the depth and velocity was obtained at a point one foot upstream of each redd in order to minimize the influence of redd construction and to approximate conditions before spawning. The velocity was determined as the average velocity in the vertical column by using the 0.6 depth (below surface level) point of measure for depths under two feet and the two-point method for depths greater than two feet.

Of the two factors examined, velocity was considered the more important. Measured velocities and minimum depths of 0.6 feet for chinook and 0.5 feet for coho and steelhead were selected for criteria. These depths were suggested as sufficient to allow the fish to effectively escape predators and to afford protection from the elements.

Smith (1973) developed depth velocity criteria for the Oregon Game Commission based on data collected statewide from 1961 to 1971. Depths were taken over undisturbed gravel just above the upstream edge of the redd. Velocities were measured 0.4 feet (0.12 m) over the same location.

Delisle (1962) added some interesting and useful data on kokanee salmon depth velocity criteria. In a California stream (Plumas Co.), Delisle found spawning kokanee using only the left half of a pool to the complete exclusion of right side use. Conditions (depth, substrate) were similar on both sides (the shading factor, if any, was not indicated) of the pool. Delisle reports a distinct line of demarcation between the sides of the pool, with the used side exhibiting consistently lower velocities (measured at 0.20 ft from stream bottom) than the unused side (Table 4). Since

Table 4. Depth and velocity of water in relation to kokanee spawning in one pool in a California stream (from Delisle, 1962).

Left Side Spawning		Right Side No Spawning	
Depth (ft)	Velocity (fps)	Depth (ft)	Velocity (fps)
1.6	1.50	2.0	2.19
1.5	1.75	2.0	2.19
1.7	1.83	2.0	2.43
1.6	1.91	2.0	2.66
2.0	1.95		
1.8	2.15		

kokanee appear to have lower spawning velocity requirements (Table 5), in some cases essentially zero, Delisle's observations may represent an upper limit of kokanee spawning velocity tolerance.

The Washington Department of Game has conducted a large number of depth and velocity measurements of salmonid redds (Hunter, 1973). These measurements were taken to establish salmonid spawning criteria by evaluating velocity differences at varying depths and positions around the redd. All of the values were obtained from active redds. Velocity measurements were taken approximately 0.5 ft upstream from the pit of the redd and at depths of 0.25 ft (for fish less than 4 lbs) and 0.4 ft (fish heavier than 4 lbs) above the substrate to adjust to a "nose-level" velocity for different size fish. Depth measurements were taken, to the nearest 0.1 ft, at the pit, tailspill and each side of center. Field experiments were carried out to determine: 1) The relationship between velocities at the 0.25 ft and 0.4 ft depths above stream bottom; 2) to evaluate the theory that velocities taken 0.5 ft upstream from the head of a trout redd are different from those at the initial point of redd construction; and 3) to determine the difference between upstream velocities of a steelhead redd at the point of initial excavation. Other measurements included redd length and area, water temperature and gravel size. Velocity correction factors were developed to allow for comparison 1) between velocities at the 0.25 and 0.4 ft levels (0.15 fps added to 0.25 ft velocity data), 2) between velocities upstream (0.5 ft) and downstream (3.0 ft) from the redd (0.1 fps for small redds and 0.2 fps for larger redds, added to upstream data), and 3) between velocities at the head of a steelhead redd and the point of original construction (0.3 fps added to upstream data). Suggested depth velocity criteria are listed in Table 5 along with others reported in the literature.

SPAWNING FLOWS DETERMINED FROM HYDRAULIC PARAMETERS MEASURED ALONG TRANSECTS

The Oregon Department of Fish and Wildlife personnel have developed a spawning flow methodology based upon field studies begun in 1961 (Thompson, 1972). This approach is referred to as the "usable width" analysis and was used as early as 1954 by fishery biologists in Washington (Sams and Pearson, 1963). The procedure is summarized as follows: 1) Three gravel bars are selected which are representative of those found in the study stream; 2) a straight-line transect is established across each gravel bar over the prime spawning area. These transects are not necessarily perpendicular to the flow; 3) at each of several flows, evenly spaced measurements (usually 9) of depth and average velocity in the vertical water column are made along the transect; 4) a velocity distribution curve (Figure 5) is drawn for each cross

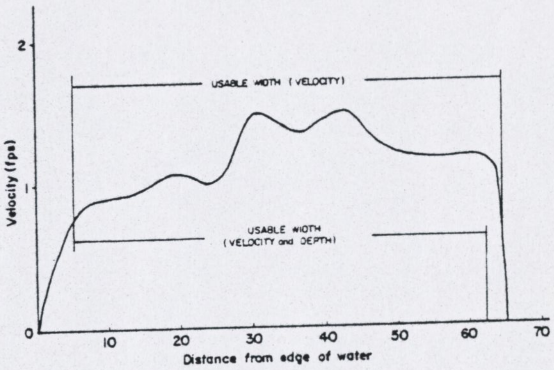

Figure 5. Representative velocity distribution curve for determining usable width (from Sams and Pearson, 1963).

section. The total portion (usable width of the transect) is measured where conditions are suitable for spawning based upon depth velocity criteria for the species present; 5) a usable width curve is then plotted with the percent of total usable width (usable width/total width) on the ordinate and flow volumes (discharges) on the abscissa (Figure 6).

An optimum spawning flow is that which provides suitable flow depth and velocity conditions over the most gravel. The discharge which created suitable flow conditions over 80 percent of the

Table 5. Reported spawning depth velocity criteria.

Species	Depth (Meters)	Depth (Feet)	Velocity (cm/sec)	Velocity (ft/sec)	Reference
Coho		1.0-1.25		1.2-1.8[a]	Chambers et al., 1955
Coho		0.3-1.90		0.50-3.0	Sams and Pearson, 1963
Coho		0.6		1.0-3.0	Thompson, 1972
Coho	.15[b]		21-70		Smith, 1973
Pink		0.5-1.75		0.7-3.3[a]	Collings, 1974
Chum		0.5-1.75		0.7-3.3[a]	Collings, 1974
Chum	.18[b]		46-101		Smith, 1973
Chum		0.6		1.5-3.2	Thompson, 1972
Fall Chinook		1.0-1.5		1.0-2.25[a]	Chambers et al., 1955
Fall Chinook		0.3-1.5		0.90-3.10	Sams and Pearson, 1963
Fall Chinook		0.8		1.0-3.0	Thompson, 1972
Fall Chinook	.24[b]		30-76		Smith, 1973
Spring Chinook		1.5-1.75		1.75-2.27[a]	Chambers et al., 1955
Spring Chinook		0.3-2.0		$<$0.43-2.80	Sams and Pearson, 1963
Spring Chinook		0.8		1.0-3.0	Thompson, 1972
Spring Chinook	.18[b]		21-64		Smith, 1973
Sockeye		1.0-1.5		1.75[a]	Chambers, et al., 1955
Sockeye		– –		1.75-1.8[a]	Clay, 1961
Kokanee		0.4-0.6		0.8-2.1	Thompson, 1972
Kokanee	0.06[b]		15-73		Smith, 1973
Kokanee		$>$0.2		0.4-2.39	Hunter, 1973
Kokanee		0.4-0.6		0.8-2.1	Thompson, 1972
Steelhead		0.6		1.0-3.0	Thompson, 1972
Steelhead		1.27		1.2-3.4	Hooper, 1973
Steelhead	.24[b]		40-91		Smith, 1973
Steelhead		$>$0.5		1.27-3.18	Hunter, 1973
Steelhead		0.4-2.3		1.2-3.57	Hunter, 1973
Rainbow Trout		0.7-1.1		1.4-2.7[c]	Hooper, 1973
Rainbow Trout	.15		43-82		Bovee, 1974
Rainbow Trout		.29-3.0		.69-3.0	Waters[d]
Rainbow Trout		0.6-1.1		1.4-2.98	Hunter, 1973
Cutthroat Trout		––		1.0-3.0	Hooper, 1973
Cutthroat Trout		0.2-1.5		.35-2.37	Hunter, 1973
Brown Trout		$>$0.8		.67-2.5	Hunter, 1973
Brown Trout		––		$>$1.5[e]	Hoppe and Finnell, 1972
Brown Trout		0.8		0.7-2.1	Thompson, 1972
Brown Trout		––		1.0-3.0[f]	Hooper, 1973
Brown Trout	.15		40-52		Bovee, 1974
Brown Trout	.24[b]		21-69		Smith, 1973
Brook Trout	9.0[b]		1-23		Smith, 1973
Brook Trout		––		0.2-3.0	Hooper, 1973
Brook Trout	.15		15-91		Bovee, 1974
Brook Trout		0.3-2.0		0.03-2.1	Hunter, 1973
Dolly Varden		0.7-1.4		1.13-2.15	Hunter, 1973
Grayling		$>$0.4			Hunter, 1973
Whitefish		$>$0.4			Hunter, 1973
Paddlefish	variable		49-91		Bovee, 1974
Shovelnose Sturgeon	0.3-0.9		75-150		Bovee, 1974
Lake Sturgeon		2.0-15.0		––	Carlander, 1969
Lake Sturgeon	0.6-4.6		––		Scott and Crossman, 1973
Sturgeon, Russian sp.		5.0-16.4		2.3-3.6	White[g]
Creek Chub	––		49-91		Bovee, 1974
Longnose Dace	.03-0.3		15-45		Bovee, 1974
Longnose Sucker	0.2-0.3		31-45		Bovee, 1974
White Sucker	0.2-0.3		31-45		Bovee, 1974

Table 5. Continued.

Species	Depth (Meters)	(Feet)	Velocity (cm/sec)	(ft/sec)	Reference
Shorthead Redhorse	0.3-0.9		31-61		Bovee, 1974
Smallmouth Bass	0.9-1.8		11		Bovee, 1974
Smallmouth Bass		2.0-20.0		--	Scott and Crossman, 1973
Largemouth Bass	0.3-.18		Still		Bovee, 1974
Walleye	1.2-1.5		0-50		Bovee, 1974
Sauger	1.2-1.5		0-50		Bovee, 1974

[a]Measured at 0.4 feet above streambed.

[b]Minimum.

[c]Measured at 0.20 feet above streambed.

[d]Unpublished data. 1975. Brian Waters, Pacific Gas and Electric Co.

[e]Measured at 0.6 water depth from flow surface.

[f]Measured at 0.25 feet above streambed.

[g]Draft proposal. 1975. Robert White, FWS.

> gravel available at an optimum spawning flow [is the] recommended minimum spawning [flow]. Thompson, 1972:33)

Unless an extremely wide range of velocities are used as the criteria for the usable width analysis, a definite peak will occur on the usable width curve. This peak represents the optimum spawning flow (Figure 6).

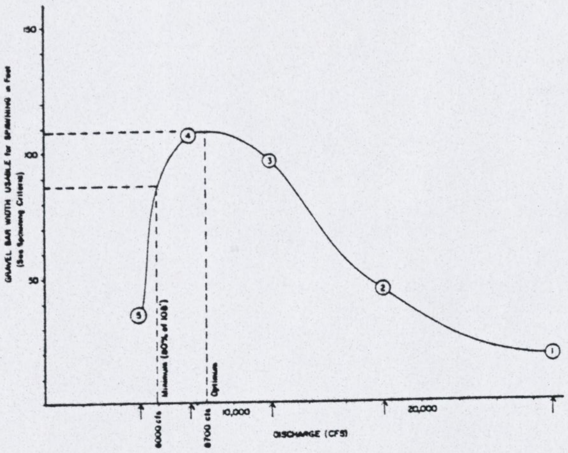

Figure 6. Representative usable width curve (from Thompson, 1974).

Sams and Pearson (1963) advocate a "weighted usable width" analysis based upon average velocity measured over the redds intersected by the transects and from which weighted velocity distribution tables are constructed (Table 6). The transect distance (width) which falls into a particular velocity category is multiplied by a factor from the weighted velocity table for the species in question. The transect distances are then summed to obtain the weighted usable width at each flow. Optimum flows are then determined as above for the "usable width" analysis.

The usable width approach to spawning habitat analysis has also been applied in Idaho to the Salmon River and tributaries (Munther, 1975) and the Snake River (Thompson, 1974) and tributaries.[12]

Sams and Pearson calculate a minimum spawning flow as that point on the usable width curve (when the ordinate is expressed as a percentage) which is tangent to a line drawn through the origin (Figure 7).

An "average velocity analysis" described by Sams and Pearson (1963) averages the velocities for all cross sections and plots those average velocities along the ordinate, and the flow volume, (discharge) along the abscissa (Figure 8). Optimum spawning flow is then read directly from the graph as the discharge corresponding to the mean velocity of all measurements over redds. Sams and

[12]Personal communication. 1975. Richard Nadeau, FWS, Boise, Idaho.

Table 6. Weighted velocity tables for spring and fall chinook, coho salmon and steelhead trout (from Sams and Pearson, 1963).

	Velocity Categories (fps)	Weight[a] Factor
Spring Chinook Salmon	0.25-0.65	0.1
	0.65-0.75	0.4
	0.75-0.85	0.8
	0.85-1.85	1.0[b]
	1.85-1.95	0.9
	1.95-2.05	0.6
	2.05-2.25	0.5
	2.25-2.55	0.2
	2.55-2.85	0.1
Fall Chinook Salmon	0.90-1.10	0.2
	1.10-1.40	0.6
	1.40-2.20	1.0
	2.20-2.50	0.4
	2.50-2.90	0.2
	2.90-3.10	0.1
Coho Salmon	0.45-0.55	0.1
	0.55-0.85	0.2
	0.85-1.05	0.6
	1.05-1.25	0.8
	1.25-1.65	1.0
	1.65-1.95	0.8
	1.95-2.25	0.4
	2.25-2.45	0.2
	2.45-3.05	0.1
Steelhead Trout	1.20-1.50	0.4
	1.50-2.40	1.0
	2.40-2.80	0.6
	2.80-3.40	0.2

[a]"Weight factors were calculated from the frequency distribution of the velocity measurements for each species" (Sams and Pearson, 1963:30).

[b]Average velocity has a weight of 1.0.

Pearson (1963) recommend that measurements be taken at five or more flows to assure obtaining flow volumes above and below preferred spawning velocities. However, if a high degree of precision is not required, it is possible to construct velocity discharge curves from measurements at only two or even one flow (discharges) by using techniques described in Section 2—e.g., by interpolation from a velocity discharge curve for which the discharge values have been predicted by mathematical formula [i.e., $Q = KD(1 + w/10)^{3/2}$]. This could result in a significant saving of time in that detailed velocity measurements need be made along only one transect with depth measurements at the others.

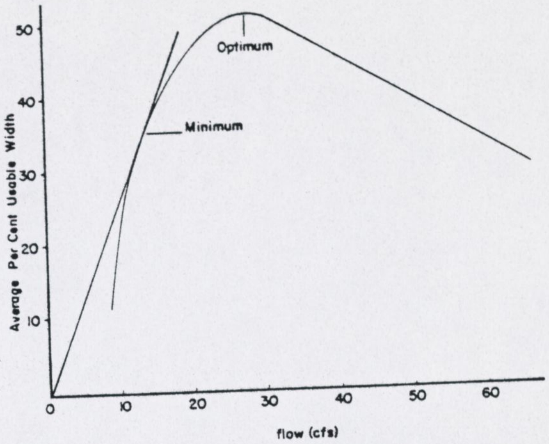

Figure 7. Representative weighted usable width curve for determining optimum and minimum spawning flows (from Sams and Pearson, 1963).

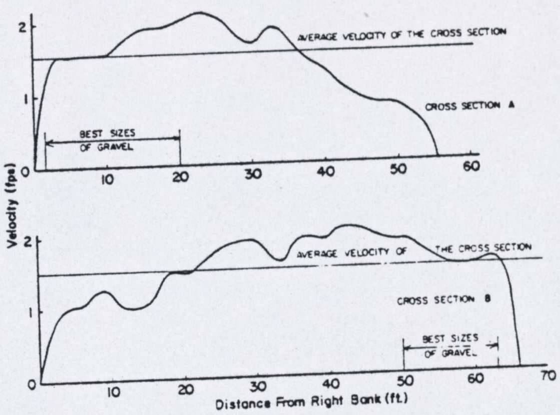

Figure 8. Representative curve showing relation of average velocity to other velocities in two cross sections (from Sams and Pearson, 1963).

A transect method utilizing weighted depth velocity criteria for evaluating rainbow trout spawning habitat has been developed for use in California streams as a result of the combined efforts of personnel from Pacific Gas and Electric Co., California Fish and Game Department, FWS, and USFS.[13] Transect stations are established below a control structure on the stream to be studied and four or more flows are released and

[13]Personal communication. 1975. Charles Fisher, California Fish and Game, Sacramento, California

appropriate measurements are taken including velocity at 0.2 feet from the bottom. Utilizing weighted depth velocity criteria (Table 7), curves are generated depicting the relationship between spawning habitat and discharge at each transect station. From these curves, optimum spawning flows as well as the effects on relative units of stream bed area providing spawning habitat can be evaluated over the range of discharges examined. Spawning habitat is usually examined along with resting microhabitat, bottom type, food producing areas and a subjective cover evaluation (see discussion under specific sections). Waters has developed a computer program which utilizes weighted depth velocity criteria for spawning, food production and microhabitat curve generation.[14]

Table 7. Spawning criteria and weighting factors as used for rainbow trout in the Pit River, California.[a]

Velocity (fps at 0.2′ from bottom)		Depth (at 0.2′ from bottom)		Substrate	
Range (fps)	Weighting Factor	Range (ft)	Weighting Factor	Type	Weighting Factor
0.00-0.69	none	0.00-0.29	none	gravel	1.0
0.70-0.79	0.1	0.30-0.39	0.2	others	none
0.80-0.89	0.3	0.40-0.49	0.4		
0.90-0.99	0.4	0.50-0.59	0.7		
1.00-1.09	0.5	0.60-0.69	0.8		
1.10-1.19	0.6	0.70-0.79	0.9		
1.20-1.39	0.7	0.80-1.29	1.0		
1.40-1.59	0.8	1.30-1.79	0.9		
1.60-1.89	0.9	1.80-2.09	0.8		
1.90-2.29	1.0	2.10-2.29	0.7		
2.30-2.49	0.9	2.30-2.49	0.6		
2.00-2.59	0.8	2.50-2.69	0.5		
2.60-2.69	0.7	2.70-2.79	0.4		
2.70-2.79	0.6	2.80-2.89	0.3		
2.80-2.89	0.4	2.90-3.00	0.2		
2.90-3.00	0.2	3.01 →	none		
3.01 →	none				

[a]Unpublished data. 1975. Brian Waters, Pacific Gas and Electric Co.

Sams and Pearson (1963) discuss a method for assessing spawning flows when only one discharge can be observed. One technique is based upon the average stream width being similar to the average pool width. A one-mile reach of stream is selected which is assumed to be representative of the stream as a whole. The stream width is measured at one hundred-foot intervals and the average pool width determined. The average pool width is multiplied by the average depth and average velocity of measurements obtained over redds of the species in question. The optimum spawning flow is determined from the following formula:

$$Q = WDV \quad \text{(8)}$$

in which W is the average pool width, D is the average depth measured over the redds, and V is the average velocity measured over the redds.

Hoppe[5] proposes an ocular estimation for trout spawning flows. This technique requires that an experienced biologist locate *the* spawning bar most critical for reproduction (critical spawning habitat) in the stream examined. The water stage necessary to cover the suitable spawning gravel to a depth of one foot is visualized. Then the stream width (W) and average depth (D) are estimated and used in Equation 8 along with 2 fps representing the desired velocity (V) to quickly calculate Q as the minimum spawning flow.

[14]Personal communication. 1975. Brian F. Waters, Pacific Gas & Electric Co., San Ramon, California.

SPAWNING FLOWS DETERMINED FROM MEASURED HYDRAULIC PARAMETERS AND PLANIMETRIC MAPPING

The Washington Department of Fisheries has developed a method for assessing spawning discharges which has evolved from the work of Westgate (1958), Rantz (1964), Deschamps et al. (1966), Collings (1972), and Collings et al. (1972a). This methodology is summarized by Bishop and Scott (1973) and Collings (1974). The steps in applying this approach are as follows: 1) Three study reaches are selected on the stream based upon known spawning activity, channel stability and representativeness; 2) four cross sections are established on each reach and the entire reach mapped (to the bankful level) for depth and velocities by plane-table methods; 3) mapping is completed at each of several discharges (usually 10) by measuring depth and velocity at 10 to 25 points along each cross section; 4) isolines of equal depth and velocity are drawn on each map and the areas with preferred depth and velocity ranges (as determined from data similar to that in Table 5) are cross-hatched (Figure 9); 5) the suitable spawning area is measured for each discharge level by the use of a

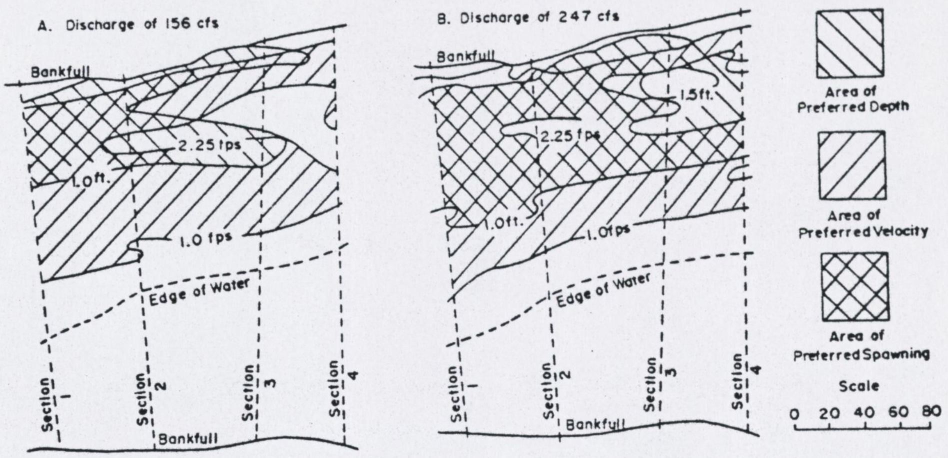

Figure 9. Example of planimetric maps for determining area of study reach preferred for spawning at two discharges. A. At discharge of 156 cfs, 15.5 percent of the bankfull area has preferred depths, 37 percent has preferred velocities, and 12.2 percent has area that is preferred for spawning. B. At discharge of 247 cfs, 33.4 percent of the bankfull area has preferred depths, 43.5 percent has preferred velocities, and 25.5 percent has area that is preferred for spawning (from Collings, 1974).

planimeter. A spawning area-discharge curve is drawn for each study reach as shown in Figure 10. The apex of the spawning area-discharge curve is considered the optimum or preferred spawning discharge.

This methodology recommends that a sustaining-spawning discharge be set no lower than 75 percent of the optimum spawning flow (Figure 11). This point can be approximated by examining the point on the spawning area-discharge curve which is tangent to a line drawn through the origin (see Figure 7 as well as Figure 11).

Critique

Existing watershed-discharge predictive models for salmonids appear to be adequate for reconnaisance studies given the associated error range. Additional validation of predictive models based upon hydrologic data is needed and regression "constants" and "coefficients" should be developed and standardized for stream situations within each major physiographic region (similar geomorphic type).

The described methods could be applied to any river system provided the species criteria were

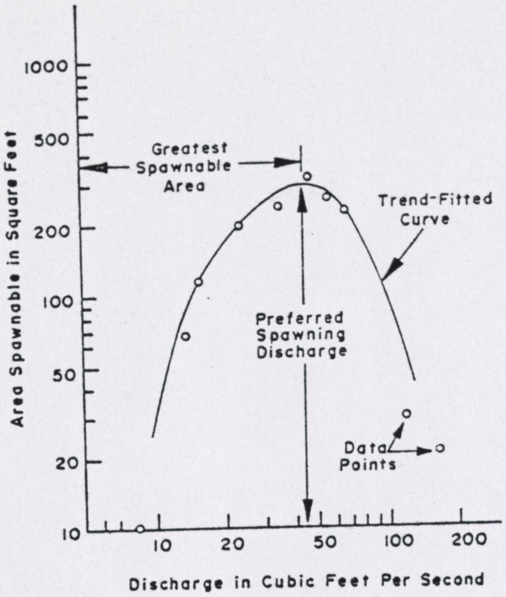

Figure 10. Representative spawning area-discharge curve (from Bishop and Scott, 1973).

known, e.g., preferred substrate, flow orientation, depth velocity, cover as well as seasonal and temporal requirements.

The suitability of any spawning habitat analysis and flow recommendation is ultimately dependent upon the adequacy of the criteria selected for the recommendation. Criteria for salmonids have been adequately translated into depth velocity values. However, the basic assumption of any spawning habitat analysis is that any radically changed flow regime will result in a paucity of suitable spawning areas, thereby limiting the population size of the species present. Extreme caution must be exercised before choosing any of the previously discussed "spawning flow" methodologies for sole use in recommending instream flows. In many cases, cover, resting microhabitat or food production may become limiting with changed flow regimes before reproduction (spawning and incubation).

Once spawning is established as the, or at least one of the, limiting factors associated with flow alteration, the presently used transect and map-

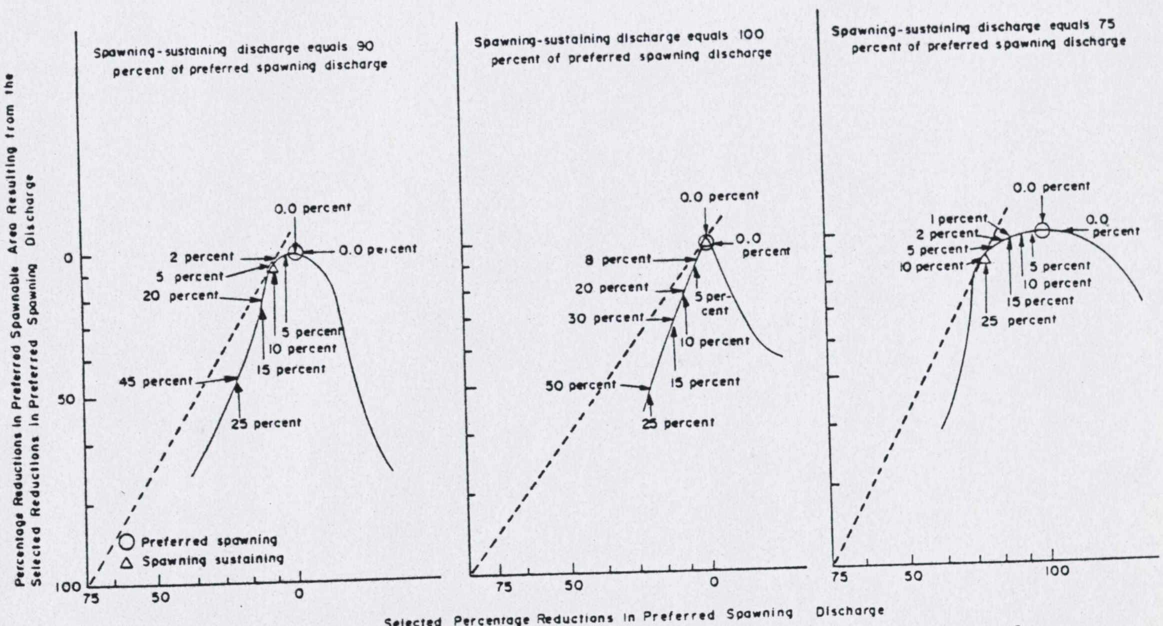

Figure 11. Graphical method of determining preferred and spawning-sustaining discharges from curves of discharge versus area of reach spawnable. Spawning sustaining discharge is chosen where the percentage reduction in spawnable area is less than or equal to the selected percentage reduction in discharge, or at the 25-percent-discharge-reduction level. Preferred spawning discharge is selected at the highest point on the curve (from Collings, 1974).

ping techniques can be applied to limited and intensive on-site field analyses, respectively.

Although presently used for salmonid species, the same techniques could be applied to any riffle spawning species. However, the state-of-the-knowledge for most other stream fishes is very sparse. Suitable depth velocity-substrate criteria must be identified before these techniques can be applied to warm water streams.

A basic assumption of the "usable width" techniques is that the greater the area available, within selected depth velocity limits, the better the conditions for spawning. A further implication that one may be led to is that the greater the spawning area, the better the reproduction, year class strength, etc. This is not necessarily true unless one also considers the intragravel conditions important to incubation and fry survival and other possible limiting factors. At least superficial examination of gravel compaction and permeability *must* accompany any field spawning habitat analysis. As has been pointed out by Sams and Pearson (1963), the range of velocity criteria chosen has a large impact upon the apex of a usable width curve and, consequently, any optimum spawning flow recommendation. Therefore, the best approach is the "weighted usable width" assigning the mean velocity a value of one and utilizing the entire range of acceptable values. Consistency would be achieved by adoption of a specified range and mean of velocities for each target species, and with a subset for each of several fish size categories. In other words, the same criteria would not necessarily be best for trout in an alpine stream and for the same species in a large river simply because the average size of the spawners would be very different.

One additional assumption inherent in the "average velocity" analysis is, when the average velocity of a cross section is equal to the mean velocity as measured over the redds (average velocity criterion) the cross-section stage and discharge are at optimum conditions for spawning. If substrate conditions are suitable and the velocity criterion is truly average for the fish present in the stream, this assumption appears valid. Given a proper set of correction factors to allow for differences in fish size, the "average velocity" analysis appears just as reliable as the usable width analyses.

The average stream width analysis appears to have potential application at the reconnaissance level on streams large enough to obtain width measurements from aerial photos. At the field measure level, the resolution would be much lower than the transect or mapping techniques, thus making its use unwarranted.

Given the same arguments and corrections mentioned above, the planimetric mapping technique, although more time consuming, should give higher resolution than the transect measure techniques. This method can be readily adapted to other reaches and applications, i.e., microhabitat, insect production, etc., given suitable depth velocity criteria.

Incubation Flows

The flows necessary for egg incubation are determined by a complex and poorly understood set of interactions between surface flows (sufficient to cover redds and influence gravel temperature) and the intragravel environment (dissolved oxygen and water movement). Little definitive information is available concerning the specific flow criteria for the incubation needs of fish species other than salmonids. Most workers do not attempt to deal specifically with incubation, but relate it to spawning flows on the assumption that flows suitable for spawning will be suitable for incubation, e.g., The State of Washington, Department of Fisheries (Bishop and Scott, 1973). Other aquatic biologists recommend incubation flows on the basis of experience and judgment and do not depend on collection of field data. The Oregon Department of Fish and Wildlife takes this approach to determine incubation flows by a combination of biological judgments and field observations.

> At each of several flows, an estimate is made of the flow required to cover gravel areas used for spawning and to create an intra-gravel environment conducive to successful egg incubation and fry emergence. The flow recommended is that which the various observed estimates seem to indicate. This generally is equivalent to about two-thirds the flow required for spawning. (Thompson, 1972:44)

Intragravel rates of flow, exchange of flowing stream and gravel water, and dissolved oxygen levels are known to be of importance during the incubation period. Coble (1961) found a positive correlation between intragravel dissolved oxygen and survival of steelhead embryos. Techniques, such as the standpipe principle pioneered at the Nanaimo, B. C. Biological Station (Wickett, 1954) and refined by Terhune (1958), are available for the determination of intragravel flows and oxygen levels (Pollard, 1955; Gangmark and Bakkala, 1958; Sheridan, 1962; and Thompson, 1974).

Terhune (1958) describes the standpipe technique for measuring the permeability of stream bed gravel. A length of steel pipe 1 1/4" diameter and perforated for its lower 2 inches is driven into the gravel to a depth of 10 inches. The water level in the pipe is lowered to a fixed amount, Δ h, and the resulting inflow rate is measured (units are cm/hr). Apparent velocity in cm/hr can then be estimated as follows:

$$V = KS \qquad (9)$$

in which V = velocity (cm/hr), K = permeability of the gravel (cm/hr) and S = the hydraulic gradient or slope of the water surface or the difference in height ($h_1 - h_o$) in a distance L; S = $\Delta h/L$.

Gangmark and Bakkala (1958) related velocities of 3.9 ft/hr through redds and dissolved oxygen contents of 8 ppm with the highest salmon egg survival. Chambers et al. (1955) report dissolved oxygen content higher in areas where salmon spawning was successful (5.70 - 9.10 ppm) than where it was not (0.10 - 6.75 ppm), Wickett (1954) found significantly increased egg survival at 10 cm/hr as opposed to 8 cm/hr.

Sams and Pearson (1963) reported chinook salmon fry survival of approximately 30 percent in a spawning channel with a mean permeability of 60,200 cm/hr in 1961-62 and a survival of only 11 percent in the same channel in 1962-63 when the mean permeability was 9,400 cm/hr. They also found that permeabilities were much higher in stream spawning areas that remained wet all year (means of 3,213 and 3,599 cm/hr) as opposed to those that were dry part of the year (means of 321 and 542 cm/hr).

Intragravel movement of water (percolation/velocity) in low gradient streams is attained by way of hydraulic shear (laminar shear force) on the the stream bottom. Hydraulic shear in the region of laminar flow (at the water-stream-bed interface) is a function of the dynamic viscosity of water and the change in velocity with respect to the change in laminar flow depth (Chow, 1964; Hoppe and Finnell, 1970).

$$T_{\ell} = \gamma \frac{dx}{dy} \qquad (10)$$

in which T_{ℓ} = laminar shear force, γ = dynamic viscosity of water, dx = change in velocity, dy = change in depth of laminar flow.

In natural stream channels, the change in laminar flow depth (dy) can be considered zero at less than critical velocity: Critical velocity levels change (reduce) laminar flow depth as a function of increased turbulence. T_{ℓ} then becomes the product γdx. It is clear that hydraulic shear (and therefore water percolation) is directly dependent upon velocity, particularly in those reaches with little or no groundwater (accretion) flows.

Although the exact relationship between criteria of this type and stream surface flow has not been precisely determined, general knowledge of the subsurface requirements for incubation has formed the basis for a limited translation of incubation criteria into flow recommendations. A common assumption is that reductions in surface water from spawning levels will not reduce incubation potential as long as the redds are covered by some water and oxygen is sufficient (Savage, 1962).

A study evaluating water requirements of the Hells Canyon reach of the Snake River utilized a combination of data types to recommend incubation flows. Surface flow conditions that were considered necessary to maintain a suitable intragravel incubation environment were related to data obtained on the spawning/incubation river reach. Since spawning and incubation criteria were considered quite similar, much of the same data was used interchangeably to arrive at flows. Locations of redds were related to stage and reduced discharge. Determination of intragravel dissolved oxygen at various surface flow depths and eyed eggs planted in selected reaches (for dewatering survival) were combined to determine flow recommendations. Distribution of spawning gravel was the most important factor influencing surface flow recommendations. The basic criterion for incubation flows was maintenance of 5.0 ppm intragravel dissolved oxygen in the gravel available at spawning flows. Incubation flow levels were determined by the flow range during spawning, e.g., if the spawning flow was above the minimum, incubation flows were adjusted upward (Thompson, 1974).

Critique

Some agencies consider passage or spawning flows, or a percentage of them, to be suitable for incubation of salmonid eggs. This approach involves no additional field work and is adequate for reconnaissance studies.

Techniques exist for determining intragravel conditions in redds and data for establishing criteria are available. An exception is in the quantification of hydraulic shear (tractive forces) necessary for maintaining sufficient percolation levels through the stream bed. This is an area where additional research is needed. The limitation of most approaches to incubation flows is the lack of data concerning the relationship of discharge to redd environment (intragravel flow-channel flow exchange, stream bed particle size, etc.). This limitation is evident in methods that consider only depth, velocity, and dissolved oxygen content of the water over the spawning gravel without examining the broader effects of flow regimes to establish a functional data base for generalizations. As a result, all incubation flow studies are, of necessity, intensive, and intragravel reconnaissance studies are not feasible at the present level of methodology development.

The influence of reservoirs must be taken into consideration when recommending incubation flows. The presence of a dam effectively traps recruitment bedload while allowing the downstream movement of existing sand and gravel below the dam. Consequently, gravel permeability may be greatly altered below dams and higher discharges may be required after reservoir construction for incubation of salmonid eggs. Also, under conditions of low velocity, permeability may be decreased as a result of fines settling from the slower water.

As was pointed out by Sams and Pearson (1963), cross sections to be used in flow determinations should be selected so they include spawning areas which have a convex bottom (stream gradient decreases in the direction of flow) to insure that water interchange is upwards, i.e., intragravel to stream.

When assessing augmented discharge, flows must be recommended that do not force the spawners from the main channel (due to excessive velocities) to the edge of the stream where gravel size is usually small and permeability lower, nor should flows be high enough to cause bedload movement during incubation (resulting in redd distruction). Because of the direct relationship of velocity and permeability, attention must be given to the effects of high flows on hydraulic shear; therefore, water exchange through the gravel, e.g., high (above critical) velocities may radically change permeability.

Considering the close relationship between incubation and spawning requirements for salmonids, the present techniques of flow analysis seem adequate until further refinement is undertaken. However, this can be assumed only when the spawning areas are continually wet throughout the year. If spawning and incubation flows were set at one water stage and lower stages were allowed at other times (i.e., during winter low flows), the permeability of the gravel could be lowered so that a given discharge might be adequate for spawning, but not sufficiently high for survival of incubating eggs.

Existing information is based almost entirely on salmonid research, resulting in a significant lack of data on the requirements for warm-water fish incubation, i.e., flows necessary to keep the gravel surface clean for riffle spawners, minimum velocities to maintain semibouyant eggs suspended in the current (e.g., striped bass), and adequate exchange over the mudwater interface for broadcast spawners when their eggs settle in pools.

Rearing Flows

Rearing refers to all requirements for successfully completing the life history stages from hatching to spawning age. For most stream fishes, this includes several size and age classes. Adequate flows and suitable water quality must be available for food production, instream microhabitat, cover, and maintenance of the riparian habitat. Existing methodologies for assessing these needs will be discussed under the headings of *Fish Food Production (Benthic Insect), Riffle Analysis, Microhabitat and Cover,* and *Total Usable Habitat.*

FISH FOOD PRODUCTION (BENTHIC INSECT)

It is generally accepted (although not well documented) that riffles are more productive of invertebrate species than are pools (Giger, 1973a), and pools with larger upstream riffles are more productive than pools with smaller upstream riffles (Pearson et al., 1970). Macan (1961, 1962) has reviewed considerable work which relates stream velocity to the abundance and distribution of benthic insects. Aquatic insect drift is a function of transport from riffles to pools with a positive correlation between current velocity and quantity of drifting insects (Waters, 1969; Giger, 1973a). McClay (1968) reported significant differences in numbers of aquatic insects in a test riffle before and after a 75 percent dewatering. Brusven et al. (1974), after examining benthic insect standing crop in the Snake River at five different discharges, concluded that:

> . . . the question of minimum flow is of secondary importance to water fluctuation which causes ecological instability to the biota exposed during dewatering as well as deeper zones through disruption of normal photosynthesis and decomposition processes. (Brusven et al., 1974:78)

Based upon these premises and depth velocity data (Table 8), the following methods have been utilized for assessing flows necessary for production.

Table 8. Reported aquatic insect depth velocity criteria.

	Preferred Velocity (fps)			
Species or Group	Mean or Median	Range	Depth (ft)	Reference
Aquatic				
Invertebrates	2.0	0.5-3.5		Surber, 1951
		2.0-3.5		Needham and Usinger, 1956
	2.0	0.5-4.0		Pearson et al., 1970
	1.2	0.5-3.0	0.25-0.5	Kennedy, 1967
		1.5-3.5	0.5 -3.0	Hooper, 1973
Ephemeroptera				
		1.2-2.6	<1.0	Needham and Usinger, 1956
			0.5-1.0	Hooper, 1973
Rhithrogena	4.0		deep	Needham and Usinger, 1956
	2.3	1.23-3.37		Arthur, 1963
Baetis	2.02	1.02-3.02		Arthur, 1963
	3.0			Needham and Usinger, 1956
Ephemerella	1.93	1.03-2.83		Arthur, 1963
Plecoptera				
Arcynopteryx	1.58	0.89-2.27		Arthur, 1963
Tricoptera				
	3.0	1.0-2.0		Hooper, 1973
		1.0		Needham and Usinger, 1956
Hydropsyche	2.35	1.03-3.67		Arthur, 1963
Diptera				
	3.0			Needham and Usinger, 1956
		0.5-1.0		Hooper, 1973
Simulium	2.80	1.91-3.69		Arthur, 1963

Curtis (1959), as part of a study for the Pacific Gas and Electric Company, examined data relating changes in river depth, water velocity, wetted perimeter and cross-sectional area to several water stages (discharges). The objective of the study was to examine the total area of stream bottom covered by water at each level of flow. This was based upon the premise that an important producer of trout food is the stream bottom area (the habitat of the organisms) which varies with volume of flow. Velocity of flow was found to decrease at a much faster rate than wetted perimeter.

The California Department of Fish and Game developed criteria for evaluating the requirements of trout for food, spawning area and shelter (Kelley et al., 1960). In 1960, these criteria were further refined and measured at four flows in Taylor Creek. Major findings, summarized by Hooper (1973), were that as flow decreased: 1) The percent loss in food producing areas and shelter was greater than the percent loss in cross-sectional and surface area; 2) the rate of loss of food producing areas and shelter increased; and 3) the cross-sectional and surface area decreased at a slower rate than the volume of flow. This agreed with Curtis (1959).

Pearson et al. (1970) found that the maximum production of aquatic insects is controlled by water velocity through the riffle and the total amount of riffle area. They recommend measuring the areas and velocities of an adequate sample of the riffles in each study stream and setting an optimum flow (for fish food production) that would cover "the greatest amount of the riffle and still provide large sections of the riffle with water velocities of about 2.0 feet per second." (Pearson et al., 1970:59).

Banks et al. (1974) identified optimum food producing habitat by breaking total surface area at each flow into 64 depth velocity categories and determined the areas (acres) with velocities of 1.5 - 3.49 fps and depth of 0.5 - 2.99 feet. Optimum flow for insect production was assumed to be that which provided the maximum surface acreage with the above depths and velocities.

The technique used in California as applied to the Pit River also utilized depth velocity analyses as well as substrate classification. These three parameters were weighted and analyzed in the same manner as described earlier under spawning (i.e., relative units of food producing habitat vs discharge). Weighting factors are listed in Table 9.

RIFFLE ANALYSIS

Riffle areas are those portions of a stream first seriously affected by changed discharges and consequently they have been suggested as a index of rearing conditions. The assumption is that the maintenance of suitable riffle conditions will result in suitable pool conditions as well (Bovee, 1974).

Oregon Department of Fish and Wildlife personnel utilize the following criteria, for recommending rearing flows for salmonids, based on observations and measurements along transects across riffle areas: 1) Adequate depth over riffles; 2) riffle-pool ratios near 50:50; 3) approximately 60 percent of riffle area covered by flow; 4) riffle velocities 1.0 - 1.5 fps; 5) pool velocities of 0.3 - 0.8 fps; 6) stream cover and shelter available (Thompson, 1972). Criteria and transect procedures are being further developed for rearing analyses.[15]

Collings (1974) describes rearing discharges for salmonids from the relationships between wetted perimeter and discharge. Typical curves show rapid increase in wetted perimeter from zero discharge to an inflection point where the wetted perimeter increases slowly as the discharge increases rapidly. The rearing flow is set somewhere near the inflection point of the wetted perimenter-discharge curve (Figure 12). Families of curves of depth and velocity are also consulted in choosing rearing discharges.

White (1975) proposes that the wetted perimeter-discharge relationship be evaluated similarly for large river systems such as the Snake River. Bovee (1974), working on warm water streams in the northern Great Plains, recommends that a riffle-inhabiting fish species be used as the "indicator species" for rearing flow analysis. Depth velocity preferences for the "swift water" species are determined and riffle productivity is analyzed on the basis of the optimum area available at a given discharge. Areal determininations are performed by the graphical method using the planimetric mapping technique (Collings, 1974) described under *Spawning Flows*.

Critique

The consideration of riffles as important food-producing areas is based on a significant quantity

[15]Personal communication. 1975. Ken Thompson. Oregon Dept. Fish and Wildlife, Portland, Oregon.

Table 9. Food-producing criteria and weighting factors as used for rainbow trout in the Pit River, California.[a]

Velocity (fps at 0.2' from bottom)		Depth (at 0.2' from bottom)		Substrate	
Range (fps)	Weighting Factor	Range (ft)	Weighting Factor	Type	Weighting Factor
0.50-0.59	0.1	0.20-0.29	0.5	Rubble (3"-12")	1.0
0.60-0.69	0.2	0.30-0.39	0.7	Gravel (1/8"-3")	0.6
0.70-0.79	0.3	0.40-0.49	0.8	Silt	0.2
0.80-0.89	0.4	0.50-0.59	0.9	Sand	0.1
0.90-0.99	0.5	0.60-2.79	1.0		
1.00-1.19	0.6	2.80-3.39	0.9		
1.20-1.39	0.7	3.40-3.79	0.8		
1.40-1.69	0.8	3.80-4.19	0.7		
1.70-2.09	0.9	4.20-4.59	0.6		
2.10-2.69	1.0	4.60-4.99	0.5		
2.70-3.09	0.9	5.00 --	0.4		
3.10-3.39	0.8				
3.40-3.59	0.7				
3.60-3.79	0.6				
3.80-3.89	0.5				
3.90-3.99	0.4				
4.00-4.09	0.3				
4.10-4.19	0.2				
4.20-4.30	0.1				
4.31 --	none				

[a]Unpublished data. 1975. Brian Waters, Pacific Gas and Electric Co.

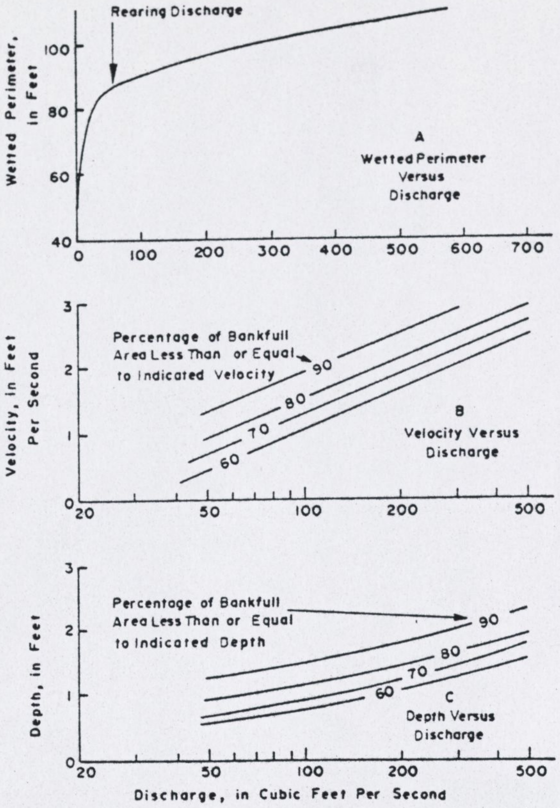

Figure 12. Example of curves used to determine and evaluate rearing discharges (from Collings, 1974).

of insect production data. Depth velocity requirements and drifting habits for certain groups of aquatic insects are available and can be related to velocity decreases. This type of data forms the base for riffle (benthic insect) production studies and the effects of reduced discharge on production. Most of the approaches to assessing insect production flows must be classed as intensive. However, given a knowledge of specific depth velocity criteria, examination of certain areas might be undertaken with a limited amount of field work. Although considerable research of the "food habits" type has been conducted, generally the relationship between aquatic insects and fish populations for all classes of streams must be examined in depth (i.e., research needed). The production and flow requirement data base needs to be broadened to include warm water streams. The existing methods seem adequate for productive, high gradient, rocky bottomed streams (e.g., those inhabited by trout, smallmouth bass, etc.) and salmonid streams in general, but may not be sufficient for low gradient, warm water streams which have considerable production in pools and bottom muds. This is difficult to assess until specific criteria are available for these stream types.

Wetted perimeter-discharge relationships are useful for evaluating riffle habitat and determining rearing flows when riffle habitat is limiting. A very distinct advantage of the wetted perimeter-discharge approach is its utility on large unwadable rivers and warm water streams. However, the lower limits of velocities necessary for maintaining sediment-free interstitial spaces is not well known. This is true for both seasonal flushing flows and continual flushing flows. The cumulative effects of the lack of flushing are poorly understood and must be considered a significant gap in the knowledge. Historic flood flows, annual runoff flows and flow duration curves should be examined for use in reconnaissance predictions for flushing flows. All present methods require intensive field measurements.

Planimetric mapping appears useful for delimiting "optimum areas" that meet depth velocity criteria of species. Mapping used in conjunction with swiftwater indicator species has much promise. The major shortcoming could be in the choice of species whose depth velocity tolerances are too broad to serve as good indicators.

Hooper (1973) presents an excellent overview of food production in streams, and factors of flow which may influence distribution and production of aquatic insects. Hooper points out that insect production is *the* important aspect of the stream environment for which the measurement of only physical (hydraulic) parameters appears very inadequate. Transport and the ultimate distribution of suspended solids and detrital materials perhaps plays the major role in primary and secondary (insect) production. The link to fish production and the relationship to streamflow represent a significant gap in the state-of-the-knowledge.

MICROHABITAT AND COVER

The microhabitat concept is useful in delineating the specific areas in which an animal may be found, but a more complete understanding of fish microhabitat criteria (emphasizing focal points) is essential as a basis for determining flows that will maintain or enhance these important stream areas. Microhabitats have been identified that cover a variety of activities (resting, feeding, etc.) that fish engage in. However, "resting microhabitat" seems to be the most significant as it functions as a "focal point residency" from which fish move out to perform other life activities (Wickham, 1967). The importance of the focal point concept was shown by Wickham (1967) in a one-way analysis of variance (eleven independent variables) comparing focal points and movements of brook trout. Brook trout spent from 92 to 96 ($\bar{x}$ = 94) percent of the time at focal points which represent less than three percent of the area of examined sections. Focal points tended to be in areas of low velocity, overlain by higher velocity water (laminar flow). Focal point modal velocities were found to range from 0.06 fps - 0.53 fps ($\bar{x}$ = 0.33 fps), with maximum velocities of 0.16 fps - 1.20 fps ($\bar{x}$ = 0.86 fps). Brown trout also seem to prefer conditions of laminar flow. At an average flow of 3.6 cfs, the bottom velocity, where trout were found, was 0.67 fps compared to surface velocity of 1.10 fps. Preferred velocities of brown trout were reported to range between 0.3 fps and 1.0 fps (Baldes and Vincent, 1969). Bovee (1974) presents tables giving the distribution of 37 species of stream fishes according to water depth and velocity. Depth in feet ranged from 0.5 to 8.0, with the majority of species occupying the 2- to 5-foot depths, and velocities from 0.06 to 5.0 fps with more species at the 0.06 to 1.3 levels than above. Although these velocity values are inferred, they closely agreed with known velocities for certain species.

Banks et al. (1974) identified "shelter" microhabitat by the same approach they used for food-producing habitat described previously under *Fish Food Production*. Their criteria for trout microhabitat requires water $\geqslant$ 1.5 feet deep with velocities of 0 to 0.99 fps. This is in agreement with other studies, indicating again the preference for low velocities at focal-point areas.

A "resting microhabitat" analysis developed in California for rainbow trout is based upon weighted values for depth and velocity, measured at 0.2' from the bottom, and substrate type. In application, transects are established across the stream and depth, velocity and substrate measured at intervals (usually 1 foot) along the transect. The weighting factors (Table 10) for depth, velocity,

Table 10. Resting microhabitat criteria and weighting factors as used for rainbow trout in the Pit River, California.[a]

Velocity (at 0.2' from bottom)		Depth (at 0.2' from bottom)		Substrate	
Range (fps)	Weighting Factor	Range (ft)	Weighting Factor	Type	Weighting Factor
0.00-0.02	0.3	0.00-0.29	none	Rubble	1.0
0.03-0.04	0.4	0.30-0.39	0.5	Gravel	1.0
0.05-0.08	0.5	0.40-0.49	0.7	Sand	0.9
0.09-0.12	0.6	0.50-0.59	0.8	Boulder	0.8
0.13-0.18	0.7	0.60-0.69	0.9	Silt	0.6
0.19-0.26	0.8	0.70 →	1.0	Bedrock	none
0.27-0.36	0.9				
0.37-0.54	1.0				
0.55-0.66	0.9				
0.67-0.74	0.8				
0.75-0.80	0.7				
0.81-0.86	0.6				
0.87-0.90	0.5				
0.91-0.93	0.4				
0.94-0.96	0.3				
0.97-0.98	0.2				
0.99-1.00	0.1				
1.01 →	none				

[a]Unpublished data. 1975. Brian Waters, Pacific Gas and Electric Co.

and substrate are multiplied together to give a relative habitat value at each point across the stream. These relative values are then summed for all points along the transects and divided by the total number to give a relative value for the entire stream width. If two or more transects are established at any particular station, all point values are averaged to determine a relative value for the stream station. This procedure is repeated at four or more discharges and a curve of relative habitat units vs discharge is drawn. Optimum microhabitat conditions are then assumed at the discharge with the highest value (apex) on the curve.

Table 11 summarizes salmonid microhabitat preferences in terms of velocity and depth criteria from the literature.

Table 11. Depth and velocity characteristics of salmonid microhabitats (from Giger, 1973a).

Species	Age	Length (mm)	Depth (m)	Velocity (m/sec)	References
Steelhead Trout	0	32	<0.15	<0.15	Everest & Chapman, 1972
	1	95	0.60-0.75	0.15-0.30	Everest & Chapman, 1972
	0, 1(?)	Varied	0.18-0.67	0.06-0.49	Thompson, 1972
Chinook Salmon	0	62	0.15-0.30	<0.15	Everest & Chapman, 1972
	0(?)	–	0.30-1.22	0.06-0.24	Thompson, 1972
Coho Salmon	0(?)	66-89	–	0.09-0.21	Pearson et al., 1970
	0(?)	–	0.30-1.22	0.06-0.24	Thompson, 1972
Cutthroat Trout	0, 1, 2(?)	Varied	0.40-1.22	0.06-0.49	Thompson, 1972
Brown Trout	–	213	–	0.12-0.21	Baldes and Vincent, 1969
Brook Trout	–	200	–	0.10 (mean)	Wickham, 1967

Closely allied to the microhabitat concept is the amount of cover available in a stream. Cover commonly falls into categories of preferred depth under turbulent surface flow, undercut banks, submerged rubble and vegetation, overhanging vegetation, and instream rubble-boulder areas. There is a high spatial correlation between cover and focal-point residency mentioned above. Sun-shade relationship studies indicated shade preference by usage (occupancy) from 81 to 100 percent (Wickham, 1967). Cover provides significant resting areas by supplying shade (photonegative response), security (predator avoidance) and shelter from the current, thereby moderating its force (the importance of the latter function is evidenced by the low velocity preferences discussed above and under *Total Usable Habitat*). The complexity and significance of the organism-cover-flow relationship, although recognized, is not well understood. However, it is not difficult to visualize fluctuating flows (augmented flow as well as reduced) causing significant variation in the quantity and quality of instream and riparian cover.

Lewis (1969) examined the physical factors influencing trout numbers in pools and found that cover was the most important factor for brown trout while current velocity was most important for rainbow trout. As current velocities increased in the study stream, trout sought out deep, slow pools and cover. A number of workers have reported a progressively increased association of fish with substrate irregularities (bottom rubble) as velocity increased (Kalleberg, 1958; Hartman, 1963; Baldes and Vincent, 1969).

Wesche (1973), analyzing undercut banks and instream rubble-boulders for brown trout cover utilization, found that 65 percent of the fish captured used the former and 35 percent the latter. Of the brown trout $\geqslant$ 6.0", 85 percent utilized undercut banks and 15 percent instream boulders. Fifty-five percent of the brown trout $\leqslant$ 6.0" used undercut banks and 45 percent instream boulders. No fish were taken in areas with a substrate size of less than 3" average diameter. Velocities measured at a cover location point ranged from 0.0 to 0.5 fps. Using data of this type, Wesche (1973) has devised an equation to rate and compare cover on a stream section at different flow levels and different stream sections at the same flow level.

$$CR = \frac{L\ ucb}{T}(PF\ ucb) + \frac{A}{SA}(PF\ a) \ldots \quad (11)$$

in which L ucb = length (ft) of undercut banks in stream sections with water depth ⩾ 0.5' and width of ⩾ 0.3'; T = length along thalweg; A = surface area (sq ft) of the stream section with water depth ⩾ 0.5' and substrate size ⩾ 3" diameter; SA = total surface area (sq ft) of the stream section at the *average daily flow*; PF ucb = preference factor for undercut banks, PF a = preference factor for instream rubble-boulders; and CR = cover rating of stream section. Preference factors were set as the percent utilization figures in decimal equivalents (e.g., 85 percent = 0.85). The rationale for the preference factor is based on each flow level having some cover areas not utilized.

This formula is based on measurements at average daily flow. If this is not possible, measurements on two separate stream sections are taken when both are at relatively the same stage (i.e., same percent of average daily flow). When comparing the same stream section at different stages, the surface area value used must be the one measured at the highest flow for which a rating is made.

Wesche (1973) presents the following example of the determination of cover rating for brown trout ⩾ 6.0" at 100 percent average daily flow (assumed to be mean annual flow expressed on a daily basis) in Douglas Creek, Wyoming (Creek A, Figure 13).

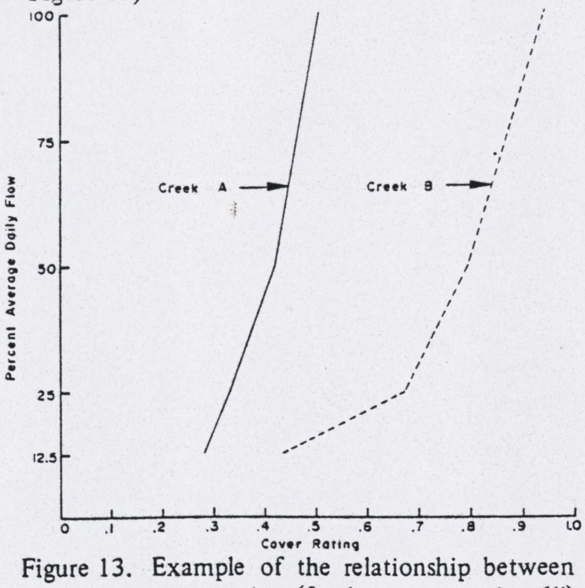

Figure 13. Example of the relationship between cover rating (for brown trout ⩾ 6") and flow reduction (from Wesche, 1973).

From Equation 11

$$CR = \frac{350'}{680'}(0.85) + \frac{7{,}055\ \text{sq ft}}{16{,}510\ \text{sq ft}}(0.15) = 0.50$$

At the same discharge in another stream reach, a CR value higher than 0.50 would indicate more cover is available. Mark-recapture population estimates verified that there were larger trout populations in areas with higher CR values. Wesche (1973) presents tables relating the CR values to percentages of the 100 percent average daily flow and showing the decrease in physical parameter values with decreases in flow. From the data it appears that the greatest rate of brown trout cover loss is at a flow reduction from 25 to 12.5 percent of average daily flow (Figure 13).

A "subjective cover" rating for rainbow trout has been developed in California. This rating scheme is an attempt to place relative values on the physical shelter (turbulence, logs, undercut banks, etc.) available for rainbow trout use. Transects are established across the stream and cover is rated at intervals along the transect (depth, velocity, and substrate measurements are also taken—see *"resting microhabitat" analysis* developed in California). Cover ratings are 0 (no cover) or 1 (cover available). The rating values taken along the transect are summed and divided by the number of rating intervals to arrive at the relative cover value. A number of transects are established at each station and measurements taken at different flows as described under "resting microhabitat" and spawning analysis.

Critique

The microhabitat concept has wide application in specifying fish requirements in relation to each of several differing activities. A reasonably broad base of information is available concerning the various activity requirements and preferences of selected fish species. Microhabitat analysis is useful for bringing this information together into a conceptual as well as factual whole. The recognition of the importance of focal point residency is conceptually valid and should be considered as a basis for microhabitat studies. Again, detailed depth velocity criteria (especially velocity) are of major importance in microhabitat evaluation.

The "resting microhabitat" analysis (California) is intended for characterization of an entire stream by intensively measuring depth, velocity, and substrate at a variable number of sample stations.

The reliability of this type of approach is dependent upon how well the sample stations represent the stream, the number of transects and transect intervals and the accuracy of microhabitat criteria and weighting factors. With reliable data, this procedure would be valuable for flow assessment by randomly sampling the entire stream.

The significance of cover (shelter in its various forms) to microhabitat needs to be more closely evaluated (e.g., flow → cover → habitat enhancement programs). Since fish spend the majority of time associated with cover, this must be considered and a detailed understanding of cover function and location (especially management implications, e.g., microhabitat in relation to increased carrying capacity) is needed.

Wesche's (1973) cover utilization technique, which evaluates preference for types of physical habitat to arrive at a cover rating for stream reaches, appears to more valid for cover-oriented salmonids (i.e., brown trout as opposed to the less cover-oriented cutthroat trout). Population estimates and cover rating seem to be correlated, at least, for brown trout. This method should be considered useful, either for cover evaluation alone, or in conjunction with other methods of assessing habitat at varying flows. With some modification (i.e., visual estimates of changes in L ucb), this cover index could be handled in much the same way as the habitat rating technique discussed under *Methodologies for Determining Instream Flow Regimes for Preservation of the Aquatic Habitat* and *Associated Environmental Resources.* Cover index-discharge curves could be constructed from cross-sectional profiles. A definite limitation is an understanding of the various aspects of cover requirements for all stream fish species. This is particularly the case for warm water species. Additional considerations of cover that must be considered in any evaluation are the implications of turbidity, shade, turbulent surface flow, seasonal variation in cover availability and use, temperature, and perhaps most important, inter and intraspecific competition and density dependencies. These considerations all require intensive on-site field studies.

The "subjective cover" rating (California) is normally considered at the same time and sample station as "resting microhabitat," spawning and food production and has value only in conjunction with these other measurements.

TOTAL USABLE HABITAT

The velocity of a stream plays a significant role in habitat selection and the spatial relationships of fish. Stream organisms must conduct their activities in a constantly moving medium, therefore, velocity is a prime factor in understanding the complexities of a lotic community. Velocity is thought to be directly related to habitat differentiation, territoriality, and, possibly, carrying capacity (Chapman, 1966; Baldes and Vincent, 1969). Frequent flow alterations that influence velocity would clearly have a disruptive effect on community stability.

Fish size is highly correlated with the selection of habitats exhibiting particular depth and velocity characteristics. Small fish cannot maintain position in stronger currents, but as they grow they move to faster, deeper water (Giger, 1973a). In large rivers, areas of deep, swift current over fairly uniform substrate constitute "runs" which may be largely uninhabitable to all but the very largest fish. Such areas may be in juxtaposition to riffles upstream and/or downstream, dependent upon the channel geometry. Generally, the uninhabitable area of a stream would be expected to decrease with decreased discharge and increase with increased discharge.

Normally, fish respond to current by orienting into the flow. Therefore, it is important that the velocity a stream fish is reacting to be high enough for position orientation, but not so high as to challenge endurence. Stated differently, there must be enough current so that stability can be maintained without continual cruising.

Maximum sustained swimming speeds for fish can be expressed in terms of fish lengths per second and utilized for assessing the habitable portion of a stream reach. With regard to endurance or cruising speeds, there is fairly wide agreement that two to three fish lengths (FL) per second can be maintained in many species for long periods (Blaxter, 1969). Salmonids and herring seem capable of sustaining three to four FL per second. The relationship between fish length and velocity has been determined by Jones (1973) for several species and is presented in Figure 14. Temperature has a considerable effect on cruising speed, with optimum performance falling within the optimum (physiological) species temperature range and reduced performance on either side of the physiological optimum.

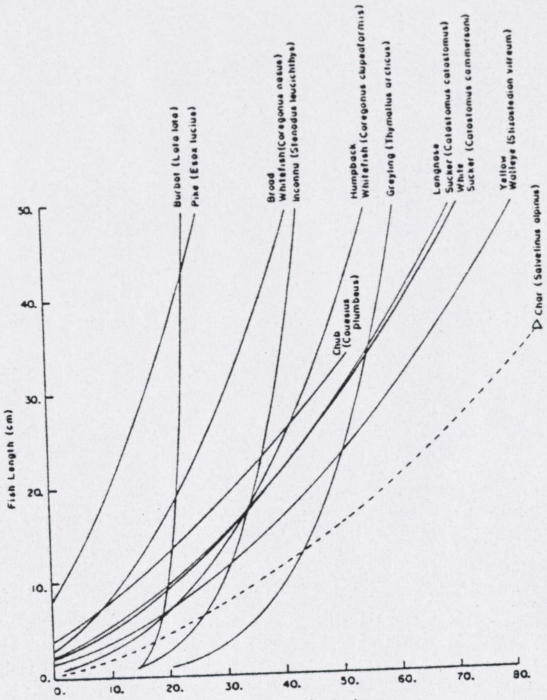

Figure 14. Example of the relationship between fish length (fork length) and ability to move 100 m against water velocities of 0 - 80 cm/sec in 10 min (from Jones, 1973).

Pearson et al. (1970) have evaluated pool velocity as an index of factors that limit the numbers of juvenile coho salmon in pools. They found that numbers of fish in pool areas were related to the average pool velocity. They assumed that pool rearing conditions would improve with increased velocities until the current becomes too swift, reducing the pool area available for rearing. From measurements taken in appropriate pools, average velocity was calculated at several discharges. They found maximum velocities of 0.7 fps where coho were present and used this figure as the optimum pool velocity criterion. The optimum flow would be that which provided most pool area meeting the criteria.

Banks et al. (1974) utilized a 64-cell depth velocity matrix (Table 12) expressed in percentages of surface area, at four discharges for a 70-mile stretch of the Green River in Wyoming. This river contained considerable "run" type habitat. Usable habitat was considered along with microhabitat and food producing habitat in recommending an optimum flow. Banks et al. (1974) selected the following depth velocity criteria for usable trout (brown and rainbow) habitat: 4" trout ($<1.0'$, <1.0 fps); 8" trout ($<2.0'$, <2.0 fps); 12" trout ($<3.0'$, <3.0 fps). Recommended optimum flow was that discharge producing the maximum surface area with depth $\leqslant 3'$ and velocities $\leqslant 3$ fps.

Critique

Methods for assessing uninhabitable (high velocity) portions of river environments have been neglected by nearly all researchers up to the present. This is primarily due to the fact that most instream flow assessment has been directed toward reductions of flow (dewatering) and little attention has been directed toward assessing augmented flows. With the increased activity associated with energy development in the United States, excessive demands are being placed upon water use. Consequently, massive transbasin water allocation schemes are being proposed and implemented. Such large scale transfers will result in greatly augmented flows with much elevated velocities and depths, essentially created year around "flood flows." Each fish species has an upper limit for sustained swimming and "burst" speeds, thus making some portions of a stream uninhabitable under extremely high flows. Smaller sized individuals may be limited to certain portions of a stream under "natural" flows as well. Therefore, size-velocity-habitat relationships need to be further investigated and criteria established for all important stream-dwelling fish species.

SUMMARY OF EXISTING METHODS AND METHODOLOGIES

Existing methods and methodologies have been discussed in depth in previous sections. Considering the nature of this material, a standard summation would not provide any additional insight or ease of comprehension. Therefore, a tabular summary (Table 13) of existing methods that assess fishery and aquatic habitat flow requirements is included. This type of format should provide the reader with a concise overview of methodologies. Table 13 includes, for each methodology, the following types of information: 1) application level, i.e., reconnaissance, limited or intensive on-site field work; 2) the size of the stream where the approach is applicable; 3) where the methodology has actually been applied; 4)

Table 12. Depth velocity matrix expressed as percentages of surface area (from Banks et al., 1974).

Depth (ft.) ↓ / Velocity (fps) →	<.5	.5-.99	1.0-1.49	1.5-1.99	2.0-2.49	2.5-2.99	3.0-3.49	≥3.5	Row Total
<.5	195 (6.7%)	26 (0.9%)	-	-	-	-	-	-	221 (7.6%)
.5-.99	90 (3.1%)	47 (1.6%)	-	41 (1.4%)	17 (0.6%)	6 (0.2%)	6 (0.2%)	93 (3.2%)	300 (10.3%)
1.0-1.49	29 (1.0%)	38 (1.3%)	32 (1.1%)	44 (1.5%)	108 (3.7%)	79 (2.7%)	38 (1.3%)	172 (5.9%)	540 (18.5%)
1.5-1.99	6 (0.2%)	29 (1.0%)	23 (0.8%)	9 (0.3%)	111 (3.8%)	131 (4.5%)	143 (4.9%)	175 (6.0%)	627 (21.5%)
2.0-2.49	6 (0.2%)	15 (0.5%)	55 (1.9%)	79 (2.7%)	41 (1.4%)	64 (2.2%)	41 (1.4%)	105 (3.6%)	406 (13.9%)
2.5-2.99	9 (0.3%)	17 (0.6%)	15 (0.5%)	12 (0.4%)	32 (1.1%)	3 (0.1%)	149 (5.1%)	-	237 (8.1%)
3.0-3.49	9 (0.3%)	20 (0.7%)	-	17 (0.6%)	47 (1.6%)	17 (0.6%)	82 (2.8%)	-	192 (6.6%)
≥3.5	-	41 (1.4%)	-	23 (0.8%)	219 (7.5%)	90 (3.1%)	17 (0.6%)	-	390 (13.4%)
Column Total	344 (11.8%)	233 (8.0%)	125 (4.3%)	225 (7.7%)	575 (19.7%)	390 (13.4%)	476 (16.3%)	545 (18.7%)	2913 (100%)

indication of general data collection techniques, data input needs, and information output; 5) what is evaluated, e.g., general habitat or life needs; 6) general remarks concerning cost, level of resolution of results and some limitations of the approaches. Methodologies that have been implementated are presented in Table 13, but those proposed or in early stages of development are not.

Table 13. A summary of methods and methodologies that assess fishery and stream habitat flow requirements.

Author	Application	Analysis	Data needs	Remarks
Tennant, 1975	Reconnaissance All size streams Widely applied to warm and cold water streams in the mid-West, Northern Great Plains and Rocky Mtn. regions	General habitat, fish, wildlife, and recreation	Type: Flow records Input: Mean annual flow records over several years Output: Preservation and survival flows, biannually	Moderate data needs Low time and cost requirements Best used when prior data exists Low to moderate resolution Characterizes entire stream
Anonymous, 1974	Reconnaissance All size streams Applied to Northern Great Plains streams	General habitat, fish, wildlife, and recreation	Type: Flow records Input: Mean daily discharge records Output: Preservation flows, monthly	Moderate data, time and cost requirements Best used when prior data exists Low to moderate resolution Needs field testing in different regions
Hoppe & Finnell, 1970	Reconnaissance Small streams and wadable rivers Applied to Frying Pan River, Colo.	Spawning, fish food production, and sediment flushing	Type: Flow duration curves Input: Flow records Output: Minimum flows for spawning, flushing and food production	Moderate data, time and cost requirements Requires prior data Low to moderate resolution Needs verification on other streams Characterizes only critical areas of stream
Robinson, 1969	Reconnaissance All size streams Applied to streams in Connecticut River Basin	Fishery flows	Type: Flow records Input: Average monthly, median and lowest flows Output: Preservation and optimum flows for fisheries	Moderate data needs Low time and cost requirements Best used when prior data exists Low to moderate resolution Characterizes entire stream Needs testing in different regions
Herrington & Dunham, 1967 Chrostowski, 1972 Dunham & Collotzi, 1975	Intensive field measures Small streams and wadable rivers Applied to many trout streams in intermountain area	General habitat; fish and reparian vegetation	Type: Transects Input: Hydraulic parameters Output: Preservation flows for fish, wildlife, and recreation	High data needs Moderate ease, high time and cost requirements Best measured at low flows Moderate to high resolution Characterizes the entire stream Needs follow-up analyses after flow reductions applied

Table 13. Continued.

Author	Application	Analysis	Data needs	Remarks
				Would be applicable for evaluating augmented flows, if tested
Anonymous, 1973 (Critical Area Method)	Limited field measures Small streams and wadable rivers Applied to trout streams on USFS lands in Colo.	General habitat, riparian vegetation, recreation, and aesthetics	Type: Transects Input: Visual examination of entire stream by team approach Output: Preservation flows and optimum flows for fish, wildlife, and recreation	Minimal data needs Moderate time and cost requirements Requires team of experts Moderate resolution Characterizes critical area of the stream Needs follow up analyses for validation
Hoppe, 1975	Reconnaissance and limited field measures Small streams and wadable rivers Applied to Frying Pan River, Colorado	Spawning, cover, riffle (food production) for trout	Type: Transects Input: Hydraulic parameters Output: Preservation flows for fish	Moderate data, time and cost requirements Requires judgement of experienced biologist Resolution dependent upon experience of biologist Characterizes only the most critical section of stream
Thompson, 1972, 1974 Oregon State Game Comm., 1972	Intensive field measures Small streams, wadable rivers, larger rivers with wadable spawning bars, Applied to several Oregon streams and the Snake River, Idaho	Passage, spawning of salmonids	Type: Transects Input: Hydraulic parameters Output: Minimum passage flows, minimum and optimum spawning flows	Moderately high data, time and cost requirements High resolution Characterizes only the riffle areas Assumes reproduction is the limiting or overriding consideration Criteria needs to be developed for additional species
Rantz, 1964	Reconnaissance Regional or basinwide All size streams Applied to Mad and Eel Rivers, California	Spawning, production of young of Chinook salmon	Type: Predicting formalae Input: Average annual flow, drainage area, average stream width Output: Optimum spawning discharge	Minimal data, time and cost requirements Low resolution Characterizes spawning bars by computing a discharge at one downstream point only; assumed optimum for spawning and incubation Must be developed for each major watershed and needs considerable field data for development
Collings, 1974	Reconnaissance, regional or basinwide All size streams Applied to	Spawning flows for five salmon species	Type: Predicting formulae Input: Drainage area, mean basin altitude, reach	Minimal data, time and cost requirements Low resolution Must be developed for each physiographic

Table 13. Continued.

Author	Application	Analysis	Data needs	Remarks
	western Washington streams		altitude, width, slope, hydraulic radius Output: Optimum spawning flow	region Needs considerable field data for development Could provide information for future regional assessment studies
Sams and Pearson, 1963 (weighted usable width, average velocity analyses)	Intensive field measures Small streams and wadable rivers Applied to four streams in Williamette River Basin	Spawning, incubation flows for Chinook, Coho and Steelhead	Type: Transect Input: Hydraulic parameters, substrate–permeability data, intragravel DO, velocity distribution curves Output: Optimum spawning and incubation flows	Considerable data, time and cost requirements High resolution Requires accurate depth-velocity criteria for each species Characterizes spawning areas only Need development of criteria for additional riffle spawning species
Sams and Pearson, 1963 (average stream width)	Limited field measures All size streams Applied to four western Oregon streams	Spawning flows	Type: Transects Input: Average pool and stream width Output: Optimum spawning flows	Moderate data, time and cost requirements Low resolution Requires velocity criteria for each species Could be used for interpretation from aerial photos on larger streams and rivers Limited to streams with average pool width ≅ to average stream width applicable to gravel spawning species for which velocity criteria are known
Bishop and Scott, 1973 Collings, 1974	Intensive field measures Small streams and wadable rivers Applied to coastal streams in Western Washington	Spawning of salmon	Type: Transects with additional random point measurements Input: Hydraulic parameters, planimetric maps Ouput: Optimum (preferred) and "sustaining" spawning flows	High data, time and cost requirements Resolution high Characterizes spawning reach only Needs additional criteria for other species Could be applicable to large rivers by using sounding devices, etc. and to reaches other than spawning, and to evaluation of augmented flows
Wickett, 1954 Terhune, 1958	Intensive field measure Small streams and wadable rivers	Incubation	Type: Standpipe technique Input: Permeability rates, dissolved oxygen levels Output: Incubation flows, percola-	Moderate to high data, time and cost requirements Resolution high Characterizes intragravel flow and percolation rates

Table 13. Continued

Author	Application	Analysis	Data needs	Remarks
			tion flows, percolation rates	Could be applied to augmented, as well as reduced flow but requires measurement at actual flow
Hoppe and Finnell, 1970	Limited field measures All flowing water Applied to Frying Pan River, troutstreams in southern Colorado	Incubation	Type: Predictive formula Input: Stream gradient, velocity measurement Output: incubation flows	Low to moderate data, time and cost requirements Low to moderate resolution Characterization and application same as Wickett, 1954, et al. Could be applied to evaluation of augmented flows
Thompson, 1974	Intensive field measures Small streams and wadable rivers Applied to Snake River, Idaho	Incubation	Type: Standpipe and egg basket Input: Permeability rates, dissolved oxygen levels, introduced incubating eggs Output: Percolation rates, incubation flows	Moderate to high data, time and cost requirements High resolution Characterization and application same as Wickett, 1954, et al.
Banks, et al. 1974	Intensive field measures Small streams and wadable rivers Applied to Green River, Wyoming	Food production, resting microhabitat, total usable habitat	Type: Transects, aerial photographs Input: Hydraulic parameters, area estimates from planimetered aerial photographs Output: Maximum surface acreage for food production, resting microhabitat and total usable habitat	Moderate to high data, time and cost requirement Low to moderate resolution Characterizes entire stream Requires measurement at varying flows. Could be applied to evaluation of augmented flow
Collings, 1974	Limited or intensive field measures Small streams and wadable rivers Applied to coastal streams in western Washington	Food production (rearing)	Type: Transects Input: Hydraulic parameters, wetted perimeter-discharge curve Output: Minimum (preservation) food production (rearing) flow	Moderate data, time and cost requirements Low resolution Characterizes riffle areas only Could be applied to evaluation of augmented flow
Wesche, 1973	Intensive field measures Small streams and wadable rivers Applied to brown trout streams in S.E. Wyo.	Cover	Type: Transects Input: Substrate size, hydraulic parameters, surface area, size of undercut banks, mapping of stream reaches Output: Cover rating	High time, data and cost requirements Moderate to high resolution Characterize the entire stream Could be applied to evaluation of augmented flows

Table 13. Continued

Author	Application	Analysis	Data needs	Remarks
Bovee, 1974	Intensive field measures Small streams and wadable rivers Presently being tested in Yellowstone River drainage in S.E. Montana	Passage, spawning, riffle productivity	Type: Transects Input: Hydraulic parameters, planimetric mapping Output: Identification of optimum flows for passage, spawning, riffle productivity	High data, time and cost requirements Moderate to high resolution Key indicator species and their depth velocity criteria need to be established Characterizes spawning reaches and riffle areas

METHODOLOGY DEVELOPMENT

The Oregon Department of Fish and Wildlife has initiated a research study on Elk Creek near Cannon Beach, Oregon. The primary objective is to determine field investigational techniques that can be used in coastal streams to evaluate the influence of summer stream discharge on fish production. Elk Creek has two forks of approximately equal size, flow and other characteristics. A pipeline diversion has been installed across the approximately 880 feet of level terrain separating the North and West forks.

> Plans for field studies are that flows in the controlled sections will follow a typical declining pattern each summer, but will be increasingly dewatered in one channel and increasingly augmented in the other until mid-August or early September when a final proportional change (25, 50, 75 percent, etc.) or specific discharge level is reached. This level will be held until natural flows increase substantially. . . . Fish production will be periodically estimated for all sections and measurements will be made of biomass of benthic invertebrates, terrestrial and aquatic invertebrate drift rates, flow characteristics, cover changes, and other features for model input and statistical treatment. A physical and chemical description of the study unit would be obtained for use in establishing channel morphometry-discharge relationships or for possible application to the model. Mathematically describable and predictable flow-channel relationships will serve as a bridge for applying results of a field study to other streams. (Giger, 1973b:8, 10)

As of this writing, changes in research design are being made.[15]

Bovee (1974) has proposed a method he terms the "indicator species-overriding consideration." Three life history phases (migration, spawning, and rearing) are proposed for consideration and the most representative indicator species selected for each. It is suggested that: 1) Migration and spawning requirements be evaluated by the usable width method developed in Oregon and discussed earlier; and 2) rearing flows be evaluated by examining the microhabitat and water quality requirements of riffle-inhabitating (swift water) "indicator species."

The assumption is implicit that as long as requirements for preservation of riffle-inhabitating fishes are met, adequate aquatic insect production will occur and consequently sufficient food will be available for all fish species present in the stream. Spawning and passage flows are determined by depth velocity criteria dictated by the species having the narrowest flow requirements. Riffle productivity and flow requirements for bank recharge and riparian vegetation maintenance are mentioned, but are not keyed to an indicator species.

The paddlefish, sauger and stonecat have been selected as indicator species for passage, spawning and rearing, respectively, for the Northern Great Plains streams in Montana. It is proposed that depth velocity criteria be further defined by observation and intensive measurements of stream reaches followed by construction of planimetric maps.

Research is continuing on establishment of the appropriate depth velocity criteria by extensive field measures of preferred depth and velocities of the selected target species. Intensive studies of all aspects of the impacts of reduced stream flows in the middle and lower Yellowstone River basin are being carried out by personnel of the Montana Fish and Game Department, FWS, University of Montana and Water Resources Division, Montana Department of Natural Resources and Conservation. Objectives are to perfect models for prediction of reduced flow impacts upon the river basin and associated uses. Various aspects of this comprehensive study are discussed in the proceedings of the Fort Union Coal Field Symposium held in Billings, Montana, April 1975. (Bovee, 1975; Elser, 1975; Peterman and Haddix, 1975).

The Bureau of Reclamation (USBR) has developed a "Water Surface Profile," computer program (see *Computer Programs*, Section 2 for description of data needs and output) which is being used in the Yellowstone River studies in Montana to generate depth-velocity matrices and/or isopleth maps for analysis of selected water stages. This program has a partitioning capability by which depth and velocity output is given for up to nine segments across the river channel. Only one set of field transect measurements are necssary for this program. The program computes discharge and channel hydraulic parameters for any additional water stages that the investigator cares to input at the upstream transect point. Output from this program is as follows: discharge tables, cross-section data, flow data, water surface elevations, channel distances, tractive forces, roughness coefficients, main channel discharges and velocities, plots of water surface profiles, and rating curves (Dooley, 1975).[16]

White (1975) has proposed a methodology for assessing passage, spawning and rearing requirements of certain target species in large, unwadable rivers. This suggests the use of the abovementioned "Water Surface Profile" model which, although not developed for instream flow evaluation, is quite useful for large rivers. Passage requirements follow the "usable width" method and spawning flows are determined from depth velocity criteria of the target species and examination of computer output data for all river reaches with suitable substrate. Minimum sustaining flows are proposed as a percentage of the optimum. The white sturgeon has been selected as the target species for passage and spawning considerations in the Snake River, Idaho. Suggested rearing flows are set at the inflection point along a wetted perimeter-discharge curve as discussed earlier. Research is continuing on establishment of depth velocity criteria for the white sturgeon. From literature reports on other species of sturgeon, White has suggested a minimum continuous depth of 1.5 m be maintained over 25 percent of the length of any potential passage block.

As a follow-up to studies completed in 1973, (Wesche and Rechard, 1973) a study was proposed by the Water Resources Research Institute, University of Wyoming to determine the feasibility of stream channel modification to improve trout habitat in streams having extended periods of flow insufficient to sustain desirable trout populations (Rechard and Wesche, 1973). A secondary objective is to develop baseline information on a stream in which the trout population has been depleted due to extended diversion of upstream water.

An extensive field research program has been initiated in Utah by the Utah Cooperative Fishery Unit supported by FWS, Utah Div. Wildlife Resources, USBR and USFS, which is aimed at field analyses of all measurable physical, chemical and biological components of a mountain trout stream system. This study will constitute a five- to six-year field validation of a General Stream Computer simulation model. This ecosystem model has been developed through the efforts of the US/IBP Desert Biome research program centered at Utah State University. The field research site will consist of three to four 1/4-mile reaches of a stream in which flows may be controlled on a continuing basis for the duration of the study. Several levels of dewatering (of experimental reaches) and a control will be maintained and monitored for use as input for the simulation modeling. The research concepts and model design are discussed by Stalnaker et al. (1975) and Wlosinski and Stalnker (1975).

The FWS, as part of the 1975 National Water Assessment, in anticipation of the development of a national program of substantive instream flow studies, has compiled two maps depicting the 1975 status of the 1) instream flow requirement data base, and 2) degree of constraint to water planning caused by lack of input data on instream flow requirements.

AGENCY METHODOLOGIES– A BRIEF OVERVIEW

State Resource Management Agencies

Washington Departments of Game, Fisheries and Ecology have recently begun using the "base flow" concept for reservation or retention of flows to maintain instream values.[2,3] Detailed flow

[16] A description of the program is available from the Sedimentation Section, Hydrology Branch, Division of Project Investigations, Office of Chief Engineer, Bureau of Reclamation, Denver, Colorado.

analyses for defense of priorities and backup information may be conducted on specific streams by construction of planimetric maps and wetted perimeter-discharge curves as discussed in previous sections of this paper. It is generally presumed that instream flows for uses other than fish (water quality, recreation, aesthetics) will be met by base flows. Exceptions are treated on an individual basis.

Oregon Department of Fish and Wildlife personnel currently employ a combination of hydraulic measurements along transects, general observations, and professional judgment in recommending "minimum" flows. Passage and spawning flows for salmonids have been evaluated by the "usable width" technique. The Oregon approach addresses four basic phases of the salmon life cycle, i.e., passage, spawning, incubation and rearing to establish "minimum perennial streamflows." Criteria and procedures for evaluating rearing flow requirements are presently being tested.

California Fish and Game evaluation techniques involve weighted depth velocity criteria for rainbow trout. From hydraulic parameters measured along transects, weighted curves for spawning, food production, and resting microhabitat as well as subjective cover are generated showing relative units of stream bed providing suitable habitat at several discharges. Criteria were developed jointly by PG&E, USFS, FWS and California F&G.[13, 14]

Idaho Fish and Game (IFG), under a contract with the Idaho Department of Water Resources, is compiling resource maintenance flow recommendations for 90 sections on 46 Idaho streams with considerations for warm and cold water fish species, waterfowl and recreation. Flow recommendations are by month and give minimum and maximum flows where applicable. IFG assessment techniques are similar to those used in Oregon for field investigations, and to Tennant's approach for interim flows from records and judgments. Priorities are being set for various streams or stream sections concerning the order for conducting flow studies and the type methodology to use for evaluation.[17] These instream flow requirements will provide input into a stream allocation model (SAM) being developed by the Idaho Water Resource Board which will indicate the optimum allocation of water between instream and diverted uses (Trumbull and Loomis, 1973).

Montana Department of Fish and Game utilizes the Water Surface Profile program of the Bureau of Reclamation. An indicator species approach is in the process of being validated at several sites in the lower Yellowstone River basin of southeastern Montana in conjunction with the University of Montana. The Water Resources Division, Department of Natural Resources and Conservation is developing a model for predicting the impacts of reduced flows in the middle and lower Yellowstone River basins. Inputs to this approach include the USBR water surface profile model, and ongoing studies of fish, invertebrates, wildlife and riparian vegetation (Anderson, 1975).

Wyoming Game and Fish Department – extensive use has been made of Tennants approach (flows of record) on unregulated streams and of empirical data collected on streams in which flows can be regulated. Added emphasis is being given to bank and instream cover for brown trout (Wesche, 1974).

Colorado Division of Wildlife – standard collection of flow data is now established with other agencies in the state and the "sag-tape" procedure adopted for transect analysis. The "critical area" approach and professional judgments along with flow duration curve analysis have generally been applied.

Federal Agencies

Fish and Wildlife Service–personnel of this agency have developed and implemented methods based upon average annual flow records. Other modifications have included use of the median annual flow and flow duration curves. Transect analyses are generally as described for the state in which the stream lies. No standard set of techniques is being applied, but rather a "shot gun approach" to instream flow recommendations is presently in effect. This is one of the primary motivations for the present state-of-the-art document.

U.S. Forest Service – three techniques for habitat appraisal have been developed in Regions 1, 2, and 4. An ocular technique is being applied in the Panhandle Forests and Montana area for relatively quick, low resolution appraisals. Quantification for flow reservations from further diversion appropriations are being made from the

[17] Personal communication. 1975. Tim Cochnauer, Idaho Fish and Game Department, Jerome, Idaho.

"sag-tape" technique. A discharge-habitat technique has been developed in Region 4 and is being applied to instream flow assessment by evaluating the percent loss of existing aquatic habitat. A combination ocular-transect approach examines "critical areas" of habitat along the stream course.

National Marine Fisheries Service – as a follow-up to the *Anatomy of a River* report, thermographs were installed in the middle Snake River to correlate water and air temperatures with rates of flow. Comparisons of data collected before and after existing dams were constructed are being made (Pacific NW River Basin Commission, 1974). The NMFS is also involved with research into anadromous fish passage problems in the Columbia and Snake River basins.

U.S. Geological Survey – much of the significant work on methods and techniques for measuring stream channel characteristics and stream hydraulics and correlating flows with spawning criteria of Pacific salmon has been by USGS personnel.

U.S. Bureau of Reclamation – a "Water Surface Profile" (WSP) computer program has been developed by the Lower Missouri Region, Division Project Investigations. This program is being applied to Montana streams to provide predicted values for hydraulic parameters and rating curves at programmed discharges (Dooley, 1975). By the incorporation of fish species depth velocity criteria, instream flows can be assessed. This program has also been proposed for use on the Snake and other large rivers in Idaho.

Environmental Protection Agency – provides technical and financial assistance to the states and has made data available (STORET), developed and run water quality models, and made preliminary recommendations for flow needs where requested (Pacific NW River Basin Commission, 1974).

U.S. Army Corps of Engineers – Fisheries-Engineering Research Program has concentrated on anadromous fish passage, but is currently broadening to include studies of power peaking effects on anadromous and resident fish species, wildlife, and commercial, Indian, and sports fisheries (Pacific NW River Basin Commission, 1974).

GENERAL LIMITATIONS, RECOMMENDATIONS AND RESEARCH NEEDS

A discussion of needs and priorities for clarity and order should proceed from the general to the specific. Therefore, this section will begin with statements on the nature of methodologies and their proper position in the problem resolution and decision-making process. Implicit in a discussion of methodological needs are the limitations of the methods themselves. Since specific limitations and needs were presented in the appropriate critiques, this section will deal with them in relation to methodologies in general.

There are two pivotal considerations in a general discussion of flow assessment methodologies. The first is what actually constitutes a methodology (criteria, measurement techniques, etc.) and second, what role it plays in the overall scope of discharge recommendation.

At present, the term "method" and "methodology" have a very general use in that they connote everything from basic data collection to ways of recommending flow. It is proposed that *method* be restricted in usage to describe the actual procedure (*technique*) by which data for recommendations are collected (i.e., parameter measurement). The implementation of the techniques, analysis of the data, and synthesis of results that ultimately lead to recommendations together constitute a *methodology*. In this fashion, the transect approach would be a *technique* used to generate input data for a *methodological* determination of actual flow values. An approach should not be considered a methodology if it does not (given the proper input) lend itself to problem resolution and clarity. This does not imply a pro or con opinion concerning the subjectivity or objectivity of an approach, but simply that semantic differentiation would contribute to clarification of approaches and placement of method (technique)/methodology in their proper and most useful perspective.

We have attempted to evaluate methodologies mainly as to how efficiently they serve the purpose for which they were designed. Considered in this context, many are entirely adequate. Often, the lack of necessary input data, not the methodology, is the major constraint. This is not to say that approaches to flow assessment are at a sophisticated level of development. In many cases, techniques for data gathering are far more advanced than methodologies for establishing a sound flow recommendation. This is perhaps the major weakness in the state-of-the-art as it now exists. Fisheries management has been a technique-oriented profession with an abundance of measurement and tabulation techniques and little development of new ideas on how to use them. We have figuratively put the scientific "cart before the horse" and, as a result, methodology development has lagged behind the ability to measure and, at the moment, is considerably behind needs. Neither methodologies nor measuring techniques, are the key issue. As they are presently considered, methods are only tools to aid in achieving a desired goal and must be viewed as a means to an end, not an end in themselves. Most importantly, it must be recognized that they are as efficient or inefficient for providing answers as the conceptual development behind them (in general, this is true for subjective as well as quantitative approaches). This is a significant point—that methodologies for discharge recommendation must be developed and utilized from a sound conceptual or theoretical base.

Assessing the effects of instream flow on the aquatic ecosystem and its components, for the purpose of discharge recommendation, *must be* viewed in the framework of a scientific endeavor. This is not meant to be overly academic, but entirely practical, in that the scientific approach will provide a general overriding consistency to flow recommendation. The foundation of any scientific pursuit is the use of conceptual models (theoretical framework) based on data or information in some form, for the immediate purpose of prediction. Prediction is implied in recommendation, e.g., a recommendation of a flow level is a prediction that certain things will or will not happen to the stream environment as a result of that flow.

As indicated throughout the foregoing text, the state-of-the-knowledge of stream component discharge relationships is fragmentary; therefore, synthesis of this information will itself be fragmentary. In view of this, the logical place to begin in any attempt at prediction is with what we know (we generally have some knowledge of a stream situation, even if it is only unverified observation). Once the information is gathered or ascertained, a tentative hypothesis or framework can be formulated to synthesize the available data into a more meaningful, consistent whole. Only when this theoretical base is established can some attempts at validation, testing and recommendation be undertaken. A high level of data sophistication, although ultimately a necessity, is not immediately crucial for this approach. This means of problem solving can be used at any study level with any information base. However, it must be understood that from qualitative observations one can only make qualitative predictions and, if quantitative predictions or recommendations are desired, then quantitative data must be obtained.

To summarize these points, when considering a stream situation the problem must first be conceptualized—that is, the situation must be put in a theoretical framework (postulate a conceptual model from facts, experience, observations, etc.) to form a hypothesis, then predict/test/recommend and, lastly, reconsider the results of the hypothesis and make necessary adjustments for its improvement. The approach that must *not* be taken is to consider a method for use in recommending discharge simply because it is available. The focus of this discussion is that attempts at solving problems or resolving conficts must be approached logically and that solutions cannot be attained solely by technique development or theoretical formulations, but by rational use of both in the proper context.

These statements on problem resolution and decisionmaking can be appropriately concluded with the following quote from the Economic Council of Canada.

> We emphasize in the strongest possible terms that progress towards improved government decision-making is *not* simply a matter of developing better information and adopting new and more sophisticated techniques. Increasingly sophisticated as they become, better information and techniques are only aids for improving judgment. Decision-making is essentially a judgmental process. What really matters is the approach to thinking about the choices that need to be made—a continuous, conscious and deliberate weighing of alternative actions on the broadest possible basis of knowledge and participation... (Economic Council of Canada, 1972:64)

All methodologies discussed in the preceding sections are directed toward the determination of preservation or maintenance flow recommendations. Some also identify "optimum" levels during the analysis phase of the methodology implementation and subsequently recommend a portion of this "optimum" as a maintenance flow.

For the purpose for which they were developed—i.e., preservation of the existing aquatic habitat or maintaining intact the "critical or limiting" habitat for important species—the presently used methodologies are adequate. However, they must remain open to modification and refinement as more knowledge is gained on the flow-dependent relationships of the aquatic community.

An important area of flow dependencies which no presently used methodology directly assesses is the magnitude and range of effects resulting from a series of changes in discharge through a natural stream channel. For rational water resource planning, these effects must be predicted and described for incremental decreases or increases of flow. The more fully documented options the planners and decisionmakers have available, the more rational and equitable the ultimate decisions.

A limitation inherent in many methodologies is the inability to correlate a totality of effects at any significant level of resolution. "Single use or effect" considerations, although sometimes necessary and certainly easier than broader scope evaluations, often resolve very little, unless a concerted effort is made to systematically identify the single most important overriding factor by the process of elimination. That is to say, it is not a wise or functional approach to consider, with a great expenditure of time, manpower and money, spawning, passage, or summer preservation flows to the exclusion of flows for overwintering eggs and fry or critical rearing habitat. Methodologies have been developed (occasionally they are ingenious approaches) that focus on establishing velocity criteria and tolerances or cover and habitat ratings, and fail to consider, in the analysis, the effects of interspecific competition or the effects on spatial distribution. A sound methodology cannot consider species without habitat and, conversely, habitat without organisms remains only a potential. To have an accurate understanding of a natural system means considering it at the systems level where inherent complexities can be evaluated within their interactive framework.

A third facet of the aquatic-riparian stream system which present methods do not address is the cumulative effects of permanent reductions or augmentations in flows. Long-term changes may be expected from cumulative effects on the following components of the system: 1) Sediment transport and depositional patterns; 2) introgravel permeability and percolation rates; 3) nutrient flow through the system and deposition of detrital materials determining microbe production rates and spatial distributions; 4) extent and time frame for vegetational changes, including emergents, the encroachment of herbaceous and woody riparian plants, and the effects on major woody plants (trees and shrubs) providing cover and shade; 5) intimately tied to the above *and perhaps most important* are changes in primary and secondary production which ultimately affect the production of fishes in a particular stream (assuming other life needs are not limiting, i.e., reproduction, cover, water quality, space).

To expedite implementation of recommendations and research needs and to place them within an operational time frame (1-3, 3-5, and < 5 years) specific recommendations and research needs are categorized as follows: 1) Recommendations 1-4 are considered in the 1- to 3-year time frame; 2) research needs 1-7 fall into the 3- to 5-year group; and 3) research needs 8-10 are long term in nature, > 5 years. Within each group, the order indicates priority. These recommendations and needs were reviewed by the IFW participants listed in Appendix 1 and generally represents a concensus of opinion as to priority.

The recommendations are considered of immediate importance as a base for standardization of planning and operation. This base is essential for furthering methodology development and will ultimately be necessary before research can contribute significantly to problem resolution and the decisionmaking process.

Recommendations

1. Standardization of Nomenclature for Instream Assessment – any effort towards operational standardization must have an accepted, standard set of terms at its disposal. Therefore, we recommend that:
   a. The nomenclature included in Section 1 should be used as a basis for arriving at a concensus of opinion concerning terminology.
   b. The discussion concerning standard nomenclature initiated at the FWS, Instream Flow Workshop (FWS, IFW), September 1975, Logan, Utah should be continued at the American Fisheries Society sponsored Symposium and Specialty Conference on Instream Flow Needs, May 1976, Boise, Idaho. A serious attempt should be made at this time to finalize and adopt standard nomenclature.
   c. The agreed upon nomenclature should be included in a "Manual of Methodologies for Assessing Instream Flow Needs" and/or otherwise made widely available to workers in this field.
2. Information Storage and Retrieval—presently, a comparatively large body of scattered information exists concerning species criteria, streamflow requirements, techniques, methods,

recommendations and results. The quantity of this type of information, as well as the need for it, is rapidly increasing. Considering the present needs and anticipating the future, a system must be adopted to provide data to involved workers in all disciplines. Therefore, we recommend that:

a. In cooperation with involved agencies and institutions, a readily accessible data storage and retrieval system should be established in a centralized location, administered by an appropriate agency. Computerized storage and retrieval are a necessity.
b. Information types should include all pertinent agency and institutional work (i.e., problem description, data needs, techniques, and analysis utilized and recommendations made). Consideration should be given to "follow-up" information, concerning the success or failure of particular projects, to complete the picture of significant projects. This approach has special value in gathering unpublished or "in-house" work and could be of considerable importance in evaluating research and water development programs.
c. All available computer programs that have direct or indirect application to the area of streamflow assessment should be compiled and included in the storage-retrieval system. Of special importance are simulations of instream hydraulic parameters at any specified stage. A wide range of disciplines should be searched for directly applicable or modifiable programs. The objective is to make these programs functional and accessible; therefore, clarification of every program must be undertaken. In most cases, this will mean writing or rewriting instructions (users guide) for inclusion in a manual (see Section 3 for additional discussion of "a modeling center").
d. Considering the immediacy of this need, the establishment of a storage-retrieval system would be best expedited by contracts for performance of this task. An 18- to 24-month contract period (includes time suggested in Section 3) should be sufficient.

3. Manual of Methodologies for Assessing Instream Flow Requirements – much of the present confusion, misunderstanding and operational inefficiency is caused by the lack of available, accurate descriptions of methodologies. Therefore, we recommend that:
   a. A concentrated effort toward completion of a "Manual" should be initiated under the auspices of an advisory group, for the purpose of evaluation of the "Manual" format and making suggestions concerning modification (possibility of contract work to expedite).
   b. Finalization of a "Manual" format and descriptions of included methodologies should be undertaken with a view towards completion and publication, in 1976, of the first segment of said "Manual."
4. Testing and Validation of Existing Methods – The direct comparison of the several approaches to reconnaissance studies utilizing historical records of flow should be carried out on at least one stream in each major U.S. drainage area (priority would put those West of the Mississippi higher). This would provide directly comparable results and would test each method under a variety of hydrologic regimes. Synthesized flow data as well as historical records should be evaluated concurrently with the above.

Research Needs

Using the preceding discussion as a base, the following research needs are outlined. An attempt has been made to place these needs in order of priority. However, this breaks down during the listing of longer term research programs in that they should be conducted simultaneously.

While items 1 and 7 below do not involve research *per se*, they are essential to a discussion of research needs and, therefore, are included here.

1. Adoption of a list of important fish species as the target organisms for instream flow assessments–this should be done for each major drainage area in the United States. Columbia, Missouri and Colorado basins should receive immediate attention. Within each basin, a further subdivision based on geohydrologic zones of the rivers present may also be necessary, e.g., pages 19-21 of Proceedings Instream Flow Methodology Workshop for classification proposed by Bauer for northwestern coastal streams (Scott, 1972). Such a standardized list of fish species should dictate the further refinement of species criteria for flow evaluation and direct research to establish additional criteria (see 2 below). Field measurements for the various species within a major drainage basin should be carried out concurrently with studies in other basins to expedite criteria

identification. Table 14 represents a first attempt (by participants at the FWS, IFW) at compiling a list of potential target organisms.

Table 14. List of candidate species for consideration as target organisms for priority research and instream flow evaluations. Prepared by participants at Instream Flow Workshop, Sept. 17-19, 1975, Logan, Utah.

Species[b]	Votes cast[a]
Rainbow trout	17
Cutthroat trout	15
Rocky Mtn. whitefish	11
Small mouth bass	9
Channel catfish	8
Brook trout	8
White sturgeon	7

[a]18 participants cast a vote

[b]57 other species were also mentioned

The compilation of the abovementioned list should take no more than one year of effort and may best be established by one or more short workshops. It is also important to establish the important competitors (undesirable fish species) in this listing.

2. Intensive research on the "target" fish species characteristics, i.e., swimming endurance, and preferred depth and velocities (criteria identification) at *all* life stages—emphasis should be placed upon early life history stages associated with the use of nursery areas.

Information of this type will be necessary before methodologies can be conceptualized for assessing the impact of augmented flows and the possible control of undesirable species by flow manipulation. Emphasis here is suggested on intensive on-site field studies of the early life stages of those target species identified above (perhaps more on the little known "undesirable species") and laboratory study of current orientation, preference and endurance of early life stages. This could be accomplished in one to three years intensive effort on each species or groups of species.

As an example of a testable hypothesis, catostomid larvae and juveniles have lower stamina than salmonid juveniles during the summer rearing period and, consequently, would suffer greater juvenile mortality under high velocity flow regimes (two to three body lengths/second).

3. Refinement of large river measuring techniques to allow for the adaptation of existing methodologies to large river environments—existing methods emphasize depth velocity criteria and rely on accurate measurements and predictions of depths and velocities throughout the study reach at different flows. This basic approach is often difficult or impossible to carry out under large river conditions. Investigations to perfect river channel mapping techniques and velocity measurement are needed. A suggested working hypothesis is that echo sounding devices and electronic direct reading probe type current meters could be adapted for large river depth velocity three-dimensional mapping. This should be solved in one to three years after initiation.

4. Intensive research is needed on the effects of extreme fluctuations and repetitive short-term fluctuations in streamflows (i.e., those resulting from peaking power operations, etc.)—emphasis should be placed on determining the life stages most vulnerable to flow fluctuations and the mechanisms by which this vulnerability is expressed. Priority should be placed on the important target species discussed above. This should involve an intensive effort of approximately five years' duration.

5. Intensive research effort on the hydraulic aspects of overwinter conditions in northern Great Plains rivers and high mountain streams where temperatures drop below - 8°C (air temperature at which subsurface ice forms) for considerable periods of time—under these extreme climatic conditions, the formation of ice (surface, frazil and anchor ice deposition can be quite extensive, often to the point of altering hydraulic parameters) and the temperature regimes of running water are intimately tied to the volume of flow. Investigations should establish the process and extent of ice formation in the interstitial spaces of gravel and rubble substrate and these processes as associated with intragravel water movement (percolation). Concurrent investigation of ice effects on invertebrates and small fishes should accompany the hydraulic research. A hypothesis to be examined is: reduced overwinter flows result in accumulations of frazil and border ice, effectively eliminating the microhabitat of small fish and forcing them into the main current of the stream where they are vulnerable to predation and exhaustion.

6. Research on the spatial dependencies, as related to velocity preferences of the indicator species in 1. above (emphasis on warm water

species) and undesirable species—a testable hypothesis could be that the optimum number of trout or centrarchids occupying a given stream reach (maximal carrying capacity) occurs at average velocities of approximately 0.5 to 1.0 body lengths/second given the same surface (stage) level.

7. Establish a list of important invertebrates much in the same manner as discussed for fish under item 1 above—perhaps this could be accomplished in conjunction with the fish species list. However, the lack of good criteria and methods for immediate application to different flow regimes is reason enough to give this recommendation lower priority.

8. Long-term (> 5 years) research is needed toward the understanding of subtle and cumulative changes in sediment and organic particulate movement in rivers. Before long-term predictions can be made concerning the fishes and invertebrates, working models of the sediment and particulate transport through the system are essential as inputs to new methodologies.

9. Long-range research is needed toward the understanding of nutrient cycling and transport in a river reach and how this is affected by permanent changes in water flows. See *Needed Methodology Development* in Section 3 for further discussion of this much needed long-term research. If computer simulation modeling is to become a useful tool to the aquatic manager, these relationships must be understood.

10. Long-term studies of aquatic insect and fish production are needed to develop discharge-production relationships which are necessary before the incremental effects of flow on carrying capacity may be quantified. This type of research under controlled discharge regimes must be monitored over several years before meaningful flow-fishery production relationships can be formulated and varified. However, once established, such relationships, in conjunction with computer simulation models of stream ecosystems, should place the biologist in the forefront in negotiating trade-offs with water development interests rather than simply reacting to dictates of these other interests.

REFERENCES CITED

ANDERSON, R.
1975. A study of the impacts of reduced stream flows in the middle and lower Yellowstone basin. Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 226-232.

ANONYMOUS.
1973. Method for recommending stream flows to meet national forest needs (critical area method). USFS. Mimeo Rept. 6 p.

ANONYMOUS.
1974. Instream needs subgroup report, work group C, water. Northern Great Plains Resource Program. Unpub. MS. 35 p.

ARTHUR, J. F.
1963. The relationship of water velocities to aquatic insect populations on the Kern River, Kern County, California. Rep. for Independent Study 290, Dept. of Biology, Fresno State College, Fresno, California.

BALDES, R. J., and R. E. VINCENT.
1969. Physical parameters of microhabitats occupied by brown trout in an experimental flume. Trans. Amer. Fish. Soc. 98(2):230-238.

BANKS, R. L., J. W. MULLAN, R. W. WILEY and D. J. DUFEK.
1974. The Fontenelle Green River trout fisheries-considerations in its enhancement and perpetuation, including test flow studies of 1973. FWS, Salt Lake City, Utah. 74 p.

BISHOP, R. A., and J. W. SCOTT.
1973. The determination and establishment of minimum stream flows in Washington State. Washington Dept. of Ecology, Olympia, Wash. Draft Rep. No. 73-033. 81 pp.

BLAXTER, J. H. S.
1969. Swimming speeds of fish. *In* Ben-Tuvia, A. and W. Dickson (eds.), Proc. FAO Conf. on fish behavior in relation to fishing techniques and tactics. FAO Fish. Rep. No. 62, Vol. 2 (FRm/R62.2). Rome, Italy.

BOVEE, K. D.
1974. The determination, assessment and design of "instream value" studies for the Northern Great Plains region. Univ. Montana. Final Rep. EPA Contract No. 68-01-02413. 204 p.

BOVEE, K. D.
1975. Assessment and implementation of "in-stream value studies" for the Northern Great Plains, Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 112-123.

BRUSVEN, M. A., C. MACPHEE and R. BIGGAM.
1974. Benthic insects, Chap. 5. *In* Bayha, K. (ed). The Anatomy of a River. Report of the Hells Canyon Task Force. Pacific N. W. River Basins Comm. pp. 67-79.

CARLANDER, K. D.
1969. Handbook of freshwater fishery biology. Vol. 1. Iowa State Univ. Press, Ames, Iowa. 752 p.

CHAMBERS, J. S., G. A. ALLEN, and T. PRESSEY.
1955. Research relating to study of spawning grounds in natural areas. Washington Dept. of Fish. Olympia, Wash. Unpub. MS. 175 p.

CHAPMAN, D. W.
1966. Food and space as regulators of salmonid populations in streams. Amer. Natur. 100-345-357.

CHOW, V. T.
1964. Handbook of applied hydrology. McGraw-Hill Book Co. N. Y. 1000 p.

CHROSTOWSKI, H. P.
1972. Stream habitat studies on the Uinta and Ashley National Forests, USFS, Intermountain Reg. Ogden, Utah. 148 p.

CLAY, C. H.
1961. Design of fishways and other fish facilities. Canadian Dept. of Fish. 301 p.

COBLE, D. W.
1961. Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. Trans. Amer. Fish. Soc. 90(4):469-474.
COLLINGS, M. R.
1972. A methodology for determining instream flow requirements for fish. *In* Proc. Instream Flow Methodology Workshop, Washington, Dept. of Ecology, Olympia, Wash. pp. 72-86.
COLLINGS, M. R., R. W. SMITH and G. T. HIGGINS.
1972a. The hydrology of four streams in western Washington as related to several Pacific salmon species. USGS, Water-Supply Paper, 1968. 109 p.
COLLINGS, M. R., R. W. SMITH and G. T. HIGGINS.
1972b. The hydrology of four streams in western Washington as related to several Pacific salmon species, Humptulips, Elochoman, Green and Wynoochee Rivers. USGS, open-file rep. 128 p.
COLLINGS, M. R., and G. W. HILL.
1973. The hydrology of ten streams in western Washington as related to several Pacific salmon species, USGS, Water-Resources Inv. 11-73, 149 p.
COLLINGS, M. R.
1974. Generalization of spawning and rearing discharges for several Pacific salmon species in western Washington. USGS, open-file rep. 39 p.
CURTIS, B.
1959. Changes in a river's physical characteristics under substantial reductions in flow due to hydroelectric diversion. Calif. Fish and Game 45(3):181-188.
DELISLE, G. E.
1962. Water velocities tolerated by spawning kokanee salmon. Calif. Fish and Game. 48(1):77-78.
DESCHAMPS, G., S. WRIGHT and J. K. MAGEE
1966. Biological and engineering fishery studies. Wynoochee Reservoir, Washington. Washington State Dept. of Fish., Olympia, Wash. Summ. Rep. 40 p.
DOOLEY, J. M.
1975. Application of U.S. Bureau of Reclamation Water Surface Profile program (WSP). Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 138-154.
DUNHAM, D. K., and A. COLLOTZI.
1975. The transect method of stream habitat inventory, guidelines and applications. USFS, Intermountain Reg., Ogden, Utah, Unpub. MS. 98 p.
ECONOMIC COUNCIL OF CANADA.
1971. Design for decision making. Ottowa, Canada. 249 p.
ELSER, A. A.
1972. A partial evaluation and application of the Montana method of determining stream flow requirements. *In* Proc. Instream Flow Requirement Workshop, Pacific N. W. River Basins Comm. Portland, Oregon. pp. 3-8.
ELSER, A. A.
1975. Fish distribution and diversity of a Montana prairie stream. Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 124-137.
EVEREST, F. H., and D. W. CHAPMAN.
1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. J. Fish. Res. Bd. Canada. 29:91-100.
FRASER, J. C.
1972. Regulated stream discharge for fish and other aquatic resources: an annotated bibliography. FAO Fisheries Tech. Paper, No. 112 (FIRI/T111), FAO/UN, Rome, Italy. 103 p.
GANGMARK, H. A., and R. G. BAKKALA.
1958. Plastic standpipe for sampling stream bed environment of salmon spawn. FWS, Spec. Sci. Rep. Fish. No. 261. 20 p.
GIGER, R. D.
1973a. Streamflow requirements for salmonids. Oregon Wildl. Comm. Job Final Rep., Project AFS 62-1. 117 p.
GIGER, R. D.
1973b. Stream flow requirements for salmonids. Oregon Wildl. Comm. Job Final Rep., Project AFS-62. 11 p.
HARTMAN, G. F.
1963. Observations on behavior of juvenile brown trout in a stream aquarium during winter and spring. J. Fish. Res. Bd. Canada 20:769-787.
HERRINGTON, R. B., and D. K. DUNHAM.
1967. A technique for sampling general fish habitat characteristics of streams. USFS Res. Paper INT-41. 12 p.
HOOPER, D. R.
1973. Evaluation of the effects of flows on trout stream ecology. Pacific Gas and Elec. Co., Emeryville, Calif. 97 p.
HOPPE, R. A., and L. M. FINNELL.
1970. Aquatic Studies on Fryingpan River, Colorado – 1969-70. BSFW, Div. of River Basin Studies. Mimeo Rep. 12 p.
HUNTER, J. W.
1973. A discussion of game fish in the state of Washington as related to water requirements. Washington State Dept. of Game, Olympia, Wash. Unpub. MS. 66 p.
HYNES, H. B. N.
1970. The ecology of running waters. Univ. of Toronto Press. 555 p.
JONES, D. R.
1973. An evaluation of the swimming performance of several fish species from the Mackenzie River. Dept. of the Envir., Fish. Marine Ser., Winnipeg, Manitoba. 53 p.
KALLEBERG, H.
1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (*Salmo salar* L. & *S. trutta* L.). Inst. Freshwater Res. Drottingholm. 39:55-98.
KELLEY, D. W., A. J. CORDONE, and G. DELISLE.
1960. A method to determine the volume of flow required by trout below dams: A proposal for investigation. Calif. Dept. of Fish and Game.
KENNEDY, H. D.
1967. Seasonal abundance of aquatic invertebrates and their utilization by hatchery reared rainbow trout. BSFW, Tech. Paper No. 12. 41 p.
LEWIS, S. L.
1969. Physical factors influencing fish populations in pools of a trout stream. Trans. Amer. Fish. Soc. 98:14-19.
MACAN, T.T.
1961. A review of running water studies. Vert. Internat. Verein. Limnol. 14:587-602.
MACAN, T. T.
1962. Ecology of aquatic insects. Annual Rev. Ent. 7:261-288.
MCCLAY, W.
1968. Effects of controlled flow reductions on aquatic insects in a stream riffle. M. S. thesis, Montana State Univ., Bozeman, Montana. 29 p.
MUNTHER, G. L.
1975. Fishery effects of irrigation diversion and related structures—An interim fisheries manage-

ment plan for the Sawtooth National Recreation Area. USFS, Reg. 4, Sawtooth National Forest. 119 p.

NEEDHAM, P. R., and R. L. USINGER.
1956. Variability in the macro-fauna of a single riffle in Prosser Creek, California, as indicated by the Surber sampler. Hilgardia 24(4):383-409.

OREGON STATE GAME COMMISSION.
1972. Determining stream flows for fish life, Appendix No. 1. *In* Proc. Instream Flow Requirement Workshop, Pacific N. W. River Basins Comm., Portland, Oregon. pp. a-m.

PACIFIC NORTHWEST RIVER BASINS COMMISSION.
1974. Need for a coordinated and expanded program of instream flow evaluation data in the Pacific Northwest. Ad Hoc Instream Flow Study Evaluation Comm. Evaluation Rep. 28 p.

PAULIK, G. J.
1959. The locomotive performance of salmonids during upstream migration. Univ. of Washington, Seattle, Wash. Ph.D. dissertation. 216 p.

PEARSON, L. S., K. R. CONOVER and R. E. SAMS.
1970. Factors affecting the natural rearing of juvenile coho salmon during the summer low flow season. Oregon Fish. Comm., Portland, Oregon. Unpub. MS. 64 p.

PETERMAN, L. G., and M. H. HADDIX.
1975. Preliminary fishery investigations on the lower Yellowstone River. Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 97-111.

POLLARD, R. A.
1955. Measuring seepage through salmon spawning gravel. J. Fish. Res. Bd. Canada 12(5):706-741.

RANTZ, S. E.
1964. Stream hydrology related to the optimum discharge for King Salmon spawning in the Northern California Coast Ranges. USGS, Water Supply Paper 1779-AA. 16 p.

RECHARD, P. A., and T. A. WESCHE.
1973. Stream channel modification to maximize available trout habitat under low flow conditions. Proposal, Water Resour. Res. Instit., Univ of Wyoming, Laramie, Wyoming.

ROBINSON, E. H.
1969. A procedure for determining desirable stream flows for fisheries. FWS, Mimeo Rep. 12 p.

SAMS, R. E., and L. S. PEARSON.
1963. A study to develop methods for determining spawning flows for anadromous salmonids. Oregon Fish Comm. Unpub. MS. 56 p.

SAVAGE, J. L.
1962. Methods used in salmon spawning area surveys. *In* Minutes of the Second Annual Meeting Calif. Dept. Fish and Game Water Projects and Pollution Conf. pp. 20-39.

SCOTT, J. W.
1972. A uniform classification system. *In* Proc. Instream Flow Methodology Workshop, Washington Dept. of Ecology. Olympia, Wash. pp. 17-21.

SCOTT, W. B., and E. J. CROSSMAN.
1973. Freshwater fishes of Canada. J. Fish Res. Bd. Canada, Bull. 184. 966 p.

SHERIDAN, W. L.
1962. Water flow through a salmon spawning riffle in southeastern Alaska. FWS, Spec. Sci. Rep. Fish. No. 407. 20 p.

SMITH, A. K.
1973. Development and application of spawning velocity and depth criteria for Oregon salmonids. Trans. Amer. Fish. Soc. 102(2):312-316.

STALNAKER, C. B., J. L. ARNETTE, I. DIRMHIRN, C. W. FOWLER, R. W. JEPPSON, R. A. VALDEZ and J. H. WLOSINSKI.
1975. Effects of reduced stream flow upon trout populations. Final Rep. on Phase I, Coop. Fish. Unit, Utah State Univ., Logan, Utah. 316 p.

SURBER, E. W.
1951. Bottom fauna and temperature conditions in relation to trout management in St. Mary's River, Augusta County, Virginia. Va. J. Sci. 2:190-202.

TENNANT, D. L.
1975. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Unpub. MS. 18 p.

TERHUNE, L. D. B.
1958. The Mark VI Groundwater Standpipe for measuring seepage through salmon spawning gravel. J. Fish. Res. Bd. Canada 15(5):1027-1063.

THOMPSON, K. E.
1972. Determining streamflows for fish life. *In* Proc. Instream Flow Requirement Workshop, Pacific N. W. River Basins Comm., Portland, Oregon. pp. 31-50.

THOMPSON, K. E.
1974. Salmonids—Chap. 7. *In* Bayha, K. (ed.). The Anatomy of a River. Report of the Hells Canyon Task Force. Pacific N. W. River Basins Comm. pp. 85-103.

TRUMBULL, L. E., and D. LOOMIS.
1973. Instream flow needs for Idaho stream development of determinative methodology. Idaho Water Resour. Bd., Boise, Idaho. 77 p.

WATERS, T. F.
1969. Invertebrate drift-ecology and significance to stream fishes. *In* Symposium on salmon and trout in streams, H. R. MacMillan Lectures in Fisheries, Univ. B. C., Vancouver, B. C. pp. 121-134.

WESCHE, T. A.
1973. Parametric determination of minimum streamflow for trout. Water Resour. Res. Inst. Rep., Univ. of Wyoming, Laramie, Wyoming. 102 p.

WESCHE, T. A.
1974. Relationship of discharge reductions to available trout habitat for recommending suitable streamflows. Water Resour. Res. Inst. Rep., Water Resour. Series No. 54, Univ. of Wyoming, Laramie, Wyoming.

WESCHE, T. A., and P. A. RECHARD.
1973. Parameters influencing minimum streamflow. Hydraulic Eng. pp. 21-30.

WESTGATE, J.
1958. The relationship between flow and usable salmon spawning gravel. Cosumnes River, 1956. Region 2, Inland Fisheries: Calif. Dept. Fish and Game. Inland Fish. Admin. Rep. No. 58-2.

WHITE, R. G.
1975. A proposed methodology for recommending stream resource maintenance flows for large rivers. *In* Stream Resource Maintenance flow Studies. A cooperative Project: Idaho Dept. Water Resour., Idaho Dept. Fish and Game, Idaho Coop. Fish. Res. Unit. pp. 3-20.

WICKETT, W. P.
1954. The oxygen supply to salmon eggs in spawning beds. J. Fish. Res. Bd. Canada 11(6):933-953.

WICKHAM, G. M.
1967. Physical microhabitat of trout. M. S. thesis, Colorado State Univ., Fort Collins, Col. 42 p.

WLOSINSKI, J. H., and C. B. STALNAKER.
1975. Development and analysis of a general stream simulation technique. Proc. Fort Union Coal Field Symp., Vol. II. Montana Acad. Sci. pp. 167-178.

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5. METHODOLOGIES FOR ASSESSING INSTREAM FLOWS FOR WILDLIFE

J. A. KADLEC

CONTENTS

Formal methodologies for determining instream flow requirements for wildlife purposes do not exist. This is true at least in the sense of, for example, the "Oregon method" for fishery considerations. The remainder of this section is therefore devoted to consideration of 1) some methods that have been used to evaluate the effects of water resource developments and might be modified for instream flow use, 2) some research currently in progress having implications for assessment of instream flow problems, and 3) needed methodologies and priority research.

Arguing from the basic ideas of wildlife science, one can postulate at least four classes of effects of altered flow regimes: 1) Removal of drinking water for terrestrial birds and mammals (not all require it); 2) altered flow patterns or volumes may directly affect aquatic wildlife such as beaver or muskrat; 3) lowered water tables will alter riparian vegetation, eliminating essential elements of habitat for some species; 4) changed patterns of flooding may affect wetland habitats such as willows and marshes which depend on flood waters for their maintenance.

Only the first two of these are direct, yet they are not likely to be of major importance unless the flow is stopped completely. Reduced flood flows might benefit beaver, muskrat, and waterfowl. Very low flows might be inadequate to compensate for increased evaporation from beaver ponds.

Most serious effects are likely to be from changed hydrologic-hydraulic regimes, including groundwater, and the resultant effects on vegetation and habitat. The importance of riparian vegetation for wildlife is well known and well documented. It is particularly critical for wildlife in arid to semiarid regions (Oliver, 1974; Carothers and Johnson, 1975). In a sense, one might consider wildlife a third-order response to changed flows; vegetation changes, second order; and hydrologic changes, first order. Methodologies to assess instream flow regimes for wildlife, therefore, depend on understanding the complex cause-effect chain.

EXISTING METHODOLOGIES

Assessment of change in wildlife resources as a result of water resource development generally fall in three categories: 1) Assessment based on area affected or animal "units" lost or imperiled (Metzgar and Wharton, 1968; Barstow, 1971; Oliver, 1974); 2) assessment based on changes in amount or quality of riparian vegetation (Russell, 1966; Burbank, 1972; Bovee, 1974; Carothers and Johnson, 1975); 3) assessment based on hydraulic changes (Leopold and Leonard, 1966; Oliver, 1974).

Wildlife studies have generally concentrated on the areas to be inundated by large water development projects (e.g., Oliver, 1974). Studies concerning riparian vegetation have been either of cultural effects (e.g., Russell, 1966; Burbank, 1972) or of total diversion (e.g., Carothers and Johnson, 1975), but studies of the effects of flow alterations are now under way.[1,2,3]

[1] Personal communication. 1975. R. Ohmart. Arizona State University, Tempe, Arizona.

[2] Personal communication. 1975. R. Martinka. Montana Fish and Game Dept., Miles City, Montana.

[3] Personal communication. 1975. J. Howerton. Washington Dept of Game, Olympia, Washington.

Methodologies used in these assessments have generally relied upon standard techniques, such as presented in the *Wildlife Techniques Manual* (Giles, 1971). The techniques involved include: 1) Cover mapping from aerial photos; 2) habitat assessment by ground methods; and 3) estimation of wildlife populations. Since none of these pertain directly to the assessment of instream flow requirements, and they are covered extensively in textbooks and manuals, they will not be discussed here. It is assumed that these sources are available to any biologist.

Various techniques may be used to evaluate the impact of change on wildlife. Generalized examples, emphasising habitat, are presented in the following: 1) *Quantity Changes* – Existing amounts of habitat may be mapped or sampled by some classification system (Russell, 1966; Metzgar and Wharton, 1968; Evans and Gilbert, 1969; Barstow, 1971; Burbank, 1972; U.S. Fish and Wildlife Service, 1974), and/or wildlife populations may be estimated directly (Oliver, 1974) and changes measured by before-and-after studies.[1] 2) *Quality Changes* – Quantity change methods may be modified to account for quality change (Allan, 1956; Barstow, 1971; Daniel and Lamaire, 1974; U.S. Fish and Wildlife Service, 1974; Carlson and Cringan, 1975). In essence, a factor is applied to weight the quantity change to account for the greater or lesser value of some habitats or greater or lesser anticipated impact on the habitat. 3) *Distribution of Vegetation* – Diversity of habitat is considered important to wildlife diversity and abundance. Beard's (1953) method of estimating interspersion might be modified to be of some use. Evans and Gilbert (1969) also made use of distribution of habitat features. The number of different habitat types per unit area can be counted, but the results of this method may be materially affected by the choice of sample unit size.[4] Measurement of the length of interfaces between habitat types (Novy, 1973; Albers, 1975) has promise, but also can be biased by sample unit size. In all these cases, it is assumed that vegetation change can be predicted and this in turn can be related to wildlife abundance.

The general approach, or selected aspects, of the above studies and techniques might be modified for instream flow assessment purposes. One might hypothesize some hydraulic change and consequent effects on various habitat types. The existing habitat types could be inventoried (e.g., air photos, ground mapping, etc.) and changes projected based on the anticipated effects. One could then either assume a proportional change in wildlife use or make weighted estimates. All elements of this procedure exist in the various reports cited. However, the extension to assessment of instream flow requirements for wildlife, to the author's knowledge, has not been made [In one case, a study of the effects of an actual change in flows has been used to recommend a flow regime for one species, the Canada goose (Merrill and Bizeau, 1972; Parker, 1973, 1975; Bayha, 1974)]. In principle, however, one could hypothesize a whole series of flow regimes, project their effects on wildlife, and present those data as a basis for decisionmaking.

On a purely hypothetical basis, one might project four kinds of relationships (Figure 1).

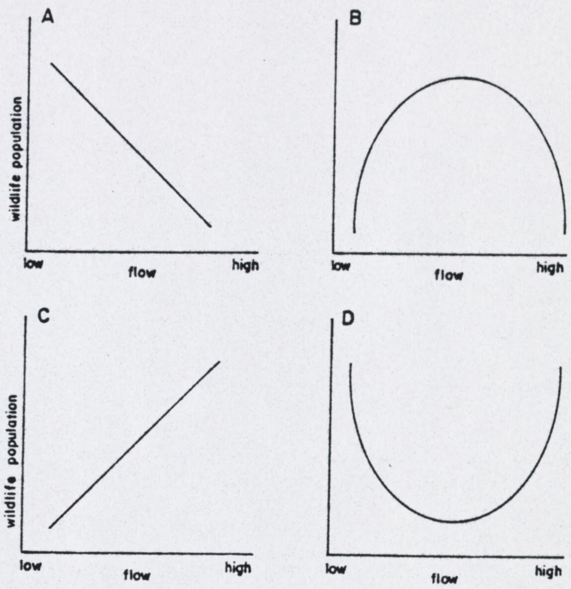

Figure 1. Generalized relationships between flow and wildlife populations.

In situations A, C, and D (Figure 1), there is no biological criterion for specifying a flow unless one first decides, on other grounds, what population level is desired. In B, a biological optimum exists, but even then any minimum or maximum is contingent on an external decision. In multiple species situations, one might expect whole families of curves and mixtures of the four types, further

[4]Personal communication. 1975. F. E. Smith. School of Design, Harvard University, Cambridge, Mass.

complicating the decision process. A special case concerning all four graphs exists where the slope of the line over the range of possible flows is 0—i.e., the line is horizontal (or nearly so) and there is no detectable effect on wildlife populations as a consequence of flow variation.

The general approach discussed above is quite similar to the habitat based approaches to assessing instream flow requirements of fish. At least two differences are important: 1) Wildlife is dependent, in many cases, on nonaffected as well as affected areas, making the relationship between habitat change and population change nonlinear; and 2) the recognition that, in many cases, externally set requirements for wildlife will affect requirements for instream flow.

It is possible, in principle, to apply this approach to studies on any level by altering the levels of assumptions and data required. For example, a reconnaissance study might use only aerial photo interpretation for data and depend heavily on assumptions about changes in habitat and habitat-wildlife relationships. Limited on-site field studies might utilize extensive ground surveys of habitat and some crude wildlife population indices. Fewer assumptions would need to be made. For intensive on-site field studies, more precise, detailed wildlife data might be obtained and knowledge of discharge-habitat relationships might be sufficient so that few assumptions would be necessary.

CURRENT RESEARCH

Several studies are currently in progress to evaluate the effects of altered flows on wildlife. In Arizona, Ohmart and colleagues are studying birds and mammals associated with riparian vegetation along the Colorado River.[1] The study is basically a before-and-after approach, but the ultimate objective is the construction of models having predictive capability. Approximately 1 1/2 years of baseline data are in hand.

Along the Snake and Columbia Rivers, another group is studying the effects of daily variations in flows due to fluctuating water use for hydropower peaking.[3] The first phase of the study is an inventory of habitats and associated wildlife conducted by the Oregon, Washington, and Idaho Cooperative Wildlife Research Units. Phase II is in the design stage and will be directed at determining changes in vegetation and the resulting effect on wildlife.

The effects of reduced flows on furbearers and waterfowl, in the Yellowstone River, Montana are being studied.[2] Beaver cache sites and goose nest sites are being evaluated in terms of the river characteristics where they exist. In conjunction with fieldwork, an historic approach is being used to evaluate habitat change by comparing recent aerial photos with others taken in the 1930's. The objective is to derive specifications for river flow patterns needed for these species.

Studies are under way on the relations among flows, sediments, and riparian vegetation on the delta of the Mackenzie River.[5]

A series of studies of goose nesting on the South Fork of the Snake River in Idaho correlated nesting success with patterns of flow (Merrill and Bizeau, 1972; Parker, 1973, 1975). The conclusion at this point in time is "that high steady spring releases (above 8,000 cfs) from Palisades Dam will provide the maximum amount of goose nesting habitat and will probably result in high numbers of goslings produced on the South Fork". (Parker, 1975:6)

In each of the foregoing studies, it is possible to recognize elements of the habitat-based approach suggested as a modification of water development assessment procedures. In several, flow or river characteristics necessary for certain species or habitats are considered. These are important links in the knowledge needed to provide input for instream flow decisions. Inventories are basically a first step in all cases. Habitat requirements for one or more species are also under investigation. The Snake River goose nesting studies are outstanding in having been carried to the point of specifying flows.

These studies are all relatively intensive, generally at the field study level, although some have application for reconnaissance studies. Research of the on-site field study type has the advantage that it provides a basis for the assumptions necessary for broader scale decisionmaking.

In this section, as in the previous, the techniques for gathering the data are habitat surveys, wildlife population estimation, and air photo interpretation. Their usefulness and/or appropriateness often depends, basically, on cost-benefit considerations. It does not seem appropriate to single out some, yet all can't be

[5]Personal communication. 1975. D. Gill. Boreal Research Center, University of Alberta, Alberta, Canada.

considered here. Perhaps it will suffice to say all might be useful on occasion.

NEEDED METHODOLOGIES

One might sum up the foregoing by reiterating the opening statement on wildlife, "Formal methodologies for determining instream flow requirements for wildlife purposes do not exist." A *de facto* method that does exist is to gather whatever information is possible on habitats and wildlife and then rely on the judgment of a trained wildlife biologist. This approach may often be biologically adequate; however, in many situations (e.g., the courts), a more sophisticated, quantitative procedure will be a necessity.

Where more definitive data are required, two strategies appear possible. One may either take into account the discharge regime → vegetation → wildlife causal chain or attempt to correlate wildlife and the discharge regime empirically. Either approach implies a detailed inventory and/or the existence of studies (data) which have established sets of relationships. Detailed inventory procedures for both habitats and wildlife are available and are constantly being improved. A basic familiarity with these procedures is assumed.

Empirical relationships between wildlife and flow regimes require studies of nearly every species vs. a variety of discharge regimes. This background data basically requires before-and-after studies of either controlled (experimental) or uncontrolled situations. In time, a body of "rules of thumb" might emerge sufficient to guide flow decisions. However, there is no guarantee that results or recommendations for different wildlife species would not contradict each other.

A two-step procedure that examines relationships between discharge regimes and habitat and then habitat and wildlife seems to have more inherent potential for generalizing to a wide variety of situations. Again, this is basically the discharge-habitat approach of the fishery biologist.

Reconnaissance Studies

At this level, only a general data base is possible. National and regional statistics on wildlife populations, hunting pressure and harvest are an example. The national inventory of forest and range resources, including fish and wildlife, mandated by the Forest and Rangelands Renewable Resources Planning Act of 1974 (PL 93-378), should provide aggregated data useful at this level of assessment. In addition to agency files (statistics and inventories), data sources may be mainly aerial photos and published, unpublished, and ongoing studies.

Relating this type of data to instream flow requirements will depend on a knowledge of the regional importance of instream flow to habitats and, in turn, the regional importance of the stream-dependent habitats. For example, in the arid Southwest, the riparian habitats far outweigh all others in wildlife abundance and variety. In contrast, in humid areas, reduced flows will have less general impact on wildlife, but certain key habitats for some species may be affected, e.g., pin oak flats for ducks (Merz and Brakhage, 1962).

The methodologies necessary for reconnaissance assessment depend on assembling information into relatively broad "rules of thumb." One might, for example, be able to attach numbers (at a specified order of magnitude) to a graph such as Figure 1-C.

Fundamentally, knowledge adequate for this level of assessment and prediction probably exists. However, it is necessary to devote enough thought to the problem to establish a set of standard procedures to 1) improve comparability of recommendations, and 2) provide guidance to personnel involved. For example, an approach modified from that used by Carlson and Cringan (1975) or the Joint Federal-State-Private Conservation Organization Committee (U.S. Fish and Wildlife Service, 1974) might be used. An approach of this type should involve an adequate inventory of habitat, using methods such as aerial photography, and subjective estimates of impacts of discharge alterations on wildlife. In this, as in all cases, a major problem will be establishing criteria for deciding what impacts on wildlife are acceptable. Given such criteria, and knowledge of regional vegetation-hydrology relationships, recommendations for flows can be made.

On-Site Field Studies – Limited and Intensive

Most of the studies identified by this survey are in this category, but still they do no more than suggest possible approaches for assessing instream flow requirements.

Part of the problem is the very large number of wildlife species which might be affected by any decision concerning existing flow regimes. Ultimately, one might want to use the detailed habitat requirements of a host of individual species ranging from songbirds to moose. Our knowledge is now at a relatively imprecise level for most of these. The degree of their dependence on riverine and riparian habitats is, in general, not well understood. The effects of changes in those habitats is often very difficult to predict.

Several possibilities can be listed as aids to approaching the problem. First, we can consider wildlife by groups rather than one species at a time. Important criteria for such grouping include organism size, mobility, and migratory habitats (specific dependence on the riverine or riparian habitat is clearly important, e.g., beaver). Either altitudinal or latitudinal migrations may result in seasonal dependence on the affected habitat. Song birds nest in large numbers in the riparian zone in summer. Many go south for the winter, but others from more northerly regions may arrive to take their place. Big game (e.g., elk, deer, etc.) may depend on river or stream bottoms as winter habitat.

For many groups and, in many cases, individual species, predictions of the effect of complete elimination of habitats are not difficult. Those restricted to the habitat (total dependence) at any time will be eliminated. If the habitat in question is only one element of the total habitat used, some lesser or even negligible effect may occur. Similarly, if the habitat is not eliminated, but only moved or reduced, it may be very difficult to make predictions based on currently available information.

Reliable data on total dependence is available in most cases. However, data for use in the less closely coupled circumstance is, in general, lacking. The effect on moose of a 50 percent reduction in willow in a mountain stream valley is not necessarily a 50 percent reduction unless that willow, as winter food, is *the* limiting factor for that moose population. It simply cannot be assumed that is the case.

As a general approach:

$Y = f(X_1, X_2, X_3, \ldots, X_n)$ . . . . (1)

in which Y is the wildlife population or population of interest; and the X_i are the habitat variables. In the simplest case,

$Y = aX$. . . . . (2)

That is, the population is linearly dependent on a single critical limiting habitat variable as in the moose-willow example above. Unfortunately, in most cases there are many X's and the relationships are nonlinear. In these instances, we often have only the crudest estimates about the effects of varying a single X. Yet that would appear to be the level of information needed for field study methodologies. For example, the X_i's for beaver might be adequate flows to maintain ponds, the amount of aspen available for winter food, the amount of herbaceous wetland vegetation for summer food, and the amounts of willow and alder as alternate foods. The X_i's for waterfowl in a northern riverine marsh might include macroinvertebrates and plant seeds for food; emergent vegetation for nesting, brood rearing, and molting; and some upland for nesting of some species; and the migration and wintering habitats required to maintain the population throughout the year. Muskrats in the same marsh may be more closely dependent on adequate water depths for winter survival under ice as well as cattails and bulrushes for food and house construction.

For big game, riparian habitats in most cases serve only a part-time need; the population is also dependent on a variety of upland habitats. The regional variation in this case is apparent; in the Southwest, the riparian vegetation may be vital.

Obviously, this sort of list could go on and on. Hence, the necessity, exists for either an indicator species approach, assignment of priorities, or grouping into relatively few, but meaningful, groups. The *Ecological Planning and Evaluation Procedures* (U.S. Fish and Wildlife Service, 1974) recognize this as follows:

> Habitat-type evaluation criteria for the species of each major fauna grouping per zoogeographic region will be developed by the State fish and wildlife agencies and the USFWS during the next 3 years. The key habitat evaluation criteria will be listed in a ***Regional Handbook for Key Habitat-Type Evaluation Criteria for the Species of Each Major Grouping of Associated Fauna.*** (U.S. Fish and Wildlife Service, 1974:24)

Quite clearly, the foregoing assumes that the effect of streamflow on the X_i is known:

$X_i = f_i(Q)$. . . . . (3)

in which Q is the flow, and f_i is the function that specifies the impact of the flow regime on the i^{th} habitat variable. Presumably, such data are available, but the scope of this survey did not include the botanical-hydrological-hydraulic literature apropos this need.

Equations 1 and 3 can be combined:

$Y = f(Q)$. . . . . (4)

This provides a relationship that functionally is often very complex and would require an enormous data base to specify adequately. For some species, such as beaver, this may be a viable approach.

Assuming that the general methodology outlined previously is logical, research necessary to improve or expand on that which is known may be categorized as follows: 1) Specifying any "f's"; 2) summarizing species or species groups by their degree of dependence on riverine habitats (should emphasize totally dependent species); 3) picking indicator species and/or groups for each major river basin and included stream categories; and 4) establishing the relationship between riparian vegetation and instream flow.

WETLANDS – A SPECIAL CASE

Among riverine wildlife habitats, wetlands are often of critical importance. Wetlands in general have received much attention over the past 50 years. It is now reasonably well documented that the most productive marshes are those subject to alternate inundation and drying (Harris, 1957; Kadlec, 1962; Kadlec and Wentz, 1974; and Wentz et al., 1974). The frequency of the fluctuations varies widely, as does the amplitude. Presumably, there are critical values of both, but they have not been established. The absence of fluctuations, following upstream dam construction, on the Peace-Athabasca Delta resulted in enormous decreases in waterfowl habitat (Dirschl, 1972). In this study, the natural regime included annual flooding that "briefly flooded most of the delta, resulting in recharging of lakes and perched basins, deposition of silt and plant seeds, ingress of nutrients and flushing of products of plant decomposition." (Dirschl, 1972:5) On the other hand, the impoundments creating high value marshes on the Bear River Delta in Utah, may be most productive under a constant water level pattern.[6] Christiansen and Low (1970) studied water requirements of marshes in northern Utah, primarily from the point of view of maintaining critical levels. Ohmart et al. (1975) have examined historical changes in wetlands associated with the lower Colorado River and concluded that most did not last more than 50 to 70 years.

From the foregoing, it is clear that: 1) many marshes require periodic inundation to maintain productivity, and 2) it is essential to have a water supply adequate to avoid unwanted drying of the wetland. Such general statements may be adequate for reconnaissance and limited on-site field studies, but, in most cases, a more detailed level of assessment is desirable if not necessary. In tidal areas, research has clarified the role of regular water movements in nutrient supply and particulate exchanges (Leach, 1971). Similar studies are needed in riverine wetlands to demonstrate the functional relationships between various hydrologic regimes and marsh productivity. Even with the enormous amount of available data on waterfowl, clear-cut, quantitative, functional relationships between habitat and populations are essentially nonexistent. In terms of the earlier discussions, the "f" in the equations is unknown.

RESEARCH PRIORITIES

General

1. Function of flood flows in maintaining nonchannel habitats such as marshes, deltas, wooded bottomlands, and riparian belts.
2. Detailed study of "f's" of species known to be highly dependent on stream and streamside habitats, e.g., moose, beaver, muskrat, otter, mink, waterfowl, herons and bitterns, passerines such as the yellow warbler, marsh wren, red-winged blackbird, and certain raptors, etc. Two approaches should be considered: a) Species groups; and b) indicator species.
3. Specification of "f's" of other species or species groups at a less precise level. Some of this can be done by appropriate literature search, summarization, and modeling.

Specific

Within category (1) above, priorities are probably best varied regionally. Riparian habitat maintenance is probably most critical in the West. Marshes and deltas seem of highest priority in the East, but are also very important in the West. The relation of wooded bottomlands to flow regimes is clear and seems in less need of immediate research.

In categories (2) and (3), the specific priorities must be based on the species or species group and level of effort involved. A possible approach would be to consider rare, endangered, or threatened species first, then exploited species, assuming the

[6]Personal communication. 1975. E. Peabody. FWS, Bear River Refuge, Brigham City, Utah.

additional threat to their numbers via habitat change may be crucial; and then a selection of a variety of other species which might be of value as indicators of habitats requiring specific instream flows.

Studies of well-known species designed to capitalize on existing knowledge by organizing, refining, and supplementing it with minimal field study would seem to promise usable information rapidly, obviously an important criterion. However, critical species, even if poorly known, would demand attention first. The information gaps are so large that it is doubtful that poorly known, incidental species could ever receive attention. There is some hazard that one of those species could turn out to be of vital importance, but with restricted resources, that is a risk that must be taken.

REFERENCES CITED

ALBERS, P. H.
1975. Avian habitat selection in a region of intensive agriculture: The red-winged blackbird. Unpub. Ph.D. Thesis, Univ. of Mich. 189 p.

ALLAN, P. F.
1956. A system for evaluating coastal marshes as duck winter range. J. Wildl. Manag. 20(3):247-252.

BARSTOW, C. J.
1971. Impact of channelization on wetland habitat in the Obion-Forked Deer Basin, Tenn. Trans. 36th North Amer. Wildl. and Natur. Resour. Conf. pp. 362-373.

BAYHA, K.
1974. Wildlife – Chap. 11. *In* Bayha, K. (ed.). Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N. W. River Basins Comm. pp. 121-122.

BEARD, E. B.
1953. The importance of beaver in waterfowl management at the Seney National Wildlife Refuge. J. Wildl. Manag. 17(4):398-436.

BOVEE, K. D.
1974. The determination, assessment, and design of "in-stream value" studies for the northern Great Plains region. Final Rep. EPA Contract No. 68-01-2413. 204 p.

BURBANK, J. H.
1972. A quick method to assess streamside wood duck breeding habitat. Proc. 26th Annu. Conf. S. E. Assoc. of Game and Fish Comm. pp. 205-206.

CARLSON, L. W., and A. T. CRINGAN.
1975. Oil shale development and wildlife in northwestern Colorado. Wildl. Soc. Bull. 3(1):7-12.

CAROTHERS, S. W., and R. R. JOHNSON.
1975. Water management practices and their effects on nongame birds in range habitats. Proc. Symp. on Manag. of Forest and Range Habitats for Nongame Birds, USFS General Tech. Rep. WO-1. pp. 210-222.

CHRISTIANSEN, J. E., and J. B. LOW.
1970. Water requirements of waterfowl marshlands in northern Utah. Pub. 69-12, Utah Div. Fish and Game. 108 p.

DANIEL, C., and R. LAMAIRE.
1974. Evaluating effects of water resource developments on wildlife habitat. Wildl. Soc. Bull. 2(3):114-118.

DIRSCHL, H. J.
1972. Evaluation of ecological effects of recent low water levels in the Peace-Athabasca Delta. Occas. Pap. 13. Canad. Wildl. Ser., Ottawa 4, Ont. 28 p.

EVANS, K. E., and D. L. GILBERT.
1969. A method for evaluating greater prairie chickens habitat in Colorado. J. Wildl. Manag. 33(3):643-649.

GILES, R. H., JR.
1971. Wildlife management techniques (3rd ed.). The Wildlife Society, Washington, D. C. 633 p.

HARRIS, S. W.
1957. Ecological effects of drawdown operations for the purpose of improving waterfowl habitat. Unpub. Ph.D. Thesis, Univ. of Minn. 209 p.

KADLEC, J. A.
1962. Effects of a drawdown on a waterfowl impoundment. Ecology 43(2):267-281.

KADLEC, J. A., and W. A. WENTZ.
1974. State-of-the-Art survey and evaluation of marsh plant establishment techniques: Induced and natural. Univ. Mich. Wetlands Ecosystem Res. Group, Pub. No. 1. 230 p.

LEACH, J. H.
1971. Hydrology of the Ythan Estuary with reference to distribution of major nutrients and Detritus. J. Wildl. Biol. Ass. U.K. 51:137-157.

LEOPOLD, A. S., and J. W. LEONARD.
1966. Effects of the proposed Rampart Dam on wildlife and fisheries. Trans. 31st North Amer. Wildl. and Natur. Resour. Conf. pp. 454-459.

MERRILL, L. B., and E. G. BIZEAU.
1972. Canada goose production as related to stream flow on the South Fork of the Snake River in Idaho: A preliminary survey. Idaho Coop. Wildl. Res. Unit. Moscow, Idaho. 39 p.

MERZ, R. W., and G. K. BRAKHAGE.
1962. The management of pin oak in a duck shooting area. J. Wildl. Manag. 29(2):233-239.

METZGAR, R. G., and D. A. WHARTON.
1968. Planning the management of Maryland wetlands. Proc. 22nd Annu. Conf. S. E. Assoc. of Game and Fish Comm. pp. 68-82.

NOVY, M. E.
1973. Habitat selection by the male red-winged blackbird. Unpub. M.S. Thesis, Univ. of Mich. 69 p.

OHMART, R. D., W. O. DEASON, and S. J. FREELAND.
1975. Dynamics of marsh land formation and succession along the lower Colorado River and their importance and management problems as related wildlife in the arid southwest. Trans. 40th North Amer. Wildl. and Natur. Resour. Conf. pp. 240-252.

OLIVER, W. H.
1974. Wildlife problems associated with hydro-power reservoirs. Bull. No. 3, Washington Dept. of Game, Olympia, Wash., 10 p.

PARKER, T. L.
1973. South Fork Canada goose study (1973). Idaho Fish and Game Dept., Unpub. Rep. 31 p.

PARKER, T. L.
1975. Survey of Canada goose nesting on the South Fork of the Snake River, Idaho. Idaho Fish and Game Dept., Unpub. Rep. 10 p.

RUSSELL, D. M.
1966. A survey of streambank wildlife habitat. Proc. 20th Annu. Conf. S. E. Assoc. of Game and Fish Comm. pp. 37-41.

U.S. FISH AND WILDLIFE SERVICE.
1974. Ecological planning and evaluation procedures. Developed by: Joint Federal-State-Private Conservation Organization Committee, January 1974, Washington, D.C. 269 p.

WENTZ, W. A., R. L. SMITH, and J. A. KADLEC.
1974. A selected annotated bibliography on aquatic and marsh plants and their management. Univ. Mich. Wetlands Ecosystem Res. Group, Pub. No. 2. 190 p.

APPENDIX 1

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APPENDIX 2

Recommendations of the Wildlife and Riparian Habitat Workgroup

Wildlife numbers are, in general, too variable to be useful measures or indicators of changes in in-stream flow. Basically, this means that the year-to-year fluctuations of most wildlife populations are due to causes other than the effects of flow alterations. Therefore, it would seem more profitable to look for species, vegetation, or factors that respond quickly to flows and are closely related to general trends in wildlife numbers. Several alternatives are suggested: 1) indicator species, such as the water ouzel (dipper), osprey, bald eagle, and perhaps some insects; 2) primary productivity, especially of near-stream herbaceous vegetation; and 3) perhaps resident birds are least variable and most likely to be sensitive to habitat changes.

The suggestion in the FWS ecological planning guide (cited in Section 5) that habitat-type evaluation criteria be established by zoogeographic region was expanded upon. As a first approximation, Merriam's life zones are recommended as a system for classifying streams or reaches of streams. The greater homogeneity within life zones would permit more accurate generalization. This view was reinforced by the Hydrology workgroup, which pointed out that the life zones are, at least roughly, correlated with important hydrologic differences. Streams in the Upper and Lower Sonoran zones generally are important in recharging adjacent aquifers and maintaining soil moisture in riparian zones. In contrast, in the Hudsonian and Canadian zones, groundwater maintains streamflows and flow variation has less of an effect on riparian vegetation.

A matrix of the life zones, significant factors and probable level of importance is on the next page.

CRITICALITY OF STREAM-FLOW/RIPARIAN VEGETATION FACTORS

Factors \ Life Zone	Lower Sonoran	Upper Sonoran	Transition	Canadian	Hudsonian
Soil Moisture	Extreme	Extreme	Moderate	Low	Low
Cross-Sectional Bank Contour	Low	Low	Moderate	Extreme	Extreme
Stream Gradient	Low	Low	Moderate	Extreme	Extreme
Livestock Use	Moderate	Moderate	Extreme	Extreme	Extreme
Water Quality	Extreme	Moderate	Low	Low	Low
Historical Land Use	Extreme	Extreme	Extreme	Extreme	Extreme
Soil Texture	Low	Moderate	Extreme	Extreme	Extreme
Water Table	Extreme	Extreme	Moderate	Low	Low

6. MEASURING THE IMPACT OF CHANGING STREAMFLOW ON RECREATION ACTIVITY

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CONTENTS

Methods for measuring the impact of changing streamflow on recreation can come from a variety of social science techniques. Approaches discussed in this chapter include longitudinal (time-line) analysis, classification techniques for constructing stream typologies, and measurement techniques that assess user satisfaction with streamflow relative to recreation. Specialized methods, such as attitude scaling, the Delphi technique, surrogate tradeoff techniques, and a methodology for modeling recreation supply are also discussed. The strengths and the weaknesses of each method are presented along with an evaluation of their applicability to streamflow analysis. The chapter concludes with suggestions for research on the relationships between streamflows and recreation use.

While the literature on recreation is voluminous, research relating changes in recreation behavior to changes in stream environments is almost nonexistent. A basic assumption of this section is that when the flow of a river or stream is altered, the type of recreation available will be altered. A second assumption is that if a specific recreation activity is not available at one site, users desiring that activity will use another site. Some recreationists may use a given area regardless of the type of streamflow. After a flow is altered, new groups may engage in different activities at the site. Thus, a site will usually continue to be used for some form of outdoor recreation even if its characteristics are changed.

What is water-oriented recreation? In defining recreation, Craighead (1962) has described recreational activities as an interaction between people and a suitable environment. Lerner (1962) describes recreation as voluntary activity engaged in by man over and above that required for broad needs. The elements in these definitions are also included in the definition of recreation in Section 1. If these elements are accepted, all nonsustenance activities related to the environment along streams may be included under recreation.

The activities listed below typify, but are not limited to, nonsustenance-type behaviors that are related to streams: 1) *Instream Recreation* – fishing, swimming, wading, boating (power, kayacks, canoes, etc.), floating (rafts, tubes), water skiing, scuba diving, water fowl hunting; 2) *Recreation Adjacent to Streams* – picnicking, camping, hiking or walking, driving, viewing, collecting rocks, observing fauna and flora. Participation in some of these activities depends, to some extent, on an appreciation of the aesthetic aspects of streams (see Section 7).

Another useful set of stream recreation activity categories was offered in a review by S. C. Davis.[1] The categories are boating on non-tranquil waters, boating on tranquil waters, water contact recreation, fishing, wetland-related recreation, cold-weather recreation, and water-enhanced recreation. They[1] point out that effective discussion of methods requires that the types of relevant recreational activities be reduced to a manageable number of groups. Such a reduction would facilitate matrix analysis and other statistical manipulations. For applications to highly specified impact analysis of streamflow change on activities, howhowever, disaggregation may be necessary.

Why study stream-related recreation? Resource managers who have multiple-use objectives must provide an appropriate mix of recreational opportunities that will serve as great a percentage of the public as possible. This requires comprehensive data on actual and potential resource conditions, ecological and social constraints, demographic characteristics, attitudes, and user interests. The managers also need to know the attributes of streams that users consider important. They can gather this information by observing, measuring, and quantifying the existing recreational participation patterns.

CRITERIA FOR METHODOLOGIES

The usefulness of a particular methodology depends on its characteristics and on the particular criteria or principles used in evaluating those characteristics. If you have the same objective(s) as the designer of a methodology, then you are more likely to find the methodology useful.

Because of the relevancy of their research objectives to their evaluation of a method, individuals assessing a given method, unless they ascribe to some common criteria, might be expected to derive different judgments concerning its merits. Boster (1974) has stated:

> Objective evaluation of any measure system is impossible without reference to a set of standards, implicit or explicit. How well a system works, indeed, if it works at all is determined by notions of what constitutes a 'working system'. Criteria may be defined as the basis for formulating such judgments as to workability. (Boster, 1974:7)

People having the same cultural referrents may concur in the elements of broad or higher level criteria such as "social well-being" or "better environment." When these broad goals are specified in terms of lower order criteria, however, differences in opinions are to be expected. *But it is precisely the specification of standards which is necessary for objective and comparable assessment.*

The following criteria for evaluation of social methodologies are modified from those developed by Boster and Daniel (1972) and previously adapted in *Aesthetics in Environmental Planning* (Redding, 1973). The criteria were developed with the basic goals of measurement as stated in Section 7, in mind.

First, the method should be as bias-free as possible. This means that the measurement device should be independent of the standards of persons applying or taking the scale. However, as discussed in Section 7, some subjectivity is almost unavoidable, especially concerning aesthetics. Also, the relative importance of different attributes of a factor involve judgment.[2] When judgment is used, it should not reflect the biases of the agency, but should indicate the attitudes of the impacted and affected public.[3]

Second, the relationship of the measurement techniques to the variable being measured should be clear, i.e., the technique should measure a specific variable. This implies a, "systematic relationship to an established theoretical structure" (Boster, 1974:9).

Third, where judgments are a part of the methodology, the judgmental standards should be clearly specified for each attribute considered. This should include specification of the group whose standard is used and how the standard was determined. Judgmental methods also require that reference points must be established to achieve comparability.

Fourth, extraneous considerations such as the following should not affect the measurement of any variable: 1) Response bias in which the evaluation is consistently affected in one direction

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[1] Jason M. Cortell and Associates.

[2] Daniel and Boster (1975) have attempted to devise a methodology to control for this in aesthetics measurement. This methodology is presently being refined. See Section 7, Scaling Methods, Scenic Beauty Estimation.

[3] Boster states, "the method must be based on unbiased mathematical and statistical routines in order to be free of the tastes and preferences of its developers or users" (Boster, 1974: 9). This requirement is not pertinent if the judgments of a particular group are desired as the standard and judgment is part of a method.

by variables external to the one being measured; and 2) non-random outside influences that cause fluctuations in the measurements.

Fifth, the method should be as widely applicable as possible. The ideal is to have applicability, without modification, to any area in any situation that involves natural resources.

Sixth, the ease of application of a method is an important practical consideration and depends on its inherent simplicity and the costs of its administration. Costs would include those incurred in adapting the method to different situations and areas and those of data collection and analysis.

APPROACHES TO RECREATION MEASUREMENT

Three main approaches have been used by social scientists as they designed instruments to measure various aspects of recreational behavior (Burdge and Field, 1972). The first approach is to measure demographic, social, and other individual and group characteristics that may be related to the recreation experience. This type of approach assesses characteristics that affect demand or potential demand for a variety of recreation resources.

A second approach is to examine the resource itself to determine the available recreation opportunities. Characteristics of the resources in question are classified according to their utility for various recreation uses. Different possible "mixes" of recreation activities for different areas are the usual output of this type of analysis.

A third approach attempts to quantify recreational benefits in terms of dollar units. Recreational behavior is measured by utilizing economic (cost-benefit or exchange) procedures. Recreation benefits are handled in terms of marketable resources. Economic approaches to the study of recreation demands depend on the assumption that recreation and aesthetics can be considered marketable commodities. Given this assumption, concepts such as marginal cost utility or opportunity costs can be used to evaluate recreation by projection curves or similar techniques. Economic regard to water-based resources, by itself necessitates a complete study to be of any use; therefore, tates a complete study to be of any use, therefore, this chapter will be restricted to the first two types of methods in the study of recreation behavior.

In the main body of this chapter, methods are described that seem particularly applicable to establishing a data base for evaluating the relationship between variations in streamflow and recreation behavior.

The methods include: 1) *Classification and Categorization of Streams;* 2) *Adequacy of Streams for Recreation;* 3) *Longitudinal Analysis;* 4) *User Satisfaction Analysis;* 5) *Delphi Technique;* 6) *Social Analysis Modeling;* 7) *Other Methods.*

Numbers 1 and 2 are descriptive techniques rather than methodologies. They are included to emphasize the need for standardized reference techniques for use in stream-flow investigations. Classification can encourage scientists researching streamflow requirements to adhere to common or standard elements.

Classification and Categorization of Streams

It is useful to adopt a particular classification method when inventorying and evaluating water bodies available for recreation. However, the problems of classification are complex. Streams may have highly variable flow regimes, from relatively constant flows to wide fluctuations between flood and zero flow. They may be miles wide or as small as a few feet or even inches. Depth, temperature, slope, related soils and vegetation and water quality may vary. Rivers and streams can be classified according to physical boundaries and parameters, such as size, and according to topographic and geohydraulic zones. They can be evaluated for quality on the basis of specific criteria for characteristics of the resource. Classification techniques, in general, analyze the ability of the stream to entertain various recreational activities by use of physical characteristics of the stream.

In 1945, R. A. Horton[4] proposed a four-step classification system for streams. A first order stream is one so small it receives no tributary channels. A second order stream is one which receives only first order tributaries. Where a second order stream meets another of comparable size or order, it becomes a third order stream.

Craighead (1962) refers to a study by Leopold and Kinnison in which they proposed ten orders based on extent of drainage area and length of the stream. They classified most streams in the United

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[4]Bulletin of the Geological Society of America. Vol. 56, 1945.

States under these orders. From such a list, an estimate can be made of channel lengths or river segments of various sizes available for recreational purposes. Craighead elaborated on Leopold and Kinnison's work by dividing their fourth to tenth orders into four additional classes for recreation: wild rivers; semi-wild rivers; semi-harnessed, developed rivers; and harnessed, developed rivers (Craighead, 1962).

Morris (1974) divided rivers into three categories according to recreational use:

> *Type 1 – High Density Recreation Rivers*[5]
> Located within or near centers of urban population, these rivers are subject to and suitable for intensive day use and a variety of recreation activities. Most of the participants walk or drive a short distance to the site.
> *Type 2 – General Recreation Rivers*[5]
> Relatively accessible to centers of urban population but usually more remote than Type 1 rivers, these rivers receive extensive day, weekend, and vacation-type use and are suited to a variety of recreation activities. Most of the participants engage in some degree of preparation before traveling to the site.
> *Type 3 – Specialized Recreation Rivers*[5]
> These rivers offer a special recreational attraction such as outstanding scenery, fast flowing "white water", high quality fishing, etc. The participants travel to the site from the local area as well as from relatively long distance. The relative accessibility of the river to population centers is not a distinguishing factor. They normally take care to plan their visit to the site at a time when the flows are suitable for their activities, such as kayacking and rafting. (Morris, 1974:2)

Morris presented a classification methodology, designed by Wolf Bauer, for categorizing streamflow parameters.[6] The reporting of Bauer by Morris (1974) deals primarily with the influence of stream gradient on recreation opportunities.

Critique

All methods for stream classification have the underlying defect of being judgmental in nature and therefore subject to the biases of the persons or organizations that conceive and/or implement the scheme. However, the effects of the judgment will be lessened if one scheme is agreed upon and then widely applied.

Classification is seen as a first step in a systematic analysis of the effects of streamflow alteration.

Single classification schemes for streams according to size or other criteria cause difficulties. Because of the dynamic nature of streams (e.g., fluctuations in size over a season) and the differential effect on various types of recreation, investigators would have to continually reassess any classification criteria. Also, no one classification would apply to most recreation activities. A recommendation for classifying recreation in relation to streamflow is to separately classify streams for each type of recreation according to the physical and biological parameters of the water-oriented recreation activity. S. C. Davis,[1] in a review-response, suggests that we need a synthesis of Bauer's physical classification and Morris' potential use classification, plus a measure of size similar to the Horton-Strahler designation of order. Davis feels that physical classification, potential use and size are necessary to a useful classification system. The idea of synthesis in developing applicable classification criteria may provide a means for improving those methods. An additional problem, however, is discovering factors and elements within them that are transferable or universally applicable as well as consistent measures.

Adequacy of Streams for Recreation

Recreation adequacy assessments are generally concerned with the physical characteristics of a stream. The recreation adequacy is assessed according to the ability of a particular stream to accommodate various types of water-oriented recreation. A summary of several of these studies follows.

Jaakson (1970) reported an inventory of reservoir shoreline recreation potentials at different lake levels. The inventory consisted of three steps: 1) Data collection, which included an extensive recording of shoreline conditions at stations located at intervals of a maximum of 400 feet; 2) mapping, which consisted of interpolating shoreline data onto schematic diagrams; and 3) analysis

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[5] Author's italics.

[6] W. Bauer, consultant to the State of Washington Interagency Committee for Outdoor Recreation. Bauer assisted in the state's study of a wild, scenic, and recreational rivers system. Readers interested in a detailed explanation of the study should consult, *"Wild, Scenic and Recreation Rivers"* a report published by the Interagency Committee in 1972.

and quantification of data on a "...Rating Scale designed to provide a uniform measure whereby shoreline conditions could be differentiated objectively" (Jaakson, 1970:427).

The main limitation of the Jaakson approach is that it is based on topography and does not reflect the preferences of recreationists who use the facility. This methodology could be modified to inventory streamflow (modification would not alter the limitations).

In March 1973, the relative effect of various flows on recreation opportunities were evaluated on the Snake River in Idaho as part of the Pacific N. W. River Basin Commission's instream flow studies. The investigation was mainly concerned with inventorying recreational, nonconsumptive utlizations of the water. The stated objective was "...to gather information, to enable us [the investigators] to judge the relative effect of various flows on recreation opportunities" (Northwest Region, Bureau of Outdoor Recreation, 1974:123).

To reach this objective, the research team controlled the amount of water in the stream and measured such items as beach slope, water velocity, and high water line at various controlled flows. Observations were targeted to measure, at each discharge, the effects on pool and riffle areas, exposed beach, channel width, visual and auditory sound quality, and navigational conditions. Based upon personal observations, each of six individuals evaluated the "relative adequacy of the flows for recreation" (Northwest Region, Bureau of Outdoor Recreation, 1974:123).

These evaluations were categorized using a modified version of the Kanawha River Basin method (Northeast Region, Bureau of Outdoor Recreation, 1970), in which evaluations of the recreational adequacy of a particular site were subjectively based on the judgment of each expert. Each site was graded along a five-point scale. The five individual categories and guidelines are given below:

> *Minimum Acceptable.* The minimum acceptable flow is that flow which provides only for the most limited recreational use of the stream. Compatible streamside recreation opportunities include picnicking, camping, and sightseeing activities, and compatible instream activities include nature study and possible swimming in the pool areas.
>
> *Low Satisfactory.* Low satisfactory flow is compatible with a range of both instream and streambank recreation pursuits, including camping, picnicking, and sightseeing. The most probable problem area at this flow rate would be the lack of sufficient water depth to adequately float a boat over a stream riffle area at some locations.
>
> *Optimum.* Optimum flow is that flow which will maintain the unique characteristics of the stream area and will provide for an optimum combination of uses. Generally, this flow will accommodate swimming, boating, sailing, canoeing, studying nature, and streambank activities such as picnicking, camping, hiking, and sightseeing. This flow produces a visual and audible enhancement of the stream resource which is generally pleasing to the recreationist and notably adds to the quality of the recreation experience.
>
> *High Satisfactory.* At the high satisfactory flow, many instream activities would be curtailed substantially, particularly swimming. All streambank recreation activities such as camping, picnicking, and sightseeing can still occur.
>
> *Maximum Acceptable.* Maximum acceptable flow is assumed to be the highest rate of flow useable by the recreationist. This flow represents an upper limit beyond which further beneficial uses of the stream for recreation are severely restricted. Recreation uses of streamside lands include picnicking, camping, and sightseeing. At this flow, instream activities such as swimming, studying nature, sailing, and leisure boating are no longer acceptable. The only instream activity that may possibly occur if this flow rate is approached is white water boating. (Northwest Region, Bureau of Outdoor Recreation, 1974:124)

The Snake River project is notable because an attempt was made to experimentally control the flow of a stream. Due to the relatively short time allotted each flow level, however, it was not possible to study the emergence of new recreation activity patterns. However, to the extent that the physical environment represents a constraint on recreation activity, the study is useful.

Another study (Bishop, 1972) consisted of a matrix constructed to display the impacts on various beneficial uses of stream water related to a measurable range of flows. Bishop's purpose was to test the theory that the flows necessary to maintain fish life would be adequate for most stream-oriented recreational activities. The matrix designed by Bishop effectively shows the tradeoffs among recreational uses and fishery uses of water at several measured flow levels (Table 1).

Another approach to assessing streamflow from a recreational perspective consists of a set of participant observation investigations of white water trips at various controlled flows. Attention is directed toward the characteristics of specified

Table 1. Low flow evaluation matrix (from Bishop, 1972).

FLOW (cfs)	IMPACTS						
	FISH			RECREATION			WATER QUALITY
	Salmon	Steelhead	Trout	Swimming	Canoeing & Kayaking	Fishing	
300	adult migration and spawning capacity reduced by 80% egg incubation reduced by 60% rearing capacity reduced by 30% smolt migration reduced by 75%	adult migration and spawning reduced by 80% egg incubation reduced by 50% rearing reduced by 30% smolt migration reduced by 60%	spawning reduced by 60% adult migration, egg incubation, and rearing reduced by 20%	Ok for wading marginal for swimming	too little water	fishing success is often poor at this flow	Water would be reduced to Class B with existing development and discharge
600	adult migration and spawning capacity reduced by 30% egg incubation reduced by 20% optimum flow for rearing smolt migration reduced by 25%	adult migration and spawning reduced by 30% egg incubation reduced by 20% optimum flow for rearing smolt migration reduced by 20%	optimum flow for adult migration, egg incubation, and rearing spawning reduced by 20%	Flow satisfactory for swimming	danger of damaging canoes on rocks	"Best" fishing conditions generally occur at this flow and above	Minimum flow to maintain Class AA water with existing development and discharges
1000	optimum flow for adult migration, spawning, egg incubation, and smolt migration	optimum flow for adult migration, spawning, egg incubation, and smolt migration	optimum flow for spawning	too much flow for wading approaching upper limit for satisfactory swimming	minimum flow for canoeing and kayaking	fishing is usually good at this flow	This flow has dilution capacity for additional development and discharge at Class AA standards.

segments of the stream, with categorization according to the "International System" of rating the degree of difficulty of running rivers.[7]

The definitions of the six grades of difficulty are as follows:

Grade I: Very easy, waves small, regular. Passages clear. Sandbanks, artificial difficulties like bridge piers riffles.

Grade II: Easy. Rapids of medium difficulty, with passages clear and wide. Low ledges.

Grade III: Medium. Waves numerous, high irregular. Rocks, eddies. Rapids with passages that are clear though narrow, requiring expertise in maneuvering. Inspection usually needed.

Grade IV: Difficult. Long rapids. Waves powerful, irregular. Dangerous rocks. Boiling eddies. Passages difficult to reconnoiter Inspection mandatory first time. Powerful and precise maneuvering required.

Grade V: Very difficult. Extremely difficult, long, and very violent rapids, following each other almost without interruption. River bed extremely obstructed. Big drops, violent current, very steep gradients. Reconnoitering essential but difficult.

Grade VI: Extraordinarily difficult. Difficulties of Grade V carried to extremes of navigability. Nearly impossible and very dangerous. For teams of experts only, at favorable water levels and after close study with all precautions. (Urban, 1965 from Welsh and Crouch, 1974:149-151)

Thompson and Fletcher (1972) identified 52 relevant physical and biological parameters of streams and lakes including the following selected items: surface area, width, average depth center, depth/surface area, shore slopes, shore width, shore length, shore characteristics, bank cover percent, bank structure, emergent vegetation, bottom slope, bottom type – irregularities, bottom type – swimming, surface obstructions, water

[7] This rating system was used by the whitewater boating evaluation team of the Hells Canyon Controlled Flow Task Force (Welsh and Crouch, 1974).

temperature – surface, coliform content, turbidity – total, bottom color, odor and taste, velocity, air temperature, climate, and shore soil type.

Different parameters were related to specific recreational activities and from the parameters given, the elements and the quality of the activity may be ranked as good, fair, or poor.

Thompson and Fletcher abandoned attempts to classify streams because a stream can be so dynamic in nature that it varies widely over time in size, flow, and other characteristics. They, therefore, defined a recreational activity and its requirements, added a time dimension, and related the activity to the stream at a particular period of time when its characteristics fit the needs of the activity. Their intent was to determine the kinds and amount of possible recreational activities and potential trade-offs between activities using the same water source (Figure 1, see also section on *Social Analysis Modeling*).

Inputs	*Kinds Model*	*Outputs*
Physical and Biological parameters	Requirements for activity performance	Kinds of recreational activities possible
	Amounts Model	*Outputs*
	User-Day Units Requirements for Each Activity	Amounts of qualified activities possible

Figure 1. A basic input-output recreation model (from Thompson and Fletcher, 1972).

Critique

Without these techniques, the activity is the stable entity and the quality of the activity is related to the characteristics of the water resource.

The techniques are restricted to physical and biological parameters of lakes and streams and were not specifically directed toward identifying differentials in streamflow. They do not deal with the extent of recreation participation nor with the factors that motivate participants.

Managers can use the techniques to estimate what kinds of activities can be planned for in relation to a specific body of water and to seasonal changes in a stream. The numerical values provided for parameters appear to be judgmental; therefore, verification is difficult.

Longitudinal Analysis

A useful way to predict events is to consider similar situations that have already occurred. Social scientists have done considerable work of a *post-factum* nature on the impact of such diverse water developments as reservoirs, community water systems, and irrigation, among others (e.g., Andrews et al., 1974). The adjustment problems of communities where water resource development might take place can be predicted on the basis of this type of study.

A similar method, called "Comparative Diachronic Analysis," has been used by Burdge and Johnson (1975) to assess the social component of natural resource development as utilized in environmental impact statements. These researchers studied a control county and an impact county as they tried to predict the occurrence of an event in the impact county. To use this method, a matching county is chosen which has been similarly affected before and shares many of the characteristics of the county to be impacted. The control county is then carefully analyzed.

Longitudinal (time-line) analyses must be conducted, on a wide variety of stream settings, utilizing a consistent classification scheme as a base to provide information on what effects streamflow alterations have produced in recreation behavior. The comparisons should cover as many different recreation sites as possible as well as utilizing different types of streams.

Critique

A major limitation of the longitudinal (time-line) approach is that not enough situations can be readily found where the stream flow was varied and recreation records were kept. So many agencies have been involved in stream flow alteration, however, that records should be available.

Secondly, recorded streamflows may not have varied enough to effect large changes in types of recreation activities; for instance, if one were interested in a change from conditions suitable for whitewater boating to those suitable for power boating, such a change may not be reflected in the empirical data.

Interpretation of a given change may be difficult from two standpoints. The magnitude of the change may dictate some judgment as to what is significant and what is not. Secondly, the quality of different recreational behaviors may be difficult to define. Would a shift from boating to wading, playing in the sand, or just picnicking represent a shift from a superior to a lesser form of recreation?

The advantage of the time-line approach as outlined here is that it does not require new data collection. Rather, available records regarding streamflow variations and recreation behaviors must be found. Our widespread reservoir construction and stream channelization efforts mean that variable streamflow regimes are quite numerous.

User Satisfaction Analysis

Satisfaction with a recreational experience is basic to the value of the experience to the individual and relates to his behavior, interests and attitudes. Satisfaction measurement is often used in relation to recreation and would be applicable to measuring streamflow-related activities. A technique for assessing user satisfaction could be applied in measuring the recreational use made of a stream as its flow varied. Different recreation activity groups that are using the streams could be interviewed utilizing survey research procedures. The intent of such research would be to determine how activity groups would change if the stream flow were altered.

One example of a satisfaction analysis methodology used in a survey was reported by Brewer and Gillespie (1967). They interviewed a stratified random sample of outdoor recreationists around St. Louis to appraise their satisfaction levels and to determine what kind of recreational activities maximized their social satisfaction. The goal was to create and test an index that would measure, among the sample surveyed, the degree of satisfaction with recreational activities.

A limiting characteristic of the satisfaction index used by Brewer and Gillespie is that it does not control for lack of adequate facilities for specific recreational experiences. Recreational activities that were not accessible to the population from which the sample was drawn could rank highly. However, the index may be useful for rating the specified alternatives.

Andrews and associates (1972; 1973; 1974; 1975) have applied several types of scales in assessing recreational activity. In one study (Andrews et al., 1974), open-ended questions were used to determine the most enjoyable aspect of reservoir-related recreation. A frequency figure was obtained from each respondent as to how often he participated in each of the activities mentioned in response to the open-ended question, the increase or decrease in the activity during the preceding ten years, the most enjoyable aspects of recreation, and the effect of recreational activity on his overall enjoyment of life. Each respondent was also asked to estimate the number of times that he engaged in particular designated activities during a certain period of time. This type of data collection is directly applicable to streamflow analysis.

Multiple-item scales have been used in conjunction with surveys to determine attitudes related to recreation. These are usually of the *Likert* type (see Section 7, *Scaling Methods).*

A specific scale on outdoor recreation orientation was recently developed (Andrews et al., 1975). The items used were: 1) Outdoor activities are the most enjoyable activities one can do; 2) I would like to have much more recreation outdoors; 3) if people were outdoors more, they would not be much better off; 4) I would not participate in outdoor recreation if someone was not with me; 5) people should spend much more of their recreation time outdoors; 6) indoor activities are as much fun as outdoor activities. This set of questions when scored, provides a means of measuring the degree of interest an individual has in outdoor recreation.

Scales such as presented above can be applied to diverse user populations to ascertain differences in the importance of recreational activities. The results of such applications may indicate a pattern of concerns for a relevant population. Clusters of attitudes related to particular recreation patterns can be measured and recreation behavior under altered streamflow conditions can be predicted.

Critique

Interviews with users can be used in two ways when assessing the effect of streamflow variation. In the first, users are observed and questioned about their present recreational use of a stream. In the second, the effects of social characteristics and of attitudes toward recreation behavior are related to changes in streamflow.

Predicting recreation patterns likely to result from changes in water allocation is more difficult than determination of use. Relevant populations that might use the altered stream for recreational purposes should be identified. Present users can be studied on the premise that they are representative of potential (future) users.

Survey methods can: 1) Provide a means for judging the effects of altered conditions, 2) help in assessing the importance of different types of activities, and 3) measure the attitudes and other characteristics of potential users. Attitude scaling techniques need to be developed further by adaptation and innovation so that researchers can obtain realistic estimates of appropriate values and attitudes that affect human actions related to streamflow.

Improved methods would allow planners and decisionmakers to evaluate probable increases and decreases of recreation opportunities. Combined with an analysis of the user population, the planners might then better meet the desires of recreationists with different interests.

Information on the relationship between temporary or permanent variations in streamflow and individuals' satisfaction with their recreation experience is applicable in planning and problem resolution at localized recreation sites where those variations actually occurred. But while strict application is localized, the results of a well-conducted investigation should be useful within a region or a river basin.

Delphi Technique

The Delphi technique is being increasingly used in evaluations of natural resources that include factors that are difficult to measure directly. This technique uses judges of the situation in an iterative or repetitive process which is designed to insure that the assessment is based on full knowledge. Usually this method is used to directly assess the characteristics of a real or hypothetical situation. The Delphi technique has also been used in estimating relationships or trade-offs in resource evaluation (Haimes and Hall, 1974).

The technique requires judges who are well informed about some or all of the problem area and have experience that qualifies them to make decisions about the area. Experts on recreational use, outdoor recreation specialists, and recreation resource managers could be used to judge the effect on recreation of a change in a natural resource. When the Delphi technique is properly applied, experts make independent judgments about the problems and solutions. The opinions of the first round are summarized and re-presented to the experts with reasons for divergent evaluations. The problems and solutions are re-assessed and rankings of the assessments are again made. The process is continued until a concensus is obtained or the results no longer vary. The original exposition of the method suggested that as many as four iterations may be necessary.

The method is applicable when social and other factors are to be related. It also allows the construction of models, trade-off functions, etc., since the method produces an ordinal number representation of the rating by the experts on a numerical scale such as +10 to -10.

The assessment of "recreation opportunity" is one of the nine major or prime public goals in the work reported in the Techcom (1974) report (Technical Committee of the Water Resources Research Centers of the Thirteen Western States). This prime goal was disaggregated deductively into "subgoals" through content analysis of public responses to open-ended questions concerning social goals. The subgoals were then related to "indicators" of the state of the subgoal. A Delphi method was used to accomplish this. Techcom reported that techniques exist and have been utilized to identify a set of indicators for specific subgoals. These approaches make use of the Delphi technique.[8] This technique provided a means for identifying social elements and numerically weighting them for use in quantitative analysis.

Another application of the Delphi technique is in the Surrogate Trade-Off Method of engineers (Haimes and Hall, 1974). In this procedure, the technique is used to assess the relative values of additional increments of factors. The basic assumption is that it is easier to assess the effects of small changes than to assess total magnitudes. The results of these weightings are used to establish the trade-offs between values termed "objective functions" (Haimes and Hall, 1974). These are equations which reflect the relationships between measurements and important variables affecting decisions. With appropriate constraints applied, the system can then be optimized. These objective functions can then be evaluated, and a set of feasible solutions obtained. The result of such an analysis essentially depends upon the accuracy of the Delphi assessment.

Critique

Ideally, the Delphi technique may serve as a short-cut for decisions relating to streamflow or in estimating public response to stream alterations.

The rationale for using the Delphi technique in the problem of streamflow assessment is that an "informed opinion" by a group of experts con-

[8]The equations resulting from the application of this technique have not been published.

cerning the effects of streamflow alterations on recreation is better than a guess by a single planner. An important consideration is the quality of the judges, i.e., their representativeness and level of expertise.

The basic assumption (and weakness) of the Delphi technique is that the experts can provide accurate judgments. This assumption implies that a person can obtain expertise through learning and experience. Unfortunately, learning and experience can lead to accurate judgment only to the extent that factors previously experienced or seen in related situations have been measured and analyzed in relation to generally accepted patterns of behavior. Without measurement standards, a person (even an expert) must make a qualitative judgment regarding the presence and influence of variables in a given situation. Therefore, decisions about variables for which measurements are not available involve subjective evaluations. The collective evaluations of a group of experts may represent a concensus, but to what extent is this evaluation true and not a result of collective reinforcement or other biasing influences?

Another objection to this technique, when applied to social variables, is that the experts are expressing opinions, and their concensus is not necessarily the opinion that should prevail. Often, the reference group that should be valued is the public. A solution might be to choose experts who are able to assess the public's valuation of a situation. In this case, the judgment is of second-order.

A parial rebuttal is that the method does use judgments of experts who have proved to be generally correct in their assessments. The method does provide a way to assign numerical values to variables that are difficult to directly measure, and it thereby allows analyses that require numbers.

The Delphi technique is applicable to almost any problem at any level and has had diverse usage in societal analysis and prediction. However, informational requirements for regional and national assessments using the Delphi technique may be large. Also, aggregation of data may obscure important information relative to recreation effects, especially on less common activities. The technique would best be used as a relatively quick decisionmaking tool for a localizing problem.

The importance of establishing controls for elitest bias cannot be overemphasized. Personnel involved in managing recreation areas may fail to understand that only a small number of the U.S. population has the knowledge, money and physical energy to seek and enjoy "superior" forms of recreation such as whitewater canoeing or kayaking. If they pursue outdoor recreation at all, it may be a simple picnic or a walk along the stream. Their satisfactions may be derived from interactions with other people rather than the aesthetic beauty of the site.

In summary, the Delphi technique can be a useful way to obtain a numerical value for recreation and/or other factors that are not directly measurable. The method can be adapted to a particular stream problem. It may tend to have an elitist or management bias.

Social Analysis Modeling

Modeling refers either to a conceptual model that describes a process or to a mathematical representation of a system that includes relationships and interactions of variables. The latter provides a means for analyzing the functions, and for relating the different types of available recreation activities. In application, a model deals with the inputs and outputs of a system.

The mathematical modeling method provides a means of estimating the potential effect of changes, but as pointed out by Davis (1974:239),

> . . . before an estimate of a change in recreation supply for a given water resource system can be interpreted as a benefit or a cost to society, it must be coupled with an analysis of demand for recreation of the same water resource system.

Modeling can be used to relate recreation supply to factors affected by streamflow variations, but the demand for recreation activities is excluded.

Before a suitable model can be constructed, Davis (1974) notes that two lists must be made. The first enumerates potential recreation activities and which of them will be considered in relation to the resources. The second notes "physical and biological parameters which comprehensively describe the characteristics of the water resource system which influences the quantity and quality of recreation opportunities to be considered for analysis" (Davis, 1974:241). These should be measurable attributes that affect the quality and quantity of the listed recreation activities. Stratification of area and time will usually be necessary to compensate for variations in activities in different seasons or areas. This

> ". . . is determined by the degree of resolution and precision required and by the homo-

geniety of land, vegetation, and water characteristics . . . " (Davis, 1974:241)

Boundary conditions are stipulated, in the model, for each resource parameter in relation to the associated recreation to obtain assessments of recreation quality and quantity. For example, for mean daily air temperatures, one could specify that the range of 60° to 70° F provides good swimming, 50° to 80° fair swimming, and 40° to 90° poor swimming. Such limits are a direct application of judgment. The lowest rating would be that obtained from any relevant physical parameter (Thompson and Fletcher, 1972).

These steps in the modeling procedure are requisite to developing any model of recreation that is to include quantity and quality. An example of the application of this method is that developed by Thompson and Fletcher (1972) and reviewed by Davis (1974). Since this technique has considerable promise, a detailed description is presented.

After collection

> " . . . of relevant physical and social data, the model will tell us which of the activities can be performed on the water body (stream or river) and at what quality level." (Thompson and Fletcher, 1972:5)

Davis describes an equation as follows:

> The maximum amount of recreational opportunity for qualified activities that each sector of the water resource system can supply is then computed by the following formula:
>
> $$UV = (AH) / (ah)(nd) \qquad \ldots\ldots\ldots\ldots (1)$$

where

> UV = the user visits of an activity per time period which can be supplied
> A = total area (space or distance) available in the sector for the activity
> H = hours per day available for the activity
> a = space or distance required for a user experience per day
> h = hours per day required for a user experience
> d = the number of days in the period of analysis (Davis, 1974:243)

Equation 1 indicates the amount of the recreation activity possible. However, not all activities can be performed simultaneously. Resolution of this problem is the task of " . . . the second stage developmental model by using a trade-off equation to express the maximum capability . . . " (Davis, 1974:244). Thompson and Fletcher (1972) state that this involves two subsequent models: 1) A trade-off matrix; and 2) a compatibility matrix.

The following assumptions are made by Thompson and Fletcher (1972) in determining the trade-off matrix:

> The first is that all activities are and can be performed in the same physical area. Secondly, A and H are constant for all activities, and thirdly, the activities are mutually exclusive . . . The purpose of our compatibility matrix was to eliminate this third assumption.
>
> The trade-off coefficients are computed according to the following formula: (Thompson and Fletcher, 1972:9)
>
> $$T_i = \frac{\text{UV of receiving activity}}{\text{UV of surrending activity}} \qquad \ldots\ldots (2)$$

T_i is computed for each pair of recreational activities, and a trade-off matrix is constructed from the values obtained.

> In conjunction with this trade-off coefficient matrix, a compatibility matrix was developed strictly on the basis of coexistence with respect to compatibility/incompatibility over the same physical area. The activities were so compared without regard for the quality level of the activity, and the resulting matrix where (1) implies the two activities can be performed mutually at any trade-off level, and (2) signifies that they can never be performed simultaneously. It must be kept in mind that this is a potential supply model and that any enhancing effect one activity may have on another (i.e., camping to swimming might have a multiplier of 2.5) would be considered on the demand side as opposed to supply where we are dealing strictly with occupation of the physical site.
>
> Using these trade-off and compatibility coefficients, it is now possible for the owner/manager to develop any set of alternatives he may desire on the water body by utilizing a set of formulas which are provided as the output of the above matrices. (Thompson and Fletcher, 1972:11)

In constructing a formula, the compatibility matrix is used to determine which activities can be done together in a given area and consequently can appear in the same equation. Davis (1974:244, 245) writes:

> For example, assume the following estimates were made for the use of a lake of three compatible activities:

Activity	Maximum User Day Capacity	Trade-off Ratio to Power Boating
X_1 power boating	10,000	1.0
X_2 boat fishing	30,000	0.33
X_3 sailing	5,000	2.0

From the following formula, user days can be distributed among activities.

$$\Sigma T_i X_i \leqslant \text{Maximum user day capacity of the comparison activity (base)} \ldots (3)$$

Davis continues:

Using power boating as the base, the equation

$$1.0 (X_1) + 0.33 (X_2) + 2.0 (X_3) \leqslant 10{,}000$$

expresses the combination of these three activities which can take place on this lake and is treated as an upper bound constraint in the linear program.

> Having analyzed the maximum carrying capacity of the system, the next step is to analyze the realities of existing facilities or developments, budgets, and recreation policy . . . this formulation can be quite varied." (Davis 1974:245)

This analysis identifies: 1) Constraints on the system; and 2) relative valuations of different recreation activities. Both of these require subjective judgments.

The constraints are of two kinds. One would be a stipulation of the minimum amount of certain activities that must be included. A second would relate to the maximum cost reflected in physical parameter modification necessary for some activities. Thompson and Fletcher say:

> . . . the owner/manager must assign a preference value to the respective qualified activities . . . This must be done . . . in order to determine a comprehensive set of feasible alternatives . . .

Under the plan formulated, the managers would do the analysis. This directly violates the criterion that judgment should be either controlled or given by the actual or potential users.[9]

Quality indices for the activities performed may also be constructed from the quality levels of recreation determined under the assumption:

> . . . that the specified resource parameter bound sets . . . have qualitative meaning to the recreation users. Previous research offers little on this point. (Davis, 1974:247)

This information in the original model is computer program input and is optimized to discover a best mix of recreation activities under specified conditions.

Critique

Davis (1974) provides an excellent and generally complete description of the difficulties with this modeling method. Paramount are the "subjectively specified value judgments" which are made several times in developing the model; the length of time required for model implementation (at least one full year); the requirement of expertise of model users; and the expense resulting from the complexity of the analyses.

Davis, however, indicates the major problem to be, ". . . that a planner or decision maker needs to be identified" (Davis, 1974:249). If a decision-maker is not identified, the basic policy inputs may not reflect the real-world situation. Decision-makers are often difficult to specify in a world of overlapping jurisdictions, special interest groups, and conflicting authority.

This method also does not provide a single valued measure for recreation, thus impairing its use for comprehensive analyses.

On the positive side, the method is a useful analytical tool from which the effect in terms of maximum benefits possible for different specific recreational activities can be determined under various conditions. Because the output is in terms of concrete recreational activities, "an analyst with limited background . . . could put the system to good use" (Thompson and Fletcher, 1972:17). When the focus is on recreation alone, the combination of complete analysis of possible recreational activities and ease of understanding of the output may make this method desirable.

This method is inapplicable for regional or national assessment. It could perhaps be implemented at great expense, on a river basin. The gathering and recording of data for a large-scale assessment would be an enormous task.

It is therefore recommended that this method be used primarily for localized analyses. On a local or specific level, it can provide the most comprehensive and detailed analyses available of the effect of changes in streamflow levels on the supply of recreation activities.

The procedure should be relatively easy to modify to provide indications of the quantity and range of activities caused by altered physical parameters resulting from streamflow changes. Some of the constraints placed on a recreational system in the original modelling effort may not be desired in a modification. Adapting this model to the specific problem of the effect of streamflows upon recreational activities requires that some of the inapplicable parameters of the original model be eliminated. Parameters that do apply can be expanded to afford greater sensitivity and/or to

[9]This bias can be lessened by obtaining the value judgments of potential users.

include additional types of recreation in the analysis.

Public preferences should be used to determine boundary conditions, importance evaluations, and other judgmental aspects of the model. With an appropriate scaling technique, public preferences could be used to weight the different kinds of potential recreational activities that are in the model. This approach could ultimately provide a single valued index for recreation.

A feasible range of mixtures of recreational activities could result from the application of a modified version of this method. Such a comprehensive and complex analysis would require considerable expertise for model construction, but the result would be a specification of the quantities of recreation activities that are available, and would be directly understandable to potential users of the resulting model. The construction of this type model for streamflow–recreation assessment is recommended when sufficient time is available and detail is desired. This method has promise since it can be applied to different flow conditions where the relevant physical data entered into the model can be varied for different conditions of streamflow. It can also be used in simulation analysis for planning purposes.

Other Methods

The following descriptions include method types that are appropriate to the streamflow problem, but are relatively general or have a special discipline orientation. They include direct user observation techniques, and the survey method.

DIRECT USER OBSERVATION

Direct observation is suggested as a general means of collecting data concerning stream-user behavior. Techniques include on-site counts of users and the recording of activities in specified areas. Mechanical counters for automobiles and roadside interviews may also be used in conjunction with observation. Another form of observation involves having the users keep diaries, which may be divided into time segments to show patterns of behavior.

Direct observations are useful, but they do not provide reasons for behavior or behavior changes. They also may not be generalizable unless the data are representative of populations.

SURVEY METHOD

The survey approach is a generally applicable method of obtaining information by using direct interviews, telephone interviews or questionaires mailed to specified populations. This method can provide statistically representative information that can be generalized from samples to a population. By using comparable questions, this approach can be used to assess the characteristics of stream users or managers, and determine their attitudes, activities and knowledge. Attitude measuring scales and similar controlled measuring devices may be incorporated in a survey. The survey method will provide a view of the status of public activity or concern.

Difficulties with this method are its cost, and its limited (one point in time) perspective. If a continuing assessment is made, however, this approach would produce highly useful indices of public interest in streamflow policies, use and related concerns.

RECREATION ASSESSMENT STUDIES

Team Rating Approach to Recreational Area Evaluation

The Bureau of Land Management (BLM) has utilized a team approach to survey and rate specific areas of recreational interest. The objective of this evaluation process is to determine on a relative scale the recreational value of the natural and cultural resources managed by the BLM. The approach is to rate the quality of experience a visitor can expect while participating in a specific recreation activity, e.g., fishing, hunting, etc. This in no way infers that a quality rating for fishing, for example, is a measurement of the total experience that a person can expect while fishing in an area. The total experience is a composite total of all the recreation use opportunities that a person can expect to experience in a given area.

Recreation is often composed of a series of activities. In these particular cases, the quality evaluation is a measurement of the total experience.

The concept of the evaluation procedure is as follows:

> The natural and cultural resources have "inherent" recreation use values that can be accurately measured without considering location, existing or potential use levels, or proximity to roads,

population centers, etc. For example, an archeological site which is in a remote and isolated location may have a greater inherent value for recreation use (sightseeing) because it is bigger, better preserved, etc. than another archeological site which is next to a road or close to a population center. The inherent value is measured entirely from the recreation user's point of view without considering the effect this use may have on the resource or other resource uses. The inherent value is recorded by giving an area a quality rating of "A", "B", or "C" ("A" being the highest). A resource can have different values for different kinds of uses: for example, a body of water may have:

- "C" value for fishing.
- "B" value for water fowl hunting.
- "A" value for powerboating and waterskiing.
- "A" value for sightseeing.

Quality ratings are based on the resource conditions as they exist during the primary visitor use season. The rating system is structured to limit "A" designations to the truly outstanding areas.

Five areas of importance are included in the BLM evaluation process.

Determining Data Needs – The resource data needed depend on the number and type of recreation activities which could occur on lands within the area. This is the first step in the evaluation process.

Inventory of Data Sources – Prepare a bibliography of all data sources, literature, agency, individual, for each recreation activity being evaluated.

Recording Requirements for Basic Resource Data – There are no set requirements for recording the basic resource data. However, it is essential that the data be presented in such a manner that it can be effectively used by the rating team.

The Rating Team – The team will usually be composed of a recreation planner (team leader), and other knowledgeable resource personnel, e.g., a team rating geologic-sightseeing opportunities should have a geologist, etc. The team should be composed of 3 to 5 members. In addition to BLM personnel, the team may include, representatives from other agencies, or representatives from user groups. Extreme care should be taken when selecting outside participants to insure that they represent a broad spectrum of users in their specialty, and that they have an intimate familiarity with the area and resources being considered. The team leader must have a thorough understanding of the concepts and procedures involved in the quality evaluation process.

Delineating Rating Areas – Delineate on an overlay the rating areas for each recreation use to be evaluated. A rating may be: 1) A large or small area which falls within certain definable boundaries such as an historic district, a lake, etc.; 2) a point-oriented feature such as a small archeological ruin: 3) a linear feature such as a stream.

Critique

The BLM Recreational Survey Method is immediately applicable. The team evaluation process can provide relevant data to categorize and rate recreational resource parameters. The results of this approach may be biased toward the managers perceptions and choices; however, the team approach tends to lessen this effect. Since its application is site specific, generalized statements may be imprecise.

Wild and Scenic River Segment Evaluation

The Bureau of Outdoor Recreation[10] is developing a river resource evaluation technique to assess rivers for inclusion in the "wild and scenic" classifications.

The method is a coordinated application of rating scales from several academic disciplines. These include hydrology, water quality measures, land use characteristics, cultural and historic resources, recreation resources, and zoological, botanical and physiographic resources.

The recreation resource measures are concerned with two differing aspects of river characteristics, river dynamics and recreation uses.

River dynamics includes both flatwater and swiftwater measures internationally recommended by river boaters. The characteristics are:

Flatwater

Class A	–	Standing or slow flowing water, not more than 2.5 mph.
Class B	–	Current between 2.5 and 4.5 mph.
Class C	–	Current more than 4.5 mph.

Rapids and Riffles

Class I	–	Occasional small riffles consisting of low, regular wave patterns. About what you might encounter on a lake on a mildly windy day. Minor obstacles in current.

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[10]Personal communication. 1975. B. Collins. Bureau of Outdoor Recreation.

Class II	–	Rapids occur more frequently, usually retaining a regular wave pattern as on a lake with a fairly vigorous wind; may be straight chutes over ledges up to 3' high.
Class III	–	Numerous rapids, with higher, irregular standing waves, hydraulics, and eddies. Ledges up to 4', waves to 3', and deeper water characterize this class.
Class IV	–	Long, extensive stretches of rapids with high, irregular standing waves, hydraulics, holes, eddies, and crosscurrents. Complex ledges with irregular passages waves, 3 to 4', or souse holes.
Class V	–	The rapids are long and continuous. Irregular waves over 4', souse holes, partially submerged boulders, and ledges are everywhere; very complex eddies and crosscurrents, are not only present, but also occur in long dazzling combinations.

Recreation use of resources associated with the riverine environment are also assessed. Some experience or professional judgment is necessary when evaluating potential recreation use or when classifying a resource.

Critique

This method was originally designed for river assessment; therefore, no elaborate modification is necessary.

However, because this method is currently under consideration, it is assumed that the values of the various river parameters have not been computed. This method cannot be implemented nationally without this information.

Recreation Opportunities, Benefits and Constraints as Related to Streamflow

Jason M. Cortell and Associates (Environmental Consultants), are conducting a study (contracted by the Bureau of Outdoor Recreation) using an approach similar to Thompson and Fletcher (1972), but with a different set of criteria.

Thompson and Fletcher analyzed the specific recreation activity to determine what flow level was necessary. Cortell and Associates are measuring the physical characteristics of a stream, and relating these data to recreational possibilities.

This study considers three basic interrelated areas concerning streamflow. The first deals with measurable physical parameters (that are altered or determined by flow level) which control stream reccreational possibilities. When the recreational possibilities at a specified flow level are determined, and related to physical characteristics (velocity, depth, width, beach area, flooded wetlands, etc.), socially defined recreational needs can be compared to hypothetical recreational situations at various flows. Cortell and Associates believe this approach will provide a basis for hierarchically ordering recreational activities relative to flow requirements.

Riverine recreational activities are grouped according to basic characteristics. Cortell and Associates have come up with five major categories of stream recreation. They are: 1) Fisheries; 2) water contact recreation; 3) boating; 4) water-dependent recreation; 5) water-related recreation.

The second area of investigation is an evaluation of the benefits associated with these five streamflow recreational opportunities. Improvement and refinement of the benefit analysis methodology will be attempted by exploring alternative methods of cost-benefit streamflow analysis.

The third area consists of investigating existing insitutional and legal constraints on streamflow. This will include prior claims under the categories of: 1) Federal law or regulation; 2) state statutes; 3) common law; 4) established usage.

SUMMARY

The purpose of this review has been to determine what *social science* methods/methodologies are available and applicable to measuring the effects of streamflows on recreation behavior.

Approaches for specifically assessing recreation-streamflow relationships have not been developed. However, several techniques can be applied to this type of assessment. In addition to classifying streams and determining their recreation potential, it is suggested that a longitudinal (through time) analysis of streamflows be undertaken along with studies of the relationship between user satisfaction and changes in streamflow. For simulative planning within an agency, we suggest the Delphi method and social analysis modeling as useful for predictive or projective purposes.

A standard method of stream classification should be agreed upon and applied on a nationwide basis. Methodologies for the categorization of streams for recreational purposes were also reviewed; judgmental error is such that such techniques should only be applied on a very local level.

We next suggest that longitudinal *post-factum* studies of the relationship between streamflow vatiations and changes in recreation behavior be undertaken. Utilizing secondary data, investigations would seek out situations where the streamflow has been altered in the past and then reconstruct changes in recreation behavior from secondary data.

We next suggest that studies be undertaken of various categories of users of streams in an attempt to determine the effects of streamflow variations on people and their recreation activities. Demographic data, characteristics of the public (users and non-users), the public's knowledge of streams, and the effects of variations in streamflows would be utilized in this approach.

The Delphi method and derivations of this technique will provide a useful means to identify and analyze the variables required in decision-making and problem resolution on all study levels.

Modeling is useful in analyzing decision and action processes. In addition, it can have an important role in simulation of solutions to provide insight (predictability) for planning.

The Thompson-Fletcher (1972) model for determining the quality of a recreational activity under varying conditions seems to be adaptable to streamflow assessment. This model does not categorize streams, but establishes numerical values for conditions of water bodies in relation to specific categories of activities. However, as designed, these values depend upon judges. Adaptation of the model to use public values must be made.

Application of the elements of the Techcom model, particularly the subgoals of the recreation goal, would be useful for recreation assessment. Considerable research and development and substantial testing would be necessary for adapting these models to the streamflow problem.

SUGGESTED RESEARCH STAGES

In reviewing the stat-of-the-art, it became apparent that there were several steps or stages that could be identified in bringing this work to direct application to instream flow problems. An attempt to identify those steps follows.

1. Identify and classify recreation and aesthetic parameters that are affected by variations in streamflow levels. The parameters at this stage in the research development must refer primarily to differences in streams. The classification methods would involve the selection and further research and refinement of one of the methods.

2. Classify streams at various flow levels according to the potential for various recreation activities. This stage in the research development would require the selection and then research and modification of one of the methods outlined in the second part of this section.

3. Utilize comparative longitudinal analysis techniques. Specific locations throughout the country where streamflow changes have occurred would be analyzed for changes in recreation behavior. Secondary participation records along with local information would be the research tools.

4. Develop methods to establish relationships between streamflow changes and satisfaction with the recreation experience. Examples of techniques would include ratio scales, weighting scales such as Likert, semantic differential and quasi-scales.

5. Measure perceptions and behavior of public in relation to specific streamflow situations. This stage would involve on-site analysis of various recreation populations.

6. Develop and/or adapt techniques designed to establish relationships between streamflow modification and recreational behaviors and satisfaction levels. Evaluate the effects of variation of streamflow on human behavior or human needs or desires.

7. Designate indicators of the effect of changes of streamflow on recreation activity and aesthetic states under specific conditions. This could result from application of the previously suggested research.

8. Develop equations or other methods for prediction of the probable type of recreation behavior related to streamflow and the aesthetic evaluations of different streamflow conditions.

9. Develop simulation models for future planning and management decisions.

10. Translate the results of this extensive social scientific research into a manual which could then be used by agency personal at the local level for making predictions regarding the future impact of changes in streamflows.

SUGGESTED RESEARCH

As a conclusion to this chapter, seven research projects are listed which the authors feel are necessary for an understanding of the human aspects of changes in streamflow levels. These suggestions should not be considered as requests for proposals. However, with some expansion they could be the basis for a comprehensive social science research program in the area of stream flow management.

1. Public Perception of Water

A study should be undertaken among the general population to determine attitudes, values, and perceptions toward water, streams, and changing streamflow. Response to these problems should be related to such items as recreation behavior and a variety of background characteristics. Data for such an extensive study of the general population should be obtained by means of personal interviews, telephone interviews or mailed questionnaires. Data should be collected on, but not limited to:

a. The relationship of water to the life-style and life interests of the respondent.
b. The general awareness among the population of some of the following water-related problems.
   1. pollution
   2. channelization
   3. diversion
   4. transportation
   5. changes in streamflow
c. General recreation behavior of respondents
d. Background characteristics of respondents

Results from such a study would place the water problem in perspective for policy decisions and could provide planners with a general idea as to public reaction to certain future water decisions.

Length of Project: 18 to 24 months
Cost: $250,000

2. Develop Methods of Categorizing Streams

Stream classification must eventually be accomplished on a nationwide basis and would provide a method of comparing research findings from one stream to another without repeating the research process.

As described in the body of the chapter, this project would entail the selection and refinement of one of the stream classification schemes for use by agency personnel.

Length of Project: 9 months
Cost: $20,000

3. Develop Methodologies for Categorizing Recreation Potential of Streams at various Flow Levels

If streams were classified according to recreation use, then the methodology should have the capability of being applied on a nationwide basis. However, due to the dynamic variation of stream flows within the same rivers, an accurate national classification may be a formidable task. As in the case of stream classification, it will be necessary for an agency to agree upon a method and then develop guidelines and standard procedures and instruments which can then be applied uniformly by agency personnel. The development of the research classification procedures should be done by social scientists.

One of the procedures as outlined in this chapter must be selected and refined for localized use. The methodologies developed here will necessarily be more complex due to the tremendous variations of the recreational opportunities at different points along the same stream.

Length of Project: 18 months
Cost: $75,000

4. Longitudinal Analysis of the Effect of Streamflow Variation in Recreation Behavior (Historical Secondary Data)

As the title states, only secondary data obtained from streams which have experienced alteration in flow in the past will be analyzed for changes in recreation behavior.

Length of Project: 18 months
Cost: $125,000

5. Changes in Streamflow Levels as a Factor in Recreation Satisfaction

Analyses of recreation user populations, as they are impacted by changing stream flows, represent an important, but expensive and lengthy, research undertaking. A three-year period is necessary to complete the initial research, because proper instruments must be developed. At least one year would be used in development and testing of the scales and other measures. In the second and third years, the developed instruments can be applied to specific rivers and areas. Workshops and training sessions should be held for interested organizations and other potential users of the developed and tested methodologies.

The research itself could utilize a series of observation points on a variety of streams. As the streamflow varied over the year, trained observers would record the changing recreation behavior. This procedure could be supplemented by interviews with selected users as to how the level of the stream influenced their level of recreation satisfaction (see Thompson and Fletcher, 1972). This would provide basic data as to how different user groups are affected by changes in streamflow resource. On-site analysis of user groups could provide answers to several basic questions.

a) What recreation activities are predominant for different types of streams at different flow levels?

b) To what degree do recreation activities remain constant regardless of the levels of the stream?

c) Are major categories of recreation activity groups likely to be displaced if streamflows are altered on a permanent basis?

Length of Project: 34 months

Cost: $380,000

6. Modification of Delphi Technique for use in Localized Streamflow Decisionmaking

The research contractor would modify the present technique for applicability to the streamflow problem and for in-house use by agency personnel.

Length of Project: 18 months

Cost: $75,000

7. Development of Mathematical Modeling Techniques for Social Science Parameters Influencing Streamflow Variation

Utilizing existing methods derived from linear programming techniques, this project should develop a model which would assist the local manager in predicting the future impact of any change in streamflow or the recreation supply. The output would be a computer program which would provide information on varying recreation opportunities as the streamflow varied.

The development of a mathematical model which would have wide applicability to changes in streamflow requires a research organization which has a sensitivity both to the important recreation parameters and to variations in linear programming techniques. The total time to develop the model would be about two years. However, once the model is developed and applied to an area, the interpretation and use of the model could be easily understood by a local manager.

Length of Project: 18 months

Cost: $125,000

REFERENCES CITED

ANDREWS, W. H., A. B. DAVIS, K. S. LYON, G. E. MADSEN, R. W. ROSKELLEY and B. L. BROWER.
1972. Identifications and measurement of quality of life elements for water resources development: An exploratory study. Res. Rep. No. 2. Inst. Soc. Sci. Res. Nat. Resour., Utah State Univ., Logan, Utah.

ANDREWS, W. H., G. E. MADSEN, and G. J. LeGAZ.
1974. Social impacts of water resources developments and their implications for urban and rural development: A post-audit analysis of the Weber Basin Project in Utah. Res. Monogr. No. 4. Inst Soc. Sci. Res. Natur. Resour., Utah State Univ., Logan, Utah.

ANDREWS, W. H., M. B. MASTELLER, J. P. RILEY and E. K. ISRAELSEN.
1975. Methodology and applications – modeling the total hydrologic-sociologic system of an urban area. Utah State Univ., Logan, Utah. (In Press).

ANDREWS, W. H., J. P. RILEY, C. W. COLTON, G. B. SHIH and M. B. MASTELLER.
1973. A preliminary model of the hydrologic-sociological flow systems of an urban area. PRWG 109-1. Utah Water Res. Lab., Utah State Univ., Logan, Utah.

BAYHA, K. (ed)
1974. Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N.W. River Basin Comm. 203 p.

BISHOP, A.
1972. An alternative evaluation matrix. Instream Flow Methodology Workshop, Olympia, Washington, November, 1972.

BOSTER, R. S.
1974. On the criterion and the possibility of quantifying the aesthetics affects of water resources projects. *In* Brown, P.J. (ed.). Toward a technique for quantifying aesthetics quality of water resources. IWR Contract Rep. 74-8.

BOSTER, R. S., and T. C. DANIEL.
1972. Measuring public response to vegetative management. *In* Proceedings 16th Annual Arizona Watershed Symposium. Watershed management effect on wildlife and recreation, Arizona Water Comm. and the Arizona Water Resour. Commit., Phoenix, Arizona.

BREWER, D., and G. A. GILLESPIE.
1967. Estimating satisfaction levels of outdoor recreationists, J. Soil and Water Conserv. 22:67.

BURDGE, R. J., and D. R. FIELD.
1972. Methodological perspectives for the study of outdoor recreation. J. Leisure Res. 4:63-72.

BURDGE, R. J., and S. JOHNSON.
1975. Assessing the social component of environmental impact statements. *In* McEvog, J. III, (ed). Social impact analysis. John Wiley & Sons, New York.

CRAIGHEAD, F.
1962. River systems; recreation classification, inventory and evaluation, Naturalist 13(2).

DANIEL, T. C., and R. S. BOSTER.
1975. Measuring scenic beauty: the scenic beauty estimation method. Rocky Mountain Forest and Range Exper. Station. USFS, Fort Collins, Colorado. In press.

DAVIS, L.
1974. Quantifications of connectives for the recreation goal of Techcom. *In* Water resources planning social goals and indicators: Methodological development and empirical test. PRWG 131-1, Utah Water Res. Lab., Utah State Univ., Logan, Utah.

HAIMES, Y. Y., and W. HALL.
1974. Multiple objectives in water resources systems analysis. The surrogate: worth trade-off method. Water Resour. Res., 10(4):615-624.

JAAKSON, R.
1970. A method to analyze the effects of fluctuating reservoir water levels on shoreline recreational use, Water Resour. Res. 6(2).

LERNER, L.
1962. Quantitative indices of recreational valves, water resources and economic development of the west. Rep. No. 11. Economics in outdoor recreation policy. Univ. of Nevada, Reno, Nevada.

MORRIS, J.
1974. Report on the need for an expanded program of data collection and evaluation of in stream-flows for recreation and aesthetics. For submission to the ad-hoc In-Stream Flow Study Evaluation Committee, Pacific N.W. River Basin Comm., N.W. Region Bureau of Outdoor Recreation.

NORTHEAST REGION, BUREAU OF OUTDOOR RECREATION.
1970. Draft report of the Kanawha River basin comprehensive study. Bur. Outdoor Recreation, Unpub. MS, 87 p.

NORTHWEST REGION, BUREAU OF OUTDOOR RECREATION.
1974. Recreation—Chap. 12. *In* Bayha, K. (ed.). Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N.W. River Basins Comm. pp. 123-147.

REDDING, M. J.
1973. Aesthetics in environmental planning. Office of Res. and Develop., EPA, Washington, D.C.

TECHCOM.
1974. Technical Committee of the Water Resources Research Centers of the Thirteen Western States. Water resources planning, social goals and indicators: methodological development and empirical test. PRWG 131-1, Utah Water Res. Lab., Utah State Univ. Logan, Utah.

THOMPSON, J., and R. FLETCHER.
1972. A model and computer program for appraising recreational water bodies. Project C-3379 – OWRT-USD3 PWRG-112-3, 48 p.

URBAN, J. T.
1965. A white water handbook for canoe and kayak. Appalachian Mountain Club, Boston, Mass.

WELSH, T. L., and D. CROUCH.
1974. White water boating – Chapt. 13. *In* Bayha, K. (ed.). Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N.W. River Basins Comm. pp. 149-154.

7. MEASUREMENT OF STREAMFLOW AESTHETIC VALUES

M. B. MASTELLER, W. H. ANDREWS,
L. C. LANGORD AND G. E. MADSEN

CONTENTS

Changes in streamflow increase or decrease the available quantity of water in a given stream. These changes can be permanent, seasonal, or fluctuating over short periods of time. A relationship is postulated between changes in streamflow and the resultant aesthetic quality of the stream environment. The purpose of this report is to document methods that can assess the extent of this relationship, and the major factors that contribute to the relationship. Where suitable methods do not exist, research needs appropriate to the problem are identified. Where adequate data bases do not exist which permit the exploration of this relationship, these needs will also be identified.

The resultant information can be used for three purposes: 1) To determine streams or sections of streams where no flow fluctuation (other than normal), throughout the year, should take place because of their extreme aesthetic sensitivity; 2) to determine a permissible range of flows where changes can be tolerated; 3) to determine what should be done to minimize the deterioration of aesthetic quality where streamflow changes are unavoidable and exceed tolerable limits.

The literature on aesthetics in relation to streamflow evaluation generally defines aesthetics as the visual valuation of the beauty of a scene.[1] Sometimes aesthetics is used in a broader sense to include any personal evaluation of the elements of a natural situation, with visual beauty as an important component. The broad interpretation can include valuing or appreciation of nature, exhilaration or emotional response, touch, smell, auditory, visual, and other effects of the environment upon the senses. Unlike recreation, which connotes activity, both of these definitions of

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[1] Aesthetic appreciation of clarity of streams or other individual attributes in themselves has seldom been studied in natural environments.

aesthetics imply a personal evaluation of a sensory response to a stimulus. A definition of this type must be functional and related to the problem under analysis in order to be used as a delineating concept for a research purpose.

WHY MEASURE AESTHETICS

The justification for measuring aesthetics is that it is an increasingly important public concern. Ecological and aesthetic concerns are linked because both indicate an interest in nature, and because often the most discernible ecological effects are those that alter the aesthetic qualities of a natural resource. This has led to directives to public agencies (NEPA, particularly Sec. 102C) to include social considerations in calculations of effects on and worth of natural resources (including aesthetic parameters). In order to do this, the important social factors must be measured in comparable and meaningful ways. These factors include recreation as well as aesthetics.

There is a practical side to these considerations. With increased public attention to scenic beauty, proposed resource allotments are often being challenged on the basis of aesthetics and recreational deficiencies. Such proposals can be implemented or avoided and contentions resolved by more than opinions, only if valid data are available.

This does not necessarily mean putting a dollar value on aesthetics. Indeed, an important recommendation of this report is that alternative quantifying units be established, so that all data are not contorted into an unsatisfactory format. Comprehensive analyses do require, however, a numerical rating of at least ordinal level.[2] At the ordinal level, provided there are a reasonably large number of score points, relationships with respect to changes in variables may be determined. When this measurement is extended to interval and ratio levels, the relative and absolute magnitudes of effects can be estimated.

Another benefit of aesthetic measurement techniques is that they can aid in ascertaining users' preferences, thereby avoiding much of the distortion that might be caused by professional decision making alone. In the United States, government agencies are supposed to serve the public interest, but this presumes knowledge of what the public interests are and the public's relative valuation of those interests.

GOALS OF MEASUREMENT

The criteria described in the first of the recreation measurement section should be applied to aesthetics measurement as well. These criteria were developed on the basis that measurement should be: 1) Valid (measure what is supposed to be measured); 2) reliable (consistent in measurement); 3) feasible (applicable with the usually available expertise); and 4) meaningful (including important and relevant attributes or variables).

Understandability, comparability, and replicability will normally be achieved if the four measurement goals are accomplished. Association of numbers with a variable is desirable only when such numbers are valid. Under these conditions, numbers facilitate the consistent interpretation of measurements and permit weightings and possible trade-offs to be determined by use of the numerical values in models.

In addition to the general methodological criteria discussed in Section 6, constraints on choosing a method with which to study relationships between streamflow and aesthetics include: 1) To which of the following areas of concern can the method(s) be applied? a. The identification of parameters critical to the evaluation of streamflow environmental aesthetic quality; b. What people perceive with respect to these streamflow parameters; or c. People's evaluations of what is perceived. 2) For which of the identified research needs can the method(s) in question be used? 3) Can they be used at national, regional, or project levels? 4) How much time and money, and what levels of expertise are required for the method(s) development, application, and interpretation? 5) Is the method suitable for measuring relationships between streamflow and aesthetics?

GENERAL COMMENTS: APPROACHES TO AESTHETIC ASSESSMENT

Neither visual attributes alone nor the psychological state that is used for interpretation appears to determine aesthetic values. It is their interaction that produces the rating.

[2] An equivalent dollar value may be obtained from comprehensive analysis by determining the trade off in units between a variable measured in nonmonetary units and one that is. This value is dependent on the particular variables being considered and should not be considered the same as direct measurement of dollar worth.

One might ask what are the causes of differential ratings of scenic beauty? Assuming consistent judgment,[3] any differences in an individual's evaluations of scenes must be a result of some characteristics of these scenes. These characteristics may either relate to the individual elements themselves or their various combinations. Qualitative attributes of a scene, such as line, balance, variety, contrast, etc., are due more to the arrangement of the objects contained in that scene than to the objects themselves.[4] Changing either the objects and/or their arrangement could alter the evaluation.

The observer of a scene reacts to the scene not as a group of unrelated objects, but to the total impression they make on his mind (Litton, 1972). Indeed, he may not assess individual objects at all until the total scene has had its impact upon him. Measures that attempt to characterize aesthetics by listing the attributes of a scene may miss assessing the additive or multiplicative effects of combinations of attributes. They also must assume a typical or unchanging response by different observers, which is unrealistic. Given a scene that remains constant, if a number of observers are asked to rate the scene, it is probable that differences in rating will occur. There are at least three reasons for this. First, the aesthetic standards on which judging is based may vary from individual to individual. Second, the context of the assessment can cause variations as people may relate the scene to personal references. For example, a scene that would be considered beautiful if assessed in relation to a suburban environment may be considered unattractive when compared to the country. Third, people vary in their response patterns. Some respondents may more readily express themselves using strong terms or numerical valuations than do others who may have similar attitudes. Methods that attempt to measure aesthetics directly by use of group or individual perceptions need to be concerned with these reasons for variability.

Many of the social science measurement methods were designed to measure traits and patterns of individual and collective behavior, not properties or qualities of environments. Important conceptual and methodological differences in the use and interpretation of these measures therefore depend upon which application is involved.

Daniel et al. (1973) have classified the problems of measuring as involving: 1) The person's sensory experience relevant to the perceptual dimension that defines the judged characteristic; and 2) the person's willingness to make discriminations at each point on the given dimension. They called these two elements, respectively, the observer's criteria and his sensitivity. This seems to be a valuable way of conceptualizing these two variables.

REFINEMENT AND ADAPTATION OF EXISTING TECHNIQUES

As is stated in the discussions of the various methods used in assessing aesthetics, a major lack is the application of existing techniques to the streamflow problem.[5] In addition, the results of the classification and social indicator type methods need to be verified by perceptual measures to insure validity.

The methods for directly assessing people's perceptions, the scaling methods, are basic because the validity of other types of analyses of aesthetics can only be checked by reference to a measure of this sort. This type of analysis needs to be developed in order to begin to move beyond the limitations of the techniques that use judges. A summated score scale of some type should be developed for measuring attitudes related to streamflow aesthetics and the applicability of the advanced *Ratio Scaling* and *Scenic Beauty Estimation* techniques (see appropriate sections) to measurement of streamflow aesthetics perception should be tested.

Development and verification of valid and reliable social scales require repeated applications of statistical and other analyses and usually several samples of respondents. This could be accomplished as the first phase of a larger study.

A classification analysis of the particular attributes of the effects of streams on aesthetics

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[3] A probability function may be used (see Daniel and Boster, 1975).

[4] Photographs, either slides or prints, are often used when assessing aesthetics. This appears to be justified by recent research that indicates the similarity of responses to perceiving photographs and actual scenes (Daniel and Boster, 1975; Zube, 1974; Shafer and Richards, 1974; Craik, 1971);

[5] The reader is referred to the discussion of each method and the section on application to streamflow assessment for suggested improvements and modifications of methodologies.

could be verified to some extent by use of a scale developed and proved to be reliable for stream aesthetics. The classification analysis should include all characteristics that could affect aesthetics, especially those that are most affected by alteration in water level. The first step would have to be a listing of all the factors (or attributes) that might be related to stream aesthetics. Once these factors were verified as significant, standards would need to be established for assessing the degree and nature of each factor.

If the factors could all be quantified,[6] the more important ones and their relative importance for prediction could be determined by a regression analysis similar to that used in the *Landscape Preference Model.* The dependent variable would be the evaluation of a scene as measured by a psychometric scale previously developed, and the independent variables would be the quantified factors. The coefficients and their significance levels would indicate the weights of the factors. Interactions of factors may be included as factors themselves.

The idea of verification should also be realized in constructing a social indicator type of model for this problem. The social indicator model (see *Social Indicator Technique*) refines the classification techniques so that relationships between factors and goals are defined. It has all measures derived from indicators whose values are measured directly in numerical terms. Almost all the other techniques given may be included in a social indicator analysis.

A successful application of the social indicator method to the effect of stream flow alterations would be valuable. Other aspects, such as recreation and biology, could also be included in one complex analysis. Such an undertaking would require the development and refinement of other more specific methods of assessment for this problem. Development of a proper social indicator model would therefore require a great deal of expertise and a considerable investment of time and money. However, methods developed early in a study for use in creation of the social indicator model could also be used to analyze parts of the effect and to determine some relationships.

Research efforts should be concentrated in fundamental research and in the application of psychometric techniques to streamflow aesthetics assessment. This could then be used in developing ways to analyze the effects on aesthetics of the physical factors that are related to alteration of water levels in streams. These goals seem attainable with sufficient effort.

The literature indicates that the major focus of studies in environmental aesthetics to date has been to identify and define scenic beauty. General scenic beauty and streamflow aesthetics are assumed to be related. The focus of the latter is narrower, however, so the variety of parameters involved in aesthetic perception may also narrow and thus simplify analyses. But the precise identification of the few pertinent factors may become more critical.

Aesthetics and recreation are correlated[7] because both provide pleasure, and a recreation activity may be undertaken to achieve an aesthetically pleasurable sensation. They have generally been distinguished in the literature by the activity giving pleasure per se while the aesthetic object provides pleasure *per se*, while the aesthetic object provides standpoint, aesthetics is one component of a cluster of attitudes and perceptions that may induce a recreational behavior. Someone who appreciated a particular scene or area for aesthetic reasons is more likely to enjoy recreation there than if the aesthetics did not appeal. This does not mean that recreation and aesthetics are the same, and attempts to measure one by the other may lack validity.

The attempt to distinguish between recreation and aesthetics provides a theoretical basis for differences in the types of methods available to measure recreation as opposed to aesthetics. Since recreation theoretically involves activity as the central focus, it involves measurable and obtainable figures such as use and expenditure figures. Consequently, in addition to sociological and social-psychological methods, economic evaluation methodologies have been applied. Aesthetics, however, involving a sensitivity or emotional evaluation, not necessarily activity, has been investigated more by psychological methods. Further conceptualization and critiques are needed to bring about additional improvement in the theoretical component of this work.

Differences in their theoretical constructs would seem to require separate treatments for

[6]Actually, qualitative variables could be considered independent by use of dummy variables. This is not recommended without set, specific instructions that achieve consistent, repeatable categorizations.

[7]This correlation has been verified. See Andrews et al., 1972, and Andrews, et al., 1974.

recreation and aesthetics, although there are important similarities in some techniques. For example, subjective evaluations such as attitudinal scaling techniques have been used for both recreational and aesthetics factors. Because of these similarities, the discussion of general criteria in Section 6 applies to both; however, methods for each are treated separately.

STAGES OF APPLICATION OF MEASUREMENT TECHNIQUES

One possible assumption for evaluating methodologies sutiable for the study of streamflow aesthetics is that the natural state throughout the year represents an aesthetic optimum, and that changes from this state reduce this optimum by degrees. Research with respect to the applications given below will be needed to determine if this is true.

Three stages of method application have been identified and are discussed below. The purpose of this identification is to provide a standard, more specific to streamflow aesthetics, by which the methods discussed in this report may be evaluated and to which research needs may be related. While the literature suggests the importance of these stages of application, they are not to be considered as the only concerns. The elements in each of these stages will interact with the others and modify them, and, in turn, they are modified by them.

I. The first step in determining relationships between streamflow and aesthetics involves a documentation of actual changes in the streamflow utilizing the following approaches: 1) *A classification of streamflow types*. It is suggested that a combination of water, shoreline, and interface factors might be a suitable basis. Although a standard interdisciplinary classification is desirable, a classification system suitable for aesthetic applications may not be the same as for another study subject. The data obtained from steps II and III may suggest another classification; 2) *A systematic recording and description of changes which take place with known quantitative changes in flow*—Factors that should be considered are listed in Table 1. They have been limited to those associated directly with the water and the shoreline of the stream study area or which may be linked with these factors. The selection was guided by their consistent occurrence in aesthetic classification systems (see Leopold, 1969b).

There are two general ways to deal with flow changes. The researcher can study similar stream types representing a range of flows, or focus on one stream where controlled releases are possible, as was done on the Snake River (Northwest Region, Bureau of Outdoor Recreation, 1974).

Table 1. Criteria for documentation.[a]

Physical Factors	Biologic and Water Quality	Human Use and Interest Factors
River width (ft)	Water color	Trash and litter
Depth (ft)	Turbidity (ppm)	Metal (no. per 100 ft of river)
Velocity (ft per sec)	Floating material	Paper
Stream depth (ft)	Water condition (general)	Other
Flow variability	Algae	Artificial controls (dams, etc.)
River variability	Amount	Accessibility
River pattern	Type	Individual
Valley height/width	Larger plants	Mass use
Stream bed material	Amount	Local scene
Bed slope (ft/ft)	Kind	Water sounds
Drainage area (sq mi)	River fauna	Vistas
Stream order	Pollution evidence	View confinement
Erosion of banks	Riparian vegetation	Utilities
Sediment deposition in bed	Land flora	Urbanization
Width of valley flat (ft)	Valley	Historic features
Stream course pattern	Hillside	

[a]The selection of these criteria has been limited to those associated directly with the water and shoreline of the stream study area. Their selection was guided by their consistent occurrence in aesthetic classification methodologies (see Leopold, 1969b).

A desirable technique may be by on-site inspection of the stream in question. The data base may be obtained from primary or secondary sources or both. The techniques used should be as diversified as is feasible and aimed at recording all factors from a maximum number of observation points. This might involve the use of still and motion photography, written descriptions, audiometers, and the taking of water-generated sound levels, as well as standard quantitative measurements of biota and water quality. If an on-site inventory is not possible for all factors, secondary sources, such as the literature, agency records, and environmental impact statements may be used. Gaps can then be filled by on-site collection. Aesthetic evaluation should not yet be attempted.

Data collection of this type, although time-consuming and expensive if done rigorously, can be worthwhile as the basis for studies focused on the relationship between streamflow and aesthetics.

II. The next step is to determine which of the water, shoreline, and interface factors identified as potential components of the aesthetic experience are actually seen at different streamflow levels, at what level of discrimination, in what interrelationships, and with what degree of importance.

Some elements may have a high flow change tolerance and others a low tolerance, leading to a development of flow range limits.

The importance of this application is emphasized because much of the completed scenic beauty research has assumed that the elements included by the researcher are the ones generally perceived by the public—a rash assumption. Also, different subgroups in the population may perceive aesthetics in different ways. The techniques developed by Appleyard et al. (1965) for viewer perception in urban and highway studies could be helpful and perhaps help generate an expansion or refinement of the preliminary aesthetic parameters.

Included in such efforts is the specific identification of general aesthetic behaviors and those which may be more particularly associated with stream environments. Direct quantitative counts can then be made by field personnel, as is done with recreation behaviors. A preliminary identification of aesthetic indicator behaviors would include: Photography of all types, drawings and paintings, observations of flora and fauna, looking and sensing, and other behaviors not requiring the active use of equipment usually associated with recreation.

III. Given I and II, the next step is to ascertain the aesthetic role, if any, of each perceived element and of combinations of elements, and their relationships to streamflow. It would be desirable to obtain hierarchical rankings.

The primary approach for this step would be user evaluation analyses. The literature is filled with arguments advocating the judgments of professional experts or general public populations. It is not known (and must be determined) whether interdisciplinary, interagency professional evaluations differ from those of the general public. These area-specific evaluations must also be placed in the perspective of social values.

SCALING METHODS

Scaling methods refer to those techniques that attempt to assign numbers to aesthetic phenomena. In general, these methods involve questionnaires and are given in surveys.

To have a response, there must be a stimulus. The stimulus in some cases is a verbal description, which may vary from a single word, such as forest, to a long description, or a visual representation, typically a photograph. Although methods using these ways of presenting the object to be rated have sometimes been separated, the ways of ascertaining reactions to the stimuli are the same. Photo techniques are therefore not treated as a separate classification in the following presentation.

Survey questions can be either open-ended or closed checkoff type. The respondent himself must initiate answers to open-ended questions. An example would be "What do you like about the scene?" By contrast, a close-ended question would present a set of answers from which the response must be chosen, such as, "Which of the following characteristics of the scene would you rate as attractive?" followed by a specific list of characteristics. A compromise is sometimes achieved by listing possible answers plus a category of "other" with a blank space so that any unlisted answers may be entered.

Open-ended questions are useful in exploratory studies in which the factors meaningful to people are to be determined. However, once this is done, the use of this technique has several drawbacks. Comparability is greatly impeded since different responses may not be compatible. Judging that two responses are equivalent and collapsing the responses into one in analysis is questionable since the respondents gave the answers and only they could evaluate their equivalence. Also, small numbers, often single instances, of some answers may occur. Further, responses may not be on the same level, with some mentioning qualitative, others quantitative, characteristics. The meaning assigned to response terms may also vary from interviewer to interviewer and from respondent to respondent. This particular problem is not eliminated by use of close-ended questions, but it can be greatly reduced.

Probably the most important practical reason for preferring closed to open questions is that they preclude the summation of the responses over several scales. Most scaling techniques are of this type. For these reasons, the following discussion will be confined to methods using close-ended questions (see Guilford, 1954).

All of the scaling techniques presented are applicable to the problem of determining aesthetic values in relation to streamflow. However, only in a few cases have scales been developed to measure aesthetics specifically, and none have been developed in relation to streamflow itself.

Rating Technique

The first scaling technique to be discussed consists simply of a single question followed by a series of responses which may be either verbal qualitative gradations, such as very ugly to very beautiful, or numerical valuations.[8] Usually, an ordinal scale results.[9] The type of questions given as examples above could be transformed into a rating scale by asking, "Please rate this (described or shown) river scene by the amount of beauty it possesses according to the following scale," followed by a designated range of responses with at least the end points labeled.

An actual example of this method is the following:

To what degree would you say the stream is a source of pleasure to you?

No Pleasure						Great Pleasure	NA	DK
0	1	2	3	4	5	6	7	8

(Andrews, et al., 1974)

NA stands for no answer and DK for don't know.

Another example is:

	Excellent	Good	Fair	No Opinion
Scenic Beauty	______	______	______	______

(Michaelson, 1974)

As can be seen, this method is simple and straightforward, and these are its chief advantages. Miller (1970) provides some useful instructions for this method: 1) Divide the continuum to be measured into an optimal number of scale divisions (approximately 5-7); 2) the continuum should have no breaks or divisions; 3) the positive and negative poles should be alternated; 4) introduce each trait with a question to which the rater can give an answer; 5) use descriptive adjectives or phrases to define different points on the continuum; 6) decide beforehand upon the probable extremes of the trait to be found in the group in which the scale is to be used; 7) only universally understood descriptive terms should be used; 8) the end phrases should not be so extreme in meaning as to be avoided by the raters; 9) descriptive phrases need not be evenly spaced; 10) pre-test. Ask respondents to raise any questions about the rating and the different points on the continuum if they are unclear; 11) to score, use numerical values as assigned.

Critique

The disadvantages of the rating technique include; the ordering ability of the question is no greater than the number of response choices given, and that one item may not adequately represent the attitude of the individual – it may be a deviant case because of a particular characteristic or for some other reason. Along the same line, the number of response options is limited by the ability of people to make meaningful categorizations. Most studies seem to indicate a maximum of seven or so response categories. Also, there is no assurance that gradations between categories will be consistent from person to person. Consequently, the interpretative meanings given by people to the categories are liable to variation. Despite these limitations, however, single questions of the graphic rating type appear to be more reliable than short versions of the following, superficially more powerful methods (Taylor and Parker, 1964).

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8 Numbers may be assigned to qualitative descriptions either during or after the responses, i.e., very ugly=0, ugly-1, etc.

9 An ordinal scale in this context is one that orders the stimuli on the basis of the responses.

Likert and Other Summated Score Scales

Likert is the most popular scaling technique that uses multiple questions and is basically an extension of the above rating technique. A Likert scale consists of a series of questions related to the object being measured. Each question has five response categories, which are numbered. The middle value, three, is always neutral. The end points, one and five, are strongly agree and strongly disagree, and the in-between points, two and four are agree and disagree. The statements ideally should be arranged so that for half the items, strongly agree indicates an attitude in a given direction while for the other half strongly disagree is the response that indicates an attitude in a different direction. This is done to avoid response set bias as much as possible for respondents who typically agree or disagree.

Items are selected initially on the basis of a subjective judgment as to their applicability. A partial check on the reasonableness of the judgment is accomplished by item analysis in which the correlation of each item with the total is computed or equivalent. As a rule of thumb, an item may be considered acceptable if its correlation is greater than $1/\sqrt{N}$, where N is the number of questions in the scale.

The responses to each retained item are added for each respondent. The total score is used as an indication of the respondent's relative position in regard to the factor being measured.

Andrews et al. (1972; 1974; 1975) have been developing a set of scales of this kind in addition to those mentioned in Section 6.[10] The results of an analysis of items related to a scale for Natural Aesthetics Orientations are as follows:

Item No.	Statement	Correlation Coefficients	Significance
1	There isn't enough time to enjoy the beauty of nature.	.3303	.000
2	A trip to the country to enjoy the scenery is sometimes not worth the trouble.	.5845	.001
3	Landscapes are often unattractive	.6102	.001
4	The scenery of an area would greatly affect whether or not I would move to that area.	.1464	.201
5	There is nothing more beautiful than scenery outdoors	.3584	.001
6	Being in the country is seldom boring.	.4421	.004
7	The enjoyment of the beauty of nature is often destroyed by dirt, bugs or weather.	.3772	.013
8	Outdoor scenery often looks alike	.3178	.032
9	There is less reason today to go places to see scenery since one can see it one color television or at the movies anyway.	.2804	.052
10	Vacations are most enjoyable when one can go and enjoy the beauty of natural scenery	.3685	.015

[10]In addition to those shown in this report, other Likert scales developed include Ecological Orientation; Willingness to Pay for Government Expenditures, Willingness to Follow Advice of Experts, Willingness to Follow Agencies proposals, and Attitude Toward Pollution (Andrews et al., 1975).

The above could serve as a basis for the development of a scale to measure Stream Aesthetic Orientation. Items 4 and 9 would be removed, and the analysis redone using the remaining items. Unless they improved, items 1, 7, and 10 would then be removed, and the balance of the items used to test additional items for a longer scale.

A related scale with an analysis designed to measure attitude toward the effect of man-made objects upon the beauty of nature follows.

Item No.	Statement	Correlation Coefficients	Significance
1	Man generally improves the appearance of areas.	.5482	.001
2	The beauty of nature is *not* destroyed by the presence of man-made objects	.6757	.001
3	Buildings near an outdoor recreation area ruin the beauty of the area.	.6113	.001
4	Flood control and similar projects destroy the beauty of the areas in which they are located.	.4738	.001

Critique

The primary advantages of Likert scales are their relative ease of construction, ease of application, and that ordering may be increased over using a single question.

The disadvantages stem from positive item to total correlation being a necessary but not sufficient insurance of unidimensionality. This means that extraneous factors may enter in. For this reason, the results of two Likert scales supposedly measuring the same factor may not always be identical. However, continued refinement of scales can bring improvement.

In addition to adding scales whose items have responses according to the Likert format described above, other items with a consistent ordered set of responses may be summed to form a scale.[11] The subjective judgment of applicability to measurement of the same phenomena is the same as with Likert scales.

Guttman Scale

As far as the authors know, the Guttman scaling technique has not been applied to streamflow. It is presented here because a scale of this type does not present the difficulties associated with Likert and other summated scales.

Miller (1970) provides a very good, simple explanation of the Guttman Scale.

> NATURE: The Guttman technique attempts to determine the unidimensionality of a scale. Only items meeting the criterion of reproducibility are acceptable as scalable. If a scale is unidimensional, then a person who has a more favorable attitude than another should respond to each statement with equal or greater favorableness than the other.
> UTILITY: Each score corresponds to a highly similar response pattern or scale type. It is one of the few scales where the score can be used to predict the response pattern to all statements. Only a few statements (five to ten) are needed to provide a range of scalable responses . . . scores reflect a given pattern of response. (Miller, 1970:94)

Miller also provides a succinct set of instructions for constructing Guttman scales (Miller, 1970).

Critique

The main disadvantage of a Guttman scale is that it is difficult to construct. However, once constructed, its meaning is definite. Two Guttman scales will produce the same results if any one item is the same in both scales.

A little used variation of the Guttman scale that produces the same practical results[12] is what Guttman called a quasi-scale. The Guttman scale essentially allows no error components, while random error components are permissible in a quasi-scale. This is revealed in a scalogram analysis which is a display of the response patterns (Guttman, 1948). It would be desirable to construct this type of scale when possible. Any unidimensional scale will meet the Guttman requirements as stated above.

Unfortunately, a multidimensional phenomena must be broken into its unidimensional or basic components in order to use a unidimensional scale. An index for the total phenomena could be constructed from the components. Understanding would be enhanced, but more time would be invested than if a multidimensional scale were applied to the total phenomena.

Latent Structure Analysis

Latent Structure Analysis was developed as a way to obtain the unidimensional components of multidimensional scales. It is based on a probability model and provides ordinal information.

> The basic postulate is that there exists a set of Latent classes such that the manifest relationship between any two or more items on a questionnaire can be accounted for by the existence of these Latent classes and by these alone . . . Unlike scalogram analysis, this technique includes imperfect scale types in the analysis without considering them as mistakes. (Miller, 1970:77)

The method basically consists of calculating the proportion of respondents who demonstrate a latent attitude relative to each question. Probability analysis establishes indices or average latent positions for each response pattern. Miller (1970) provides succinct instructions and an example of a latent distance scale.

Critique

Originally presented in *Measurement and Prediction* (Stouffer et al. 1973; see Lazarsfeld, 1948), this should be a useful method. It has been used very little, however, probably due to the mathematical expertise required and its complicated theory.

Semantic Differential

The semantic differential technique consists of a set of bi-polar adjectives such as good-bad, ugly-beautiful, strong-weak, etc. at each end of a series of seven, position-broken lines. The respondent is asked to check where he believes the

[11] The term Likert scale is often incorrectly used to represent any simple summated scale that does not have special procedures, such as the subsequent scaling techniques require.

[12] In actual use the most important practical aspect of Guttman or quasi-scaling is that the correlation of any outside criterion with the total scale score is as great as the multiple correlation with all the items comprising the scale. This is remarkable and means that nothing is lost by using the index instead of all the items in the scale. This single number can thus adequately represent the variable in analyses. The same attribute would apply to the results of any other unidimensional scaling method.

stimuli to be properly placed between the paired extremes.

This method may be thought of as a series of rating scales in regard to the factor being measured, and has several applications. Similarities can be noted within the cluster of responses revealed by factor analysis, to discover the dimensions behind the assessment of a factor. Each of the ratings may be treated in itself, and the mean and other statistics computed. Once dimensions are determined, mean scores can be computed for each dimension. Factor analysis methodology may also be used to confirm or deny theoretical suppositions as to the nature of a subjective phenomena.

Critique

The versatility of the Semantic Differential, and because a scene is an appropriate stimulus, have led to this techniques use in appraising aesthetics (Meredith and Ewing, 1969; Calvin and Dearinger, 1972; Mueller et al., 1974; Shafer and Richards, 1974). Craik (1972) has developed an adjective check list that should be useful in semantic differential applications. Details of the method are presented by Osgood et al. (1957). An excellent brief discussion is also found in Oppenheim (1964).

Equal Appearing Intervals

Thurstone developed a number of techniques for classifying statements along a continuum. Equal Appearing Intervals and Paired Comparisons are his most common, and both attempt to obtain meaningful ordinal categories.

The method of Equal Appearing Intervals uses a group of judges to sort a large number of items into (typically) eleven categories (middle category for neutral statements) about the attitude or other psychological state being measured.

After the sorting, the median value and the spread measured by the semi-interquartile range are calculated for each statement. Items with low variability are included, and each is given the median value of the judges for that item.

> . . . Respondents will only be asked to either agree or disagree with each statement. . . . If all goes according to plan, our respondent should only agree with a very few statements . . . the one or two items that best reflect his particular attitude. (Oppenheim, 1964:131)

Critique

Although the categories decided upon appear to be equal, they are not necessarily equal. Discriminations may vary with the value of the statements and the personal viewpoints of the judges. Consequently, the results should be treated as ordinal.

> The reliability of Thurstone scales tends to be adequate and they have the additional advantage that often a parallel form emerges from the item analysis. Reproducibility (in the technical sense) would, presumably, be good in the ideal case where a respondent endorses only a single item, but since this happens very rarely, the scales may be criticized on this account. The validity of these scales has occasionally been demonstrated with the aid of criterion groups whose attitudes were allegedly known, but since these other measures may be less reliable than the scale that is being validated or may refer to different attitude facets, doubts do remain. (Oppenheim, 1964:132)

Oppenheim also points out that any claim of unidimensionality is a priori on the basis of general agreement among judges and that this is quite different from proven results. Unidimensionality can be checked, however, by defining the internal pattern of responses when the scale is given to another group. People having backgrounds similar to those of the respondents should be employed as judges.

This method is adaptable to streamflow problems, but is tedious to develop, requiring numerous judges evaluating a large number of statements.

Paired Comparisons

The Method of Paired Comparisons (MPC) presents pairs of stimuli to respondents and has them select a preferable stimulus on the basis of the factor being scaled. This obviously can be directly applied to the problem of scenery and has been used with photographs (Peterson and Newman, 1969; Jackson, 1972).

The MPC uses the following steps (photographs may be substituted for statements in these instructions and scene for attribute):

1) Select statements that relate to the attribute being measured; 2) combine statements in all possible combination of pairs $\left\{\frac{N(N-1)}{2}\right\}$; 3) ask judges to select which statement of each pair is the more favorable; 4) calculate the proportion of judgments each statement received over every other statement; 5) total the proportions for each

statement; 6) translate the proportions into standardized scale values; 7) apply an internal consistency check by computing the absolute average discrepancy; 8) present statements to respondents and ask them to indicate favorableness or unfavorableness to each statement; 9) respondent's score is the median for his favorable responses (Miller, 1970).

Critique

Comparative ordering is generally more valid and reliable than arbitrary rating methods. The primary difficulty is inherent in point 2 above. With large numbers of statements, the technique is unwieldy and, therefore, impractical. Ten stimuli would require 45 comparisons, 20 would need 190, and 435 comparisons would have to be done for 30 items. Therefore, this method is limited to a small number of photographs or other items and would require adaptation to the streamflow situation.

Comrey Method and General Allocation Technique

Both Comrey (Comrey, 1950) and General Allocation techniques (Metfessel, 1947) require the allocation of points, usually one hundred, between two stimuli according to the preference for each stimulus. The object in using points rather than simple preference is to obtain a measure of the degree to which one stimulus is preferred over another.

When this idea is applied to two stimuli at one time, as in the Comrey Technique, the method is a direct extension of the method of paired comparisons. This is, however, considered a method for obtaining ratio scaling rather than ordinal scaling.

It was applied to a recent study (Techcom, 1974) and was summarized as follows:[13]

> The Comrey technique requires that all possible pairs of stimuli (e.g., six stimuli yields fifteen pairs) be considered . . . The transformation of such paired comparison allocation data to a ratio scale commences with the summing of the total number of points received in comparative judgments for each stimulus and the arranging of stimuli in rank order by preference. The average of the points assigned for each stimuli in comparative judgments is determined, and the ratios between adjacent stimuli in the rank-order series are calculated using the following formula:

$$R_{y(y+1)} = \frac{1}{n-1} \cdot \sum_{\substack{x=1 \\ x \neq y}}^{n} \frac{P_{xy}/P_{xy}}{P_{(y+1)x}/P_{x(y+1)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where $R_{y(y+1)}$ = ratio of stimulus y to the next stimulus in the rank-order series

n = number of stimuli in the rank-order series

P_{yx} = the average number of points from 100 given y in comparison with x

P_{xy} = the average number of points from 100 given x in comparison with y

Knowing the ratios ($R_{y(y+1)}$) between adjacent stimuli in the rank-order series and assigning an arbitrary scale value of 1.00 to the least preferred stimuli permits the computation of scale values of the more preferred stimuli (s_y) as multiples of 1.00 using the following formula (Gum et al. 1974: 38-39):

$$S_y = R_{(n-1)n} \times R_{(n-2)(n-1)} \times \ldots \times R_{y(y-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

The Metfessel General Allocation Test was chosen for a general study (Gum, 1974), possibly because of its comparative simplicity. When subjects are asked to allocate points among several alternatives at once, the need for Equation [1] is obviated. Also, only a single question may be asked rather than several.

> "INSTRUCTIONS"
>
> . . . Each question contains a list of terms related to one of these areas. Please allocate 100 points among the terms in each list so that the term which you feel has the greatest need for improvement receives the greatest number of points, the term which has the next greatest need for improvement receives the next greatest number of points, and so on. Before distributing your 100 points, it may be helpful if you first order the terms by placing a 1 to the left of the term which you feel deserves the greatest number of points, a 2 to the left of the term which you feel deserves the next greatest number of points, and so on. (Techcom, 1974: Appendix B)

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[13] The Thurstone Method of Equal Appearing Intervals can be used to obtain ratio scaling if certain assumptions are made, but the validity of these assumptions are debatable. See discussion in Gum et al. (1974:37-38)

An example in relation to aesthetics is the following:[14]

> Aesthetics can be explained as the pleasant feelings you have about your surroundings such as the air, water, and landscape. This part of the questionnaire measures your desire for improvement in the following aspects of aesthetics.

Visibility	__________
Odor	__________
Floating Objects	__________
Sum	__________(Techcom, 1974:157)

Critique

The following comments were made on the Comrey Method as to possible ways of quantifying aesthetics:

> The scale values generated by the Comrey technique undoubtedly exhibit a higher order of measurement than the interval scales obtained by traditional paired comparison methods. The implicit nature of ratio judgments in the Comrey test itself and Comrey's own validation of the technique by achieving a very high correlation between judged physical ratios and actual physical ratios confirms the attainment of ratio scales by this technique. Since it has been proven that people can make point allocations between pairs to express 'mental ratios' (Stevens, 1960) and also since this specific technique makes no questionable assumptions, is relatively concise in nature, and can generate both group and individual weight sets, the Comrey technique appears to be very appropriate in our quest for a weighted preference system. (Gum et al., 1974:38-39)

These comments also apply to the General Allocation Technique as used in the Techcom (1974) study.

Items judged to be equal are given the same numbers and the relative importance of factors is determined by the ratio of their allocated points. Advantages over most preceding methods is that

> . . .in general, it may be stated that while the psychophysical methods . . . are concerned with arriving at a dichotomy (equal and not equal) either directly or indirectly, the rise of the scale of cardinal numbers for reporting comparative judgments imposes no such restrictions. (Metfessel, 1947:230)

More information is gained than by rank-ordering alone; therefore, differences in both raters and objects can be more easily ascertained. Metfessel (1947:234) states:

> the limitations may be in: (a) the degree of arithmetical sophistication required of the subjects, and (b) in the necessity in some instances of a training program in quantitative thinking. These objections are not too serious as most people can fairly easily be taught to make consistent ratio judgments.

Another possible difficulty is that judges must restrict themselves to a specific total number of points. This requires an additional judgment for allocation as well as for relative importance.

Ratio Scaling

Ratio scaling (as used in attitude measurement) is a technique that originally came from psychophysics (Stevens, 1960; 1962) and is based on the discovery that

> . . . there appears to be a general law which describes the relationship between the magnitude of an attitude (A) and the magnitude of its related social stimulus as in the equation $A = c^n$ . . . when the attitudinal variable and the social-stimulus variable are both measured . . . from the origin of the relationship. (Hamblin, 1974:114)

In the case of simultaneous determination of an attitude by several factors, the equation shown undergoes a simple multivariate extension.

Conventional ratio scaling may be thought of as the function given above with an exponent of one (i.e., $y = cx^1$). Forms of the equation other than this special case result, generally, in unequal ratio scales which can be used to obtain results comparable to standard scales as used in standard physical measurements.[15] ". . .the parameters in the resulting equations differ in predictable ways. Hence, at least from the functional perspective, they are all equally good." (Hamblin, 1971:197)

The application of this method is quite simple, considering the high level of measurement it can

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[14] This analysis resulted in the following equation:

$$Z = X^b \cdot Y^c \cdot W^d \text{ where}$$

Z = measure of water aesthetics
X = measure of water odor
Y = measure of water clarity
b = weight for odor (.451)
c = weight for clarity (.212)
W^d = the measure and weight of floaters which was held constant. (see Gum et al., 1974:42-49)

[15] An exception to this in physics would be the measurement of loudness where a non-standard ratio scale is used.

produce. The rater is simply provided with a standard somewhere near the middle of the stimulus range which is designated by a number such as 10 or 100 which is easily multiplied or divided. The respondent is left completely free to apply any number to the stimulus being evaluated on the basis of how many times worse or better it is than the standard.[16] The same results may be expected from various standards, but different standards should not be applied at the same time (see Hamblin, 1974).

A principal problem in attaining ratio scales is the respondents becoming adapted to small amounts of stimuli, which can result in increased sensitivity at low levels. The problem appears frequently "in social–attitude phenomena, however, since expectations, or relative origins, apparently condition easily . . ." (Hamblin, 1974:83) This effect must be offset to obtain a ratio scale. Instructions for so doing can be found in Hamblin (1974).

Critique

This method has direct relevance to measurement of streamflow aesthetics although it has not yet been applied to this specific problem. The stimulus would be a scene, the response an evaluation of the scene's beauty.

If beauty and ugliness were two separate, although related, continuums, then zero would indicate an absence of both. The same scene could then be given a rating greater than zero on both variables since it could contain both beautiful and ugly elements. A neutral scene would be one having equal "amounts" of ugliness and beauty. This idea of both ugliness and beauty ratings indicating the presence of the attributes for the same scene may at first seem unreasonable. A reason for this situation might be that the reference points which a person uses when asked to rate scenes as to its ugliness is higher than that which is used when he rates the scene on beauty.

However, if ugliness-beauty is a single continuum with a neutral point, then theoretically it may be difficult to use this method in stream assessments. Previous applications of this technique indicate that the above problem may not exist. Stevens (1966) reports successful application of ratio scaling to (among other things) aesthetic value of handwriting and preference for watches. Hamblin (1974) used the technique in a non-aesthetics subject area, but one that required a hypothesis similar to the one mentioned above for explaining the results of aesthetics measurement: that of two continuums with different zero points. Ratio scaling has been used elsewhere (Stevens, 1960, 1966; Hamblin, 1971, 1974), and is very effective in achieving the highest level of measurement. It apparently can be directly applied to the determination of aesthetics in relation to streams.

Scenic Beauty Estimation

Scenic Beauty Estimation (Daniel and Boster, 1975), which is based on the theory of signal detection (Swets et al., 1961), provides an evaluation independent of judgmental criteria, both the standard and sensitivity of the rater. Although a rating scale is used, the resulting measurement is said to be at the interval level.

This method is based on the assumption that

> . . . the required judgment depends simultaneously upon the observer's perception of the specific stimulus array and upon his past experience and expectations regarding such arrays . . . and aesthetic judgment is the joint product of the perceptual effect of the environmental display and the esthetic standard of the observer . . . Furthermore, . . . without separate knowledge of the observer's criterion (standards) . . . the meaning of any esthetic judgment is ambiguous. (Daniel et al., 1973:3)

Due to a number of factors, such as variations in individual sensitivity over time and complexity of scenes, "the perceptual effect of an environmental display is represented . . . by a probability distribution . . ." representing a set of Scenic Beauty Estimates (Daniel et al., 1973:4)

To obtain a series of evaluations for the same landscape, a series of photographs of randomly chosen landscape views is used. The random choice is said to insure normally distributed judgments (Daniel and Boster, 1975). The placement, on a rating scale, of a probability distribution for a scene is a function of the standard of the observer (Daniel et al., 1973). The amount of variation in response to the beauty of the scenes is a result of the sensitivity of the rater.

[16] From his experience, Hamblin notes, "that it is desirable to define zero . . . as, for example, no dislike or feeling . . . to insure that the magnitude scale will be at the ratio level" (Hamblin, 1974:94).

Variation in sensitivity among observers is accounted for by normalizing the response scores (i.e., dividing the scores by the mean standard deviation of views over all landscapes evaluated). Differences in perceived scenic beauty between one landscape and a set of other landscapes can be seen by plotting the cumulative probability of the (normalized) ratings (1-10) for one landscape against the cumulative probability of the ratings (1-10) respectively, for each of the other landscapes (Daniel and Boster, 1975). Each bivariate graph is called a relative operating characteristic (ROC). The distance of the ROC from the positive diagonal is a measure of the perceived scenic beauty of a landscape (Daniel and Boster, 1975). There are several procedures for determining this distance. Three are provided in Daniel and Boster (1975). The values obtained by using this method are free of the judgmental standard of the rater. What is obtained is a measure of the difference in perceived aesthetics between the comparison scene and the scene assigned a Scenic Beauty Estimate by this method.

Critique

This methodology does not allow the determination of a neutral point between beauty and ugliness. One of two assumptions is necessary. One is that extreme ugliness equals the absence of beauty. This implies that the only continuum is beauty alone. The second assumption is similar to that discussed in the *Ratio Scaling* section, that beauty and ugliness are two separate dimensions. In this case the method would measure the beauty dimension, and a second application would be required to determine a value for ugliness. If beauty and ugliness are two opposites (with a neutral midpoint), this method could not be used because of its rating scale (1=very low, 10=very high). With a changed rating scale, e.g., -5 to +5 with zero designated as neutral, however, the method is applicable.

A question as to the true interval level of the measurement occurs because of the use of a rating scale. The limitations listed for rating technique appear as the weakest link in a chain of measurements determining the level of the final data. However, this may be only a technical consideration and of little effect on the data.[17]

Daniel and Boster have tested this measurement model for reliability, validity, and feasibility in a number of studies (the method was applied to several groups) with impressive results (Daniel and Boster, 1975; Arthur, 1975). Their applications have been directly parallel to the problem of assessing the effect of streamflow on aesthetics. If the scenes reflected the effect of streamflow on the scenery, this method could be used for assessing aesthetic values under varying flow regimes.

CLASSIFICATION METHODS

Aesthetic classification methods categorize scenery according to specific physical and biological characteristics or by evaluating certain components of the scene (Redding, 1973; Fabos, 1971). Most approaches will not be discussed as they are not directly applicable to the determination of aesthetic values relative to streamflow. Although the particular characteristics or elements chosen vary from method to method, the basic principles (therefore, the critiques) that apply in one method also are true of many of the other methods.

A scene can contain a great many elements and if one is to obtain a valid indication of its total aesthetic effect, many of these may need to be included. This can produce a complex, difficult-to-interpret matrix. The complexity may be reduced by using the comprehensive, but imprecise, terms employed by landscape architects, such as enclosure, variety, etc.; however, the interpretability and value of the analysis is impaired.

Descriptive inventories or classification methods may result in either numerical or non-numerical evaluations, and have been used as a basis for classifying methods (Redding, 1973). The essential difference between these two types of

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[17] Personal Communication. 1975. T. Daniel. Department of Psychology, University of Arizona, Tucson, Arizona. The output, the Scenic Beauty Values, could be considered as at the ratio level if each rater were consistent with himself under given experimental conditions in his evaluations. Daniel questions the utility of distinctions between ratio and interval measurement. Ratio scales have an origin or a zero point from which all measurements begin; and, in a sense, this point is provided by the scene chosen as standard in this method. However, it is also useful and normal for the zero point to have some theoretical meaning, typically the absence of a property.

classification methods is simply the assignment of numbers to categories. This assignment is often based on an evaluation of the original relationship of the categories to aesthetics and amounts to "merely numerical translations of landscape descriptions. Visual and physical features are first inventoried and then divided into quantitative or qualitative scales . . ." (Arthur et al., 1975:13). As such, they are based on subjective judgments which are generally those of the planner. Another related difficulty with the quantitative classification method is that in order to obtain an index for aesthetics, the components need to be weighted— which itself is a matter of judgment.

Another problem pointed out by Arthur et al. (1975) is that the whole is more than the sum of its parts in reference to scenery. It is how the components of a scene are put together as well as the nature, number, and relative frequency of the elements in a scene that comprise its beauty (Litton, 1972; U.S. Forest Service, 1973).

Litton Method

Litton (1968; 1971) developed a non-quantiative classification method for landscape. He conceptualizes the aesthetics of water in a land-scape as deriving from the interrelationships of the components of water, vegetation, landform, and human effect on the landscape. The objective is to analyze the effects of combinations of the components on beauty.

Litton breaks down the landscape into three units: the *landscape*, which refers to a broad comprehensive perception of an area. Generalized impressions rather than details are important. The *setting* is concerned with the interaction of water and landscape and the effect of their combinations. Details of water and its shoreline are included in the *waterscape*. Particulars of each of these units are evaluated as enhancing, degrading, or being compatible with the landscape. Figure 1 illustrates the basic elements of Litton's system.

The basic criteria used in this system are unity, variety, and vividness. "Unity is that quality of wholeness in which all parts cohere . . . as a single harmonious unit. Variety can be . . . how many different objects or relationships are present . . . Vividness is that quality in a landscape which gives distinction and makes it visually striking" (Litton, 1971).

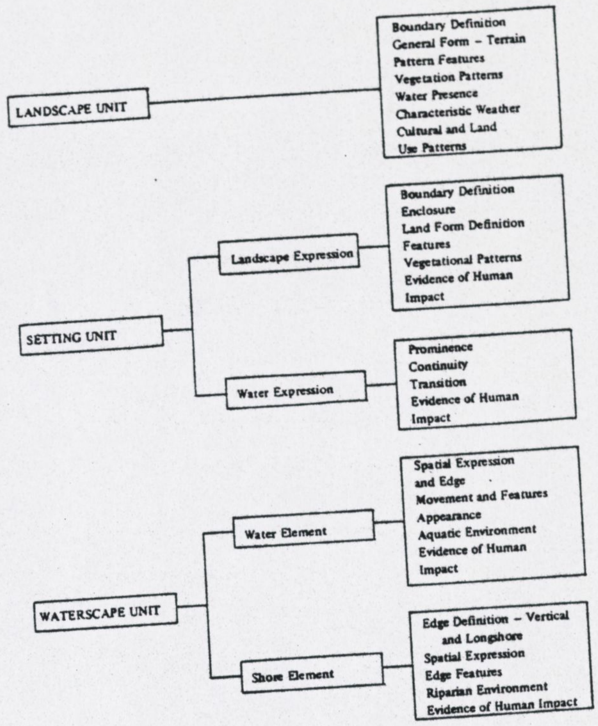

Figure 1. Classification framework for Litton's method (from Litton, 1971).

To provide a rater with a basis for judgment, descriptions of high and low quality situations are provided. An example is the following:

High Quality	Low Quality
Overlooks and view-points are located to permit view of boundary and extent in a more complete manner than is visible in a moving vehicle.	Few overlooks and view-points, Those available are limited to local features or roadside incidents. (Litton, 1971)

Elements within a scene are described in five categories: linear, area, mass, enclosing, and point. Each component of each unit is also analyzed as to whether it: 1) Tends to unify the scene; 2) focuses attention; 3) helps enclose the scene in a positive manner; 4) organizes by forming patterns; and 5) enhances by providing relationships between other elements of the scene.

Critique

Redding (1973), in a very favorable evaluation of this method, comments:

The report reviewed does an exceptional job of covering a full range of aesthetic attributes in the visual classification system inventory. The basic framework is structured to show the appropriateness of the factors to the scale being considered (from unit to elements).

At the outset Litton states 'this study will not carry an emphasis of behaviorial response to the landscape and to water for the very simple reason that there is so little information in this area. We will not make conjectures about what the landscape and associated water mean to the beholder.' Not only did Litton make continual reference to user preference studies, but he went on to develop three general variables which classify aesthetic experience. These variables represent the basic responses of the observer-user to a particular landscape; 'the observer's state of mind, e.g., such as his current perceptual set, past experiences, future expectations, and environmental life style; the context of observation, e.g. boating, photographing, swimming; and the environmental stimulus itself.'[18] (Redding, 1973:73)

Although the categorization used is based on explorations of user perceptions, the technical terms of landscape architecture can be expected to cause difficulty in interpretation. Also, it is doubtful that most professionals would agree on the interpretation of scenes on the basis of their attributes. Litton tried to control the lack of standardization of results by specifying high and low characteristics for each factor. This may reduce the problem, but it does not eliminate it.

Litton's objective was to provide "the decision-maker with information which shows precisely how . . . man-made facilities enhance, are compatible with, or degrade the visual landscape . . . " (Redding, 1973:74). Adaptation of this method for the determination of the effects of streamflow alterations on aesthetics would be to focus attention on potential or actual altered conditions caused by reduced or augmented flows.

Leopold Systems

Luna Leopold has produced two quantitative classification methods which may be the most common methods for evaluating aesthetic elements (Redding, 1973). These methods, although largely subjective, are relatively straightforward and " . . . allow planners an elaborate checklist for identifying critical areas of concern . . . " (Redding, 1973:51)

One system (Leopold, 1969a; 1969b) was developed to provide a means of assessing the total environmental impact of a project, or other activity, on an area. One aspect of this is aesthetics. It is a subdivision of cultural factors and includes such items as scenic views, wilderness qualities, open spaces, design, uniqueness, etc. In Leopold's system, for each of a series of potential characteristics such as those listed, the effect is indicated by two sets of numbers. One set reflects the magnitude of an impact and can range from -9 for an extremely adverse effect to +9 for an extremely beneficial effect. The other ranges simply from one to nine and is intended to show the importance of each impact, with a higher number meaning greater importance. Magnitude here refers to degree, extensiveness, or scale while importance means the significance of the impact. "The intent is to clearly separate the evaluator's value judgment from the factual material" (Redding, 1973:51). Nevertheless, this method is a codification of subjective assessments.

The other method developed by Leopold (1969a; 1969b) was designed for aesthetics and, although also subjective, may be more applicable to streamflow aesthetic assessment.

Leopold classified factors relevant to aesthetics as being of three types. The first type is physical features (stream channel and watershed parameters) of an area. The second type includes features concerned with the region's biology (flora, fauna and water quality). The third type consists of human interest and use factors (accessibility, views, degree of development, etc.), because of "certain phenomena which are associated with the sites or where unusual events have occurred" (Leopold, 1969b:38).

Evaluation numbers from one through five are assigned to each factor within each type. The evaluation numbers for each of the 46 factors ". . .serve a descriptive function only; evaluation number one, for example, is not to be interpreted as 'superior' to evaluation number five, or vice versa . . . " (Leopold, 1969b:40) The evaluation generally becomes increasingly subjective as one moves from the top, the physical factors, through the middle, biologic and water quality factors, to the bottom, human use and interest factors. All factors of any type are thought to be related to aesthetics.

The remainder of the analysis is based on the premise that "landscape that is unique either in a

[18]These may be considered as norms, referent, and stimulus. This formulation is similar to Daniel and Boster (1975) which resulted in an entirely different type of analysis.

negative or positive way is of more significance to society than one that is common . . . " (Leopold, 1969b:40). For each factor, a "uniqueness ratio" is computed which is equal to the reciprocal of the number of sites sharing the category value. For example, if four sites are in the same category, each of the four would have a uniqueness ratio of one divided by .25. One obvious deficiency of this index is that it is dependent on the number of sites assigned; it would only be generally interpretable if standardized norms were established and applied to cross-sectional random samples of standard size types of sites. A total uniqueness ratio is obtained for each site by adding the values for each factor for a site. A graph can be constructed to show the total score for each of the three types of factors. The uniqueness ratios for each site are plotted on the same graph. From this graph, those sites with the most unique features can be readily recognized.

However, uniqueness may be good or bad. In order to determine which sites are positive and negative, another series of steps is required. Leopold does this by selecting factors that are thought to be related to valley character and river character, respectively. He starts with height of nearby hills and combines this with width of valley to obtain a "landscape scale." After this is computed and the sites ranked, this is crossed with "scenic outlook" which results in a "landscape interest" scale. Then this landscape interest scale is combined with the degree of urbanization of the site to form the final index of valley character. A similar analysis using river width, depth, and the presence or absence of rapids, riffles, and falls is conducted to obtain a "scale of river character." Two measures, river character and valley character, then become the axis of an another graph of which all sites are plotted. The sites with the most desirable characteristics then can be seen directly from the graph. For details of these procedures, see Leopold (1969a:7-12; 1969b:41-44).

Melhorn and Keller (1973) extend the Leopold method of assessing aesthetics in a system called LAND, an acronym for Landscape Aesthetics Numerically Determined. They state that " . . . fluvially-derived features are the most significant single physiographic element" (Melhorn and Keller, 1973:2) and choose their parameters or facts affecting aesthetics accordingly. The concept of uniqueness is extended. Uniqueness Index is defined as the percentage of the total possible uniqueness. An Aesthetic River Index is also designed. Factors amenable to assessment by field, air photo and mapping methods are distinguished and listed separately. Study sites are always five hundred times the channel width and each of the sites are divided into ten equally spaced stations prior to assessment. The average of the assessment value of the stations provides a value for the site.

Critique

Leopold states that ". . .the selection of factors does involve personal judgment as to which ones appropriately describe the landscape characteristics . . ." (Leopold, 1969b:42). A basic weakness of this method is that the opinions of one judge as to which factors are correct may not agree with those of another judge. User preference studies might help validate a selection.

A related problem occurs in considering adaptation of this method to assessment of aesthetics caused by streamflow alterations. A list of factors must be specific in order to be meaningful and reduce unreliability in interpretation. As a result, a list of factors constructed for evaluating one type of site may not be right in another situation. The factors listed in Leopold's studies relate to wild river canyons and may not apply to more developed streams.

Despite objections, Leopold's aesthetic classification scheme has utility in factor inventories associated with rivers. This is particularly true for those factors that have specific standards for assigning numbers. It may be desirable to construct a table even when other methods, such as Ratio Scaling or Scenic Beauty Estimation (see appropriate sections), are used in order to help specify the characteristics associated with high and low aesthetic perceptions.

Hamill's (1975) analysis of Leopold's quantitative comparisons of landscape aesthetics noted that the addition of uniqueness ratios produces difficulties of comprehension and interpretation.

The use of this method as presented by Leopold is questionable beyond the use of uniqueness ratios. Specifically, "valley and river character" types are entirely personal judgments on the effects of certain conditions. Many assumptions are made, such as one foot increase in valley width is the same in effect as one foot decrease in height of surrounding mountains, or that the components of each "scale" are of equal importance. Also, the choices of factors themselves constitute major assumptions.

The application of Leopold's method to streamflows can be done by compiling factors connected with streamflows that affect aesthetics. Specific descriptions of conditions designating each possible category from one through five for each factor must be stated as precisely as possible. Then each factor would need to be evaluated for each of a series of sites and values recorded. After this process is performed and repeated, a comprehensive list of factors for streamflow aesthetics assessment and instructions for using the list may result.

OTHER QUANTITATIVE METHODS

Social Indicator Technique

The social indicator technique relates general goals, such as aesthetics, to specific measures of phenomena that are considered linked to the more general or higher level goal. A social indicator in this sense is any concrete measurement that can be related to a social effect.

There are two notable applications of this concept. Both of these are comprehensive analyses which include aesthetics assessment as a general goal. One application was designed to assess the total impact of major water resource changes and was presented in the Techcom (1974) report. The second was in a study by Battelle-Columbus Laboratories (1972) to determine a method for projecting the environmental effects of water resource changes.

BATTELLE SYSTEM

The Battelle project divided environmental impacts into four categories, of which aesthetics was one. These were then broken into "environmental components," which are composed of "environmental parameters." Finally, the environmental parameters are indicated by measurable components of the parameters. The scheme consists of proceeding from the most general goal down to measurements containing the most specific information (Figure 2).

The basic criteria for parameters in this scheme are that they should be highly comprehensive indicators of environmental quality, easily measurable in the field, measurable on a project scale, and as limited in number as possible while retaining comprehensive character (Battelle, 1972).

Each group of measurements must be synthesized to obtain an indication of each parameter. This was achieved by placing each measurement in an equation and weighting it to obtain an index for a parameter. The parameters under each category were combined to obtain an assessment of the state of each environmental category. To accomplish this, all parameters were transformed into "indices of environmental quality" which vary between zero for extremely bad quality to one for extremely good quality. The ability to obtain meaningful ratings of this type varied greatly from parameter to parameter.

After environmental quality indices were obtained, the relative importance of each parameter to total environmental quality was determined. This was done by having professionals allocate 1000 "parameter importance units" among the parameters. Weights for categories were obtained by adding the importance units assigned to all parameters within each unit.

In order to obtain some measure for comparison, the environmental quality index (EQI) and the parameter importance units (PIU) were multiplied to give common environmental impact units (EIU) for each parameter. The above task is repeated for each site to which the scheme is applied. Redding writes that this method, " . . . provided a means for measuring or estimating selected environmental impacts . . . in commensurate units, EIU. Results . . . include a total EIU score with or without the proposed project; the difference between the two scores is one measure of environmental impact" (Redding, 1973:49). It might be added that the difference in the EIU score within the aesthetics category is a measure of the effect on aesthetics.

An interesting and unique aspect of the method presented in the Battelle report is the use of "red flags." Red flags are assigned to a parameter whose EQI, when compared without and with the project, decreased greatly, indicating a potentially adverse effect. Red flags were also used to designate parameters with insufficient measurements. Either use means that additional information is needed for that parameter, and additional effort should be focused to this end.

The chief criticisms are based on the continual and heavy use of subjective judgments. A specific criticism of the Battelle social indicator method in its present form is that the scheme needs to be

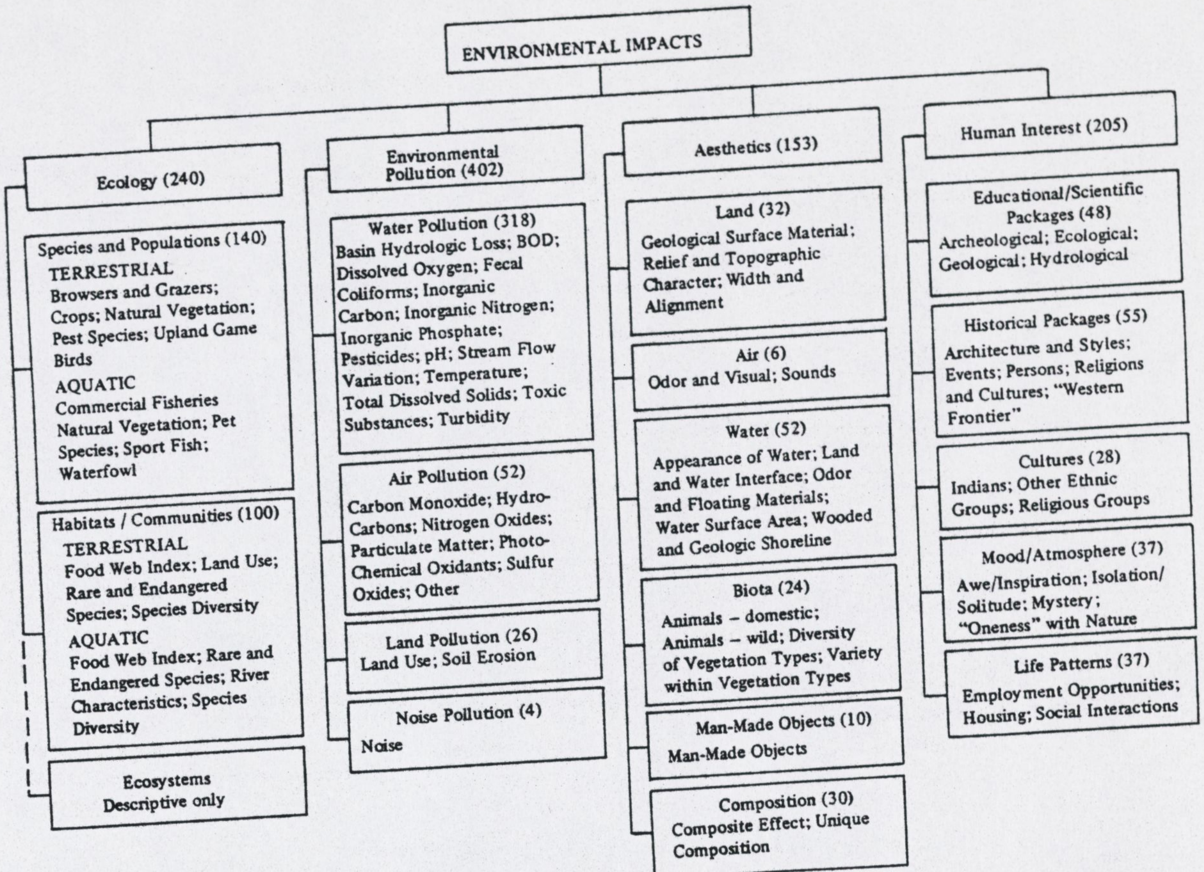

Figure 2. The environmental evaluation system (from Battelle, 1972).

redone for each application. A useful development would be a comprehensive list of parameters and possible measurements. In some cases, the values of the parameters may be close to zero, but such a consistent classification would facilitate comparison of parameters from site to site. Another useful change would be to have the EQI's vary from minus one to plus one, with zero as neutral, rather than from zero to one. In this case, a negative value would indicate an adverse condition and positive, a beneficial situation. There would also be an advantage when these EQI's are added or used to form a common environmental impact unit. In the former case, a negative value would indicate an overall poor environmental condition; and in the second case, a negative value would retain the meaning of an adverse condition existing for that parameter.

TECHCOM SYSTEM

The Techcom "methodology is visualized as having the potential for narrowing the great gap which exists between the definition of national goals . . . and the implementation of action programs to achieve such goals . . . " (Techcom, 1974:xi). To accomplish this, the methodology consists of disaggregation of goals into more specific factors until measurable components are reached. Since the goals from which the process started are socially defined, the measurable components are called social indicators.

The general goal specifically related to aesthetics in this study was "aesthetic opportunity."[19] The disaggregation of this is shown in Figure 3. The particular type of measurements used are listed in Table 2. Each of those items whose last digit is in parenthesis is a social indicator. These social indicators are defined in Appendix B of the Techcom (1974) report.

The similarity of the Techcom system and the

[19]"Recreational opportunity" was also a goal. The modeling method described in Section 6 is a result of this analysis.

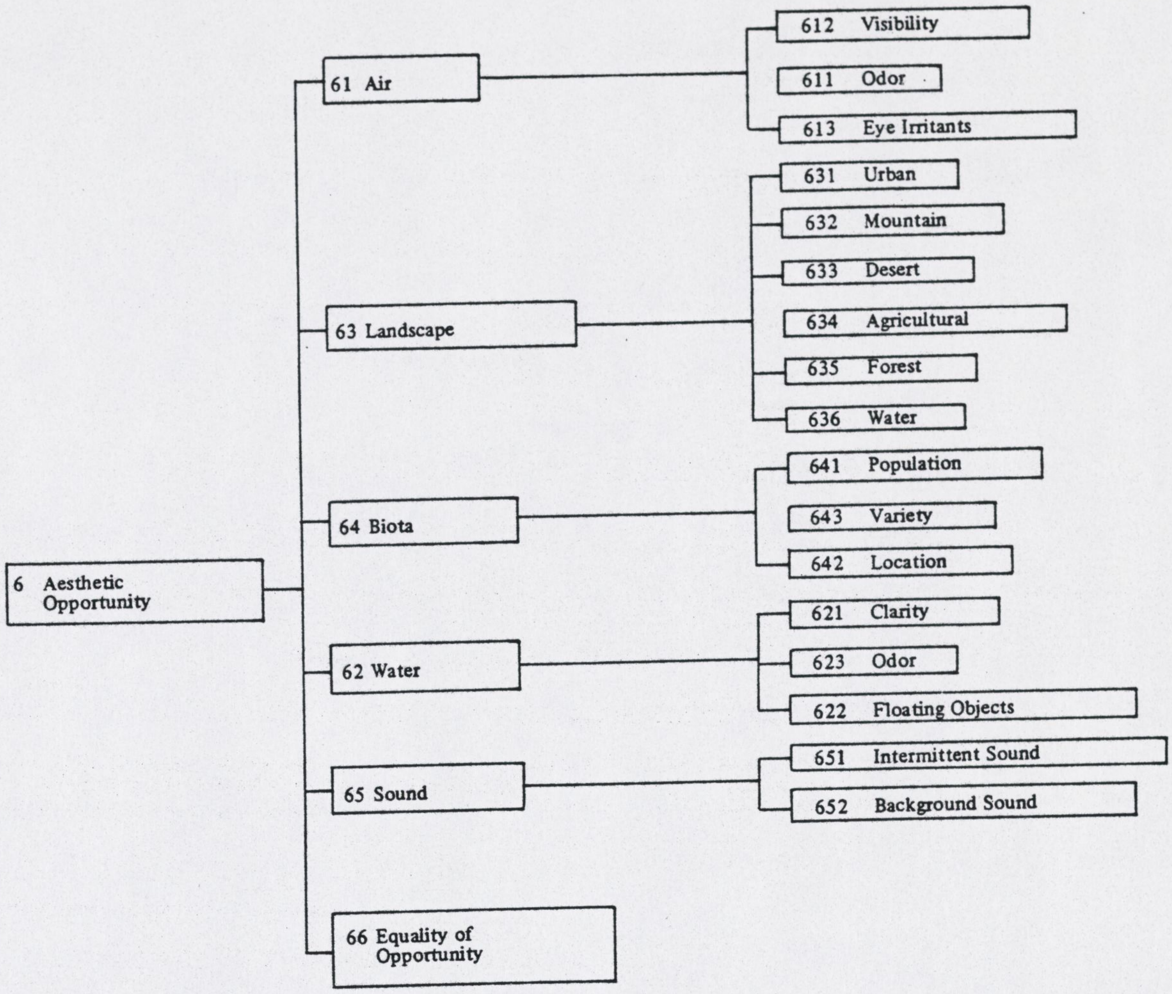

Figure 3. Hierarchical goal structure of aesthetic opportunity (from Techcom, 1974).

Battelle system is immediately apparent by comparing Figures 2 and 3. Both of these start from a general goal and show three levels of increasing specificity. The fourth level generally could be that of social indicators. The primary difference between the systems is that the Techcom method is more encompassing, with a broader range of goals and a greater degree of development.

As with the Battelle study, some methods of breaking each goal at one level into factors at a lower level need to be used. The Techcom report describes the use of different methods at different levels. Content analysis of public perceptions from interviews using open-ended questions was used to obtain the first and second level subgoals below that of the prime goals (Gum, 1974; Techcom, 1974). Expert opinion, "... those people who have both a knowledge of the measurement of social indicators and a perception of the achievement of subgoals ..." (Techcom, 1974:92),[20] was used to obtain the social indicators. Indices were formed from these indicators also using experts and technicians as judges of impacts of changes using a modified Delphi approach.[21] The indices were normalized so that they range from zero to one. These indices may be the result of a weighted sum of indicators or a product of indicators (Techcom, 1974).

[20]These were weighted with reference to higher goals by use of the General Allocation Technique discussed in the section on Scaling Methods.

[21]See Section 6 for discussion of the Delphi Technique.

Table 2. Aesthetic opportunity – measures used for disaggregation (from Techcom, 1974).

6.	Aesthetic Opportunity
61.	Air Aesthetics
611.	Odor (Elimination of)
611(1).	Concentration of SO_2
611(2).	Concentration of Hydrocarbons from Sewage Chemicals (ppm)
612.	Visibility
612(1).	Miles of Visibility
613.	Irritants
613(1).	Concentration of SO_2 (ppm)
613(2).	Concentration of Nitrogen Oxides (ppm)
613(3).	Concentration of Ozone (O_3) and PAN (ppm)
613(4).	Particulates (ppm)
62.	Water Aesthetics
621.	Clarity
621(1).	Suspended Silt Load (ppm)
621(2).	Biochemical Oxygen Demand (ppm)
622.	Floaters
622(1).	Percent of Total Sewage Effluent which is Untreated
623.	Odors (Elimination of)
623(1).	Biochemical Oxygen Demand
623(2).	Phenols (ppm)
636(2).	Percent of Area Covered by Water
636(3).	Average Flow (Millions of acre feet per year)
636(4).	Miles Above-Ground Transmission Lines per Section
636(5).	Visitor Day Use Per Acre
64.	Biota Aesthetics
641.	Population
641(1).	Biomass (tons per acre)
641(2).	Population (number of animals per acre)
642.	Location
642(1).	Pe rcentage of Area Where Species are Located
643.	Variety
643(1).	Number of Species (per cent of species in natural ecosystem of the area)
63.	Landscape Aesthetics
631.	Urban Dominated
631(1).	Acres of parks per Capita
631(2).	Percent of Area Covered by Below-Ground Transmission lines
631(3).	Percent Industrial Area
631(4).	Percent High Density Residential Area
631(6).	Percent Freeway Area

Table 2. Continued

632.	Mountain Dominated	636(1).	Percent of Area of Bosque Developed (industrial or residential)
632(1).	Miles of Above-Ground Transmission Lines per Section	65.	Sound Aesthetics
632(2).	Visitor Day Use per Acre	651.	Intermittent Sound
633.	Desert Dominated	651(1).	Maximum dB Level
633(1).	Miles Above-Ground Transmission Lines per Section	651(2).	Average dB Level
633(2).	Vistor-Day Use per Acre	652.	Background Sound
634	Agriculture Dominated	652(1).	Average Natural dB Level
634(1).	Percentage Time Land Fallow	66.	Equality of Aesthetics Opportunity
634(2).	Miles Above-Ground Transmission Lines per Section	66.(1).	Gini Coefficient of Income Distribution
635(3).	Visitor Day Use per Acre	66(2).	Distribution of Neighborhood Parks per Capita by Income (gini coefficient)
636.	Water Dominated		

Critique

As indicated in the previous discussion, the social indicator technique is a multiple extension of the classification method with the relationships between factors and a category specified. The basic assumptions are "that adequate representation of a goal" can "be made by discovering a finite and relatively small number of subgoals or word groups defining the goal's domain" (Techcom, 1974:5) and that this assumption would be true repetitively until measurable subgoals are attained. The result of this process is a hierarchical structure with all higher values being calculable from a composite of lower values which ultimately derive from measures.

One advantage of using the social indicator technique is that the relationships between factors are specified. One must construct a social indicator model to analyze the situation in order to determine important components and relationships. Systematic evaluation of the entire process is a requirement of this method. However, this process will be a further extension of personal judgment (which is the chief criticism of the classification methodology) of the planner unless certain procedures are undertaken.

One way of reducing the effects of judgment is by use of the Delphi technique discussed in Section 6. This is a codification of expert judgment.

Although the Delphi method may be used as a starting point, all results should ideally be verified by use of the public, which will be using the resource. This could either be done by experimentation and observation to establish the relationships or indirectly by comparing the value of the lowest subgoal (Techcom terminology) or parameter (Battelle terminology) with the perceptions of the relevant public. Adjustments in the social indicators could then be made to increase the match between the publicly determined values and the predicted values from the social indicators.

Accomplishment of this would require considerable research, but the results would be worthwhile in terms of a valid model. As mentioned above, everything in this type of analysis depends, for their values, on the accuracy and weighting of the social indicators. Battelle project personnel implicitly acknowledge this as they state that representatives from a cross section of society should assign functions and weights, although they used expert judgment because of limitations of time and money (Battelle, 1972; Redding, 1973).

The Techcom research used content analysis of open-ended questions to specify meaningful components of goals and a public scaling method, the General Allocation Technique, to weight goals. These and similar techniques should be utilized so that the results will be as free of bias as possible.

It is suggested that after a social indicator model is established, the output values for each second level goal or category (in this case, aesthetics) from the model be compared with overall public perceptions as measured by techniques such as Scenic Beauty Estimation or Ratio Scaling. This process is analogous to the second procedure suggested above for verifying relationships at the lowest level of subgoals or parameters. This process is again recommended for the same reason—it would greatly help insure validity, in this case, of the total analysis.

In the Techcom report, the advantages of this type of methodology are seen:

> . . . as promising to (1) provide systematic evaluations taking into account items not included in conventional benefit-cost analysis as well as those that are; (2) permit evaluations of water resource alternatives in a comprehensive context of general welfare; (3) provide a basis for integrating or comparing water resources alternatives with other public development plans, e.g., land use; and (4) provide a basis for examining consistency between water resources development actions and stated public goals. This also has the capability of systematically organizing comprehensive preference information and presenting it in a meaningful and orderly fashion for planning and decision making. (Techcom, 1974:25)

However, this method, because of its complexity, systematization, and comprehensiveness, requires a great deal of expertise and is expensive to implement.

An analysis based on the principles of the social indicator approach and similar to the analyses described above could be applied to the assessment of streamflow aesthetic considerations. However, the parameters and potential measurements have to be selected for this particular type of situation.

The focus of the resulting social indicator analysis would be narrower than in the presented examples. On the other hand, greater resolution may be desired to assess differential effects of finer significant differences than in the two studies discussed. This may necessitate a greater number and more refined measurements, i.e., more and better social indicators.

Landscape Preference Model

Shafer and Mietz (1970) showed that the use of physical measurements of portions of a scene can be, used to predict the evaluation of landscape photographs. In order to do this, he divided scenes shown by the photograph into eight zones and took measurements of the perimeter and area of each zone. From this, a regression equation using measurements from six of the areas was determined. One hundred landscape photos were used to obtain the following equation:

$$Y = 184.8 - .5436\, X_1 - .09298\, X_2 + .002069\, (X_1 \cdot X_3) + .0005538\, (X_1 \cdot X_4) - .002596\, (X_3 \cdot X_5) + .001634\, (X_2 \cdot X_6) - .008441\, (X_1 \cdot X_6) - .0004131\, (X_4 \cdot X_5) + .0006666 X_1^2 + .0001326\, X_5^2 \qquad (3)$$

where

X_1 = perimeter of the immediate tree-and-shrub zone, X_2 = perimeter of intermediate other-features zone, X_3 = perimeter of distant tree-and-shrub zone, X_4 = area of intermediate tree-and-shrub zone, X_5 = area of water zone, X_6 = area of distant other-features zone.

The r^2 or multiple correlation achieved using this equation was about .6 when it was applied to the judgments of 50 day-users in a recreation area in the state of Utah.

Critique

One weakness in the methodology employed is that the assessment of aesthetics was based on comparisons among groups of photographs rather than on the merits of each scene itself. This means that the aesthetic values obtained were not independent of the particular scenes chosen for evaluation. Some scenes would be rated low in aesthetics by comparison, but when judged on an absolute scale, they might be quite high. This is compounded by the fact that all photographs evaluated had some prominent or spectacular feature in them. This also leads to questions about the applicability of the results of the analysis to ordinary scenes. Another problem with the photographs themselves is that details of features, such as the extent of water in the landscape, were sometimes unclear.

The basic method of applying regression analysis to aesthetics evaluation with measures of scene components as independent variables could be applied to the determination of streamflow aesthetics. However, one would have to essentially start from the basics. Photographs of many different conditions that may be associated with different stream types and flows would need to be taken. This would then have to be evaluated by members of an appropriate group using one of the scaling methods previously presented for aesthetics. The result of this evaluation could then be run against the measures of components and interactions of these components. From this procedure, an equation of maximum predictive ability using this type of independent variable could be determined.

Although an equation of this type itself could be used for aesthetic prediction purposes, the primary benefit may not be this, but rather understanding. Shafer and Meitz (1970) state that by recognizing that particular features in the photos of a landscape affect its aesthetic appeal, resource managers and planners can have a factual basis for decisions in addition to an intuitive one.

SUMMARY

Attempts to evaluate environmental aesthetic quality to date have generally been inadequate. There have been primarily two general types of aesthetics measurements: 1) Scaling, which emphasizes viewer evaluation, and; 2) classification, which evaluates qualities inherent in the environment. A preferred methodology would incorporate and relate both approaches.

Specific applications to stream flow are meager. Leopold's (1969b) classification system was developed specifically for stream systems. However, it has been criticized, as have others of its type, as being too judgmental and requiring the on-site presence of experts of one kind or another.

No scaling methodologies have been applied specifically to changes in aesthetic perception as related to changes in streamflow. Some assessments have been made of particular rivers (Michaelson, 1974), but the methods employed have not been developed and do not, in their present form, meet standards desirable for general applicability.

To summarize this section, which has considered the specific techniques for evaluating streamscape aesthetics, an initial categorization (from the literature) of techniques in relation to scaling, classification and other quantitative methods has been prepared (Tables 3 and 4).

Table 3. Aesthetics matrix – scaling techniques[a].

				Time Frame		
Method	Applicability	Meets Concern	Suitability	Development	Application	Interpretation
Rating Technique	1, 2	3	1, 2	1	1	1
Summated Score	1, 2	3	2	2	1	1
Guttman	1, 2	3	3	2, 3	1	1
Latent Structure Analysis	1, 2	3	3	2	1	2
Semantic Differential	1, 2	2, 3	1, 2	2	1	2

Table 3. Continued

Method	Applicability	Meets Concern	Suitability	Time Frame: Development	Time Frame: Application	Time Frame: Interpretation
Equal Appearing Intervals	1, 2	3	3	2, 3	1	1
Paired Comparisons	1, 2	2, 3	1, 2	2	1	2
Comrey General Allocation	1, 2	2, 3	2	1, 2	1	2
Ratio Scaling	1, 2	2, 3	2	1, 2	1	1
Scenic Beauty Estimation	1, 2	2, 3	1, 2	2	1, 2	2

Method	Type of Personnel for: Development	Type of Personnel for: Application	Type of Personnel for: Interpretation	Cost for: Development	Cost for: Application	Quantification	Comments
Rating Technique	1, 2	1	1, 2	1	1	1, 2	Single Question
Summated Score	2, 3	1	1, 2	2	1, 2	2	Widely applied
Guttman	3	1, 2	2	2	1	2	Consistent measurement achieved has valuable property for predictive purposes
Latent Structure Analysis	3	1, 2	3	2	2	1	Has had little application
Semantic Differential	2	1	2	2	2	1; 2	Useful for analyzing for relevant factors and components
Equal Appearing Intervals	3	1	2	2	1, 2	2	Panel of judges needed
Paired Comparison	2, 3	1	2, 3	1, 2	2	2	Impractical for large numbers of stimuli
Comrey General Allocation	2	1	2, 3	1	1, 2	2, 3	Useful for weighting of subgoals components to goal or main objective

Table 3. Continued

Method	Type of Personnel for			Cost for			
	Develop-ment	Appli-cation	Inter-pretation	Develop-ment	Applica-tion	Quantifica-tion	Comments
Ratio Scaling	2, 3	1	1, 2	1, 2	1	3′	Adaptability may depend on nature of phenomenon-see text.
Scenic Beauty Estimation	3	1, 2	2, 3	1, 2	2	2, 3	Tested and validated for similar purposes

[a]For meaning of code numbers see key to aesthetics matrix.

Table 4. Aesthetics matrix – classification and other quantitative methods[a].

Method	Applica-bility	Meets Concern	Suita-bility	Time Frame		
				Develop-ment	Applica-tion	Interpre-tation
Litton	1, 2	1, 2	2	1, 2	2	1
Leopold	1, 2	1, 2	1, 2	1, 2	2	1
Social Indicators	1, 2	1, 2, 3	2, 3	2, 3	2, 3	2
Landscape Preference Model	2	1, 2, 3	2	2, 3	2, 3	2

Method	Type of Personnel for			Cost for			
	Develop-ment	Applica-tion	Interpre-tation	Develop-ment	Applica-tion	Quanti-fication	Comments
Litton	3	2	3	2	2	1	Uses artistic characteristics; requires landscape architecture expertise
Leopold	3	2	2	2	2	1, 2	Includes physical, biological, and social factors
Social Indicators	3	3	2, 3	3	2, 3	2, 3	Quantitative relationships determined
Landscape Preference Model	3	2	2, 3	2	2	2, 3	Weights parameters by regression analysis to aesthetic evaluation

[a]For meaning of code numbers see key to aesthetics matrix

Key to aesthetics matrix (Tables 3 & 4).

Applicability to Level of Planning
1. Regional river basin planning – Reconnaissance studies
2. Project specific analyses – Limited or extensive onsite field studies

Types of Concerns Analyzed
1. Identification of stream flow parameters
2. Identification of perceived stream flow elements or possible recreation activities available
3. Identification of aesthetics evaluation or recreation behavior

Suitability in Relationship to Stream Flow Evaluations
1. In present form or with slight modification
2. Adaptable with further study
3. Approach usable, but must be redeveloped for this problem

Time Frame Requirements
1. 3-6 months
2. 3-12 months
3. 1 year or more

Types of Personnel Needed
1. Can usually be done by agency staff
2. Expert advice needed
3. Extensive use of experts required

Cost
1. Minor (Approximately ⩽ $10,000)
2. Medium (Approximately between $10,000-$100,000)
3. Major (Approximately ⩾ $100,000)

Quantification
1. Nominal (categorical)
2. Ordinal (hierarchical)
3. Interval or ratio

RECOMMENDED DEVELOPMENT, RESEARCH STAGES AND PRIORITIES

In the workshop reviewing the second draft of the present document, a model was developed by the Recreation and Aesthetics Workgroup showing the relationship of streamflow alterations to recreational activities and aesthetic experiences. This is shown in Figure 4. This flow chart identifies consequential changes in the physical, social and aesthetic elements as changes in streamflows occur.

Figure 5, also developed by the workgroup, identifies a sequence of four researchable problem areas: 1) Determine relevant parameters; 2) develop evaluation methods; 3) determine the relationship between stream parameters and recreation and aesthetic resources; and 4) determine social-cultural values and other external factors affecting recreation and resource uses.

These four research areas are keyed to a series of suggested research needs (see below). A preliminary listing of elements related to each area is presented in Table 5.

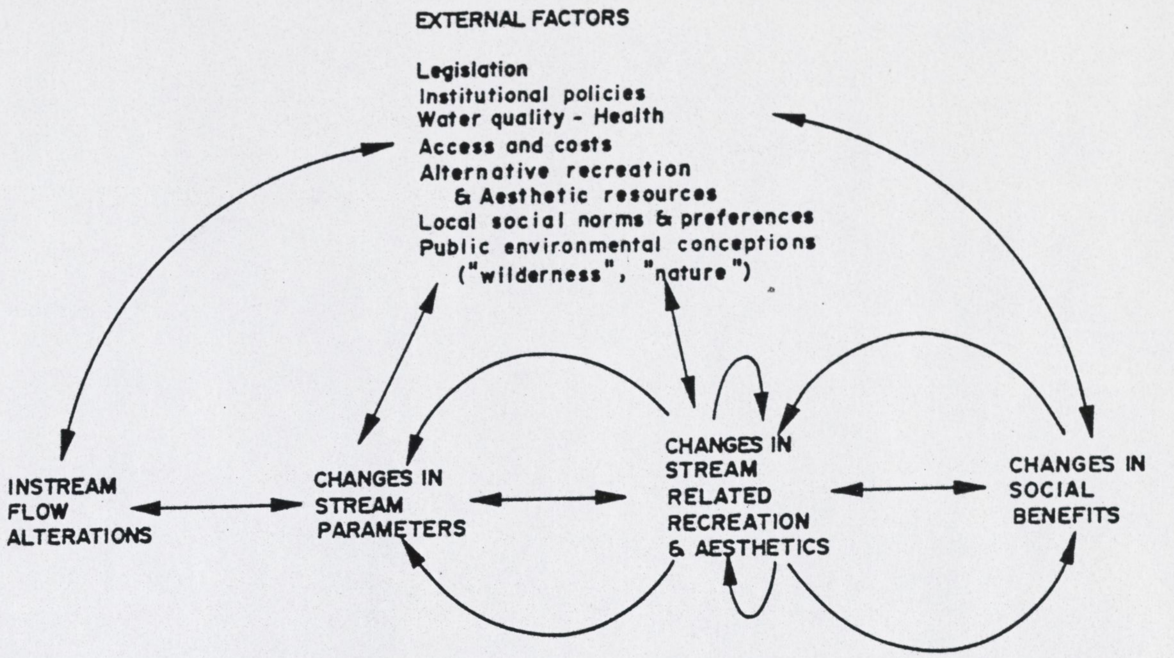

Figure 4. Model of relationships between instream flow alterations and recreation/aesthetic resources.

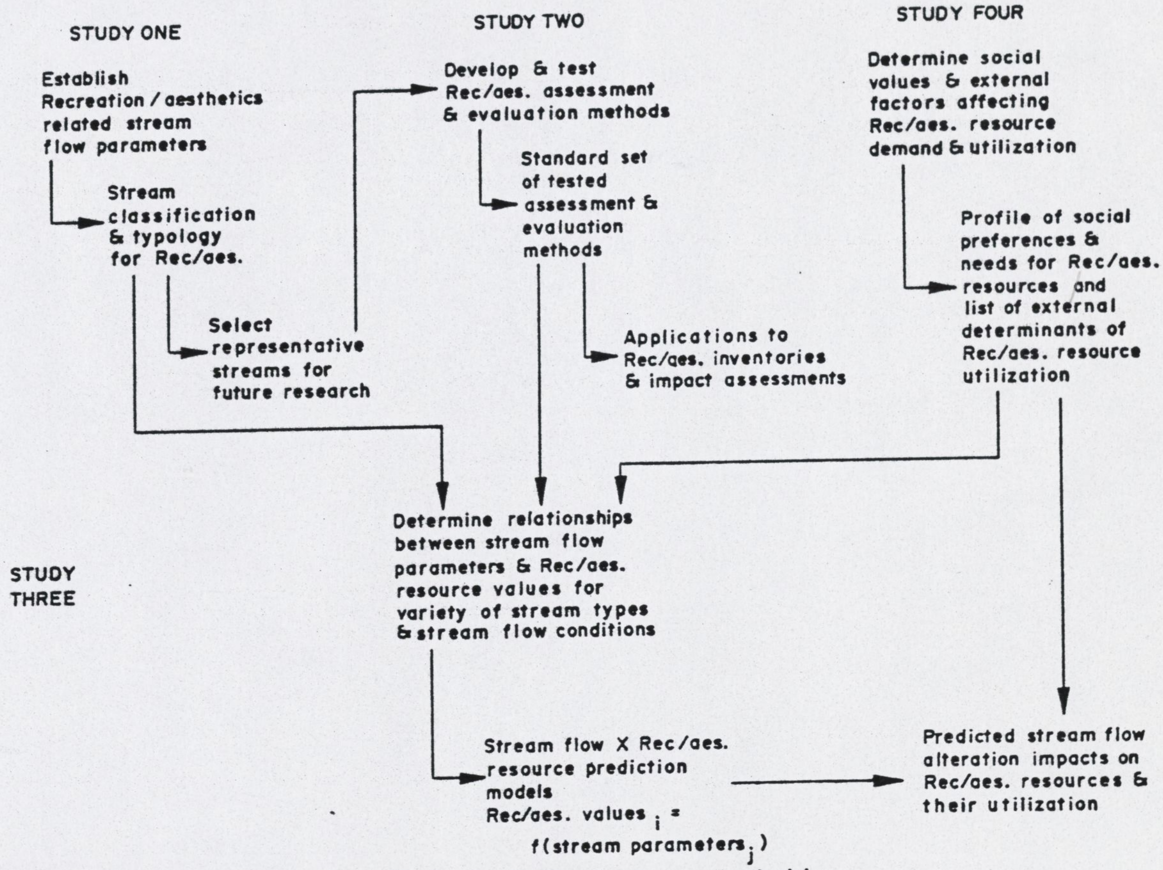

Figure 5. Schematic representation of proposed research needs and priorities.

Table 5. Basic elements relative to the proposed sequence of research needs (see Figure 5).

1) Stream parameter specifications

Gross classification: General stream types
Descriptive inventories: Litton-type, visual landscape component analyses
Perceived properties: Perceptually relevant features
Physical/biological parameters: Air, water, soil, vegetation, wildlife

2) Stream-related recreation/aesthetic resources

Delineate recreation/aesthetic types
Determine relevant dimensions of recreation/aesthetic activities
Determine interrelationships

Assessment and evaluation
Environmental representation observer-population samples method
- direct user observations
- indirect user observations
- verbal surveys/reports
- psychometric methods
- economic methods

3) Relation of stream parameters to recreation/aesthetic resources

Assess stream parameter changes related to flow
Assess recreation/aesthetic activities for variety of stream flow conditions
Relate A & B via statistical regression/modeling procedures

4) Social values (and other external factors)
Assessment

- Social indicators
- Economic analyses
- Political analyses
- Surveys of dominant social values
- Legislative mandates
- Institutional policies & Commitments
- Physical factors

General Stages of Development

The following are suggested stages of development that are required to bring the aesthetics and recreation measurement techniques to the stage of application to the effects of changes in streamflow levels. These also identify, in some order of priority roughly parallel to the stages, a series of research problems or problem areas associated with streamflow variations.

1. Identify, classify, and refine aesthetic and recreation parameters that are affected by variations of streamflow levels. The parameters must be connected to effects of decreased or augmented streamflow. The classification methods could involve adaptations of the Leopold method, Thompson and Fletcher, Litton, and others.

2. Test and examine the identified parameters separately and in relation to each other on various publics in order to determine those elements

which actually are affecting the publics.

3. Develop and test methods to establish relationships between streamflow changes and the recreational and aesthetic parameters. Examples of methods would include an adaptation of the Thompson and Fletcher method, the Techcom model, the Comrey techniques as used in the Techcom model, ratio scales, weighting scales such as Likert, the semantic differential, and Guttman quasi-scales.

4. Measure perceptions and behaviors of publics in relation to specific streamflow situations.

5. Designate indicators of the effects of streamflow changes on aesthetic and recreational activity under specific conditions. This could result from application of the previously suggested research.

6. Develop equations or other methods for aesthetic evaluations of different streamflow conditions and the probable types of recreation behavior related to each streamflow.

7. Develop environmental simulation techniques to provide laboratory designs for studying on-going and complete environmental situations associated with aesthetics and to analyze behavior in total experience or "wraparound" systems. This would provide a wide, varied combination of environmental parameters that could be readily applicable in experimental designs.

8. Analyze socialization and other aspects of the social psychological development that creates aesthetic responses. What are the relationships to a time framework as to slow or rapid changes and their relationships to learning in various parts of experience, such as work, and to different stages of the life cycle.

9. Determine the importance of aesthetic experiences in the natural environment as they affect interest and behavior relating to streamflow. Are they decreasing, staying the same, or increasing?

10. Analyze the aesthetic evaluations of professionals and the general public to determine the real differences using broad sampling techniques.

11. Study the importance of aesthetics to resource decisionmaking and the effects of aesthetic parameters on decisionmaking.

12. Study additional approaches and methodologies which may be useful in the search for the determination of effects of changing streamflow on aesthetics. Some possible methods in addition to those already identified may be such things as gaming, mental mapping, and biofeed psychology, especially the generation of alpha waves. These may provide techniques for directly measuring "behavior" rather than user preference studies.

13. Analyze the quality of aesthetics sections in environmental impact statements to determine the present relationship of aesthetic and environmental problems.

Specific Research Needs, Priorities, and Time and Cost Estimates

A serious obstacle to research on environmental aesthetics is the difficulty of knowing what has been and is being done, and then obtaining pertinent materials. The magnitude of these materials is not yet unmanageable, from the viewpoint of collection and cross-referencing. It is therefore strongly recommended that information on such research activities be centralized and made available to interested agencies upon request. It is further urged that this include international developments.

Four research areas are considered to be of high priority for determining the relationships between streamflow and recreation/aesthetics. They are related to the model (see Figures 4 and 5) developed for this report. All can be implemented in parallel, but their results will consistently reinforce one another. Some areas developmentally precede others.

1. Fundamental to all further research is the establishment of those streamflow parameters pertinent to recreation behaviors and aesthetic experiences. It is suggested that the interdisciplinary Delphi method represents one effective way of accomplishing this objective, perhaps complemented by viewer perception and evaluation studies. The result will be a working list of stream parameters which can be used to establish the gross and detailed stream classifications needed for study-stream selection. The other research discussed below may well modify and refine these results.

Time – 6 months to 1 year
Cost – $30,000 to $40,000

2. Recreation behavior and aesthetic experiences. It is urged that the research steps discussed here be viewed as necessarily related.

a. To delineate aesthetic behaviors and determine interrelationships between and among recreation activities and aesthetic experiences. The result may well be a list of aesthetic factors parallel and complementary to the categories of recreational behavior established by BOR. In addition, some indication of competitive and complementary relationships among the activities and experiences should be produced.

Time – 1 year
Cost – $30,000 to $40,000

b. The interdisciplinary development of effective methods for the assessment and evaluation of recreation behaviors and aesthetic experiences as related to streamflow. It is assumed that some methods can be developed and/or refined quickly, while others will demand more time and effort. Involved would be pilot applications of the developed methods to the assessment and evaluation of stream-related recreation behaviors and aesthetic experiences. A particularly important component of this stage would be the development and testing of reliable and valid instruments for quantitative assessment of recreation/aesthetic resources.

Time – 18 months to 2 years
Cost – $150,000 to $200,000

3. To determine the impact of streamflow parameters on recreation activities and aesthetic experiences. These studies are, in many ways, addressed to the ultimate goals of all of the proposed research and will draw upon the results of each of the other study areas. The objective is to produce functional equations (models), in terms of measured streamflow parameters (physical and biological), that will reliably predict quantified changes in recreation activities and aesthetic experiences. Part of this study will also address the problems of feedback effects of recreation/aesthetic uses of stream environments on physical/biological parameters (e.g., water quality, wildlife, habitat, fish populations). While of necessity, entailing long-term analyses, an immediate and regular process of monitoring and feedback can permit the ongoing application of resultant data into the other research areas and decision-making processes.

Time – 2 1/2 to 3 years
Cost – $300,000 to $400,000

4. Social values. To determine the present and projected public interest in and demand for recreation and aesthetic experiences. Included would be a review of external factors (e.g., legislation, institutional policies, access, local recreation/aesthetic alternatives and preferences, etc.) that may affect demand for and use of stream-related recreation/aesthetic resources. This study is viewed as synthesizing existing data, rather than developing new data bases. This research can and should be begun at once. The results can provide additional support needed for further justifying the research needs given above.

Time – 1 year to 18 months
Cost – $40,000 to $50,000

REFERENCES CITED

ANDREWS, W. H., W. C. DUNAWAY and D. C. GEERTSEN.
1972. Social aspects of flooding in the urbanized east Salt Lake County area. Res. Circular No. 1, Inst. for Soc. Sci. Res. on Natur. Resour. Utah State Univ., Logan, Utah.

ANDREWS, W. H., G. E. MADSEN and G. J. LEGAZ.
1974. Social impacts of water resource developments and their implications for urban and rural development: A post-audit analysis of the Weber Basin Project in Utah. Res. Monogr. No. 4, Inst. for Soc. Sci. Res. on Natur. Resour., Utah State Univ., Logan, Utah.

ANDREWS, W. H., M. B. MASTELLER, J. P. RILEY and E. K. ISRAELSEN.
1975. Methodology and application–Modeling the total hydrologic-sociologic system of an urban area. Inst. for Soc. Sci. Res. on Natur. Resour. and Utah Water Res. Lab, Utah State Univ., Logan, Utah.

APPLEYARD, D., K. LYNCH, and J. MYER.
1965. The view from the road. MIT Press.

ARTHUR, L. M.
1975. Testing the predictive utility of scenic beauty estimation technique. Unpub. Ph.D. Thesis, Univ. of Arizona, Tucson, Arizona.

ARTHUR, L. M., T. C. DANIEL and R. S. BOSTER.
1975. Scenic beauty assessment: A literature review. Rocky Mountain Forest and Range Exper. Station, USFS, Fort Collins, Colorado. In Press.

BATTELLE.
1972. An environmental evaluation system (EES) for Water Resour. Planning. Battelle, Columbus Lab. Columbus, Ohio.

CALVIN, J. A., and J. A. DEARINGER.
1972. An attempt at assessing preferences for natural landscapes. Environment and Behavior, 1(1):7-35.

COMREY, L.
1950. A proposed method for absolute ratio scaling. Psychometrica. 15(3): 317-325.

CRAIK, K. H.
1971. The assessment of places. *In* McReynolds, P. (ed.). Advances in psychological assessment. Science and Behavior Books, Palo Alto, California. pp. 40-62.

CRAIK, K. H.
1972. Appraising the objectivity of landscape dimensions. *In* Krutilla, J. V. (ed.). Natural environments: Studies in theoretical and applied analysis. Resources for the Future, Inc. John Hopkins Univ. Press, Baltimore, Maryland.

DANIEL, T. C., and R. S. BOSTER.
1975. Measuring scenic beauty: The scenic beauty estimation method. Rocky Mountain Forest and Range Exper. Station, USFS, Fort Collins, Colorado. In Press.

DANIEL, T. G., L. WHEELER, R. S. BOSTER and P. R. BEST JR.
1973. Qualitative evaluation of landscapes: An application of signal detection analysis to forest management alternatives, Man and Environ. Systems. 3(5):330-344.

FABOS, J. G.
1971. An analysis of environmental quality ranking systems. *In* Recreation Symp. Proc. Northeastern Forest Exper. Station, USFS, Upper Derby, Pa. pp. 40-55.

GUILFORD, J. P.
1954. Psychometric methods, 2nd ed. McGraw-Hill New York, N.Y.

GUM, R. L.
1974. Identification weights and measurement of social goals. *In* Techcom, 1974. Water resources planning, social goals and indicators: Methodological development and empirical test. PRWG 131-1, Utah Water Res. Lab., Utah State Univ., Logan, Utah.

GUM, R. L., R. HEDGE, D. KIMBALL, and W. WILSON.
1974. Quantifying aesthetics opportunity. *In* Brown P. J. (ed.). Toward a technique for quantifying aesthetic quality of water resources. Utah State Univ., Logan, Utah.

GUTTMAN, L.
1948. Chapters 3-9. *In* Stouffer, S. A. et al. Measurement and prediction. Gloucester, Mass.

HAMBLIN, R.
1971. Ratio measurement for the social sciences. Social Focus. 50(2):191-206.

HAMBLIN, R.
1974. Social attitudes: Magnitude measurement and theory. *In* Blalock, H. M. Jr. (ed.). Measurement in the social sciences. Aldine Publ. Co. Chicago, Illinois, pp. 61-120.

HAMILL, L.
1975. Analysis of Leopold's quantitative comparisons of landscape aesthetics. J. Leisure Res. 7(1):16-18.

JACKSON, C. L.
1972. Scenic Resources: A study of scenic preferences. Dept. of Recreation Resour. Colorado State Univ. Fort Collins, Colorado.

LAZARSFELD, P. F.
1948. Chapters 10 and 11. *In* Stouffer, S. A. et al. Measurement and prediction. Gloucester, Mass.

LEOPOLD, L. B.
1969a. Landscape esthetics: How to quantify the science of a river valley. Natural History. pp. 37-44.

LEOPOLD, L. B.
1969b. Method for measuring landscape appeal. Natural History. pp. 36-45.

LITTON, R. B.
1968. Forest landscape description and inventories: A basis for planning and design. Res. Paper PSW-49, Pacific Forest and Range Exper. Station, USFS, Berkeley, California.

LITTON, R. B., et al.
1971. An aesthetic overview of the role of water in the landscape. Prepared for the National Water Comm., Dept. of Landscape Architecture, Univ. of California, Berkeley.

LITTON, R. B.
1972. Aesthetic dimensions of the landscape. *In* Kuitilla, J. V. (ed.). Natural environments: Studies in theoretical and applied analysis. Resources for the Future, Inc. John Hopkins Univ. Press, Baltimore, Maryland.

MELHORN, W. N., and E. A. KELLER.
1973. Landscape aesthetics numerically determined: Applications to highway corridor selection. Purdue Univ., Dept. of Geosciences, pp. 1-16.

MEREDITH, D. B., and B. B. EWING.
1969. Systems approach to the evaluation of benefits from improved Great Lakes water quality. *In* Conf. Proc. of the Internat. Assoc. of Great Lakes Resour. Manag. pp. 843-870.

METFESSEL, M.
1947. A proposal for quantifying reporting of comparative judgments. J. of Psychology. 24: 229-235.

MICHAELSON, E.
1974. Aesthetics of wild and scenic rivers: A methodological approach. Water Resour. Inst., Univ. of Idaho, Moscow, Idaho.

MILLER, D. C.
1970. Handbook of research design and social measurement. 2nd ed. McKay and Co., New York.

MUELLER, G. H., R. MCLACHLAN, and D. A. MORRISON.
1974. Visual perception in outdoor environments. Northeast Exper. Station, USFS, Upper Derby, Pa.

NORTHWEST REGION BUREAU OF OUTDOOR RECREATION.
1974. Recreation–Chap. 12. *In* Bayha K. (ed.). Anatomy of a river. Report of the Hells Canyon Task Force. Pacific N.W. River Basins Comm. pp. 123-147.

OPPENHEIM, A. N.
1964. Questionnaire design and attitude measurement. Basic Books, New York, N.Y.

OSGOOD, C. E., G. J. SUCI and P. H. TANNENBAUM.
1957. The measurement of meaning. Univ. of Illinois press, Urbana, Illinois.

PETERSON, G. S., and E. S. NEWMAN.
1969. Modeling and predicting human response to the visual recreation environment. J. Leisure Res. 1(3):237-239.

REDDING, M. J.
1973. Aesthetics in environmental planning. Office of Res. and Develop., EPA, Washington, D.C.

SHAFER, E. L., JR., and J. MIETZ.
1970. It seems possible to quantify scenic beauty in photographs. Res. Paper N.E.-162. Northeast Forest Exper. Station, USFS, Upper Derby, Pa.

SHAFER, E. L., JR., and T. C. RICHARDS.
1974. A comparison of various reactions to outdoor scenes and photographs of these scenes. Northeast Forest Exper. Station, USFS, Upper Derby, Pa.

STEVENS, S. S.
1960. The psychophysics of sensory function. Amer. Scientist. 48(2):226-253.

STEVENS, S. S.
1962. The simplicity of sensory metrics. Amer. Psychology. 17:29-39.

STEVENS, S. S.
1966. A metric for social consensus. Science. 15:530-541.

STOUFFER, S. A., et al.
1973. Measurement and prediction. Gloucester, Mass. Peter Smith (Reprint of 1948 edition of Princeton University Press).

SWETS, J. A., W. P. TANNER, JR. and T. G. BIRDSALL.
1961. Decision processes in perception. Psychological Review. 68(5):301-340.

TAYLOR, J. B., and H. G. PARKER.
1964. Graphic ratings and attitude measurement: A comparison of research factors. J. of Applied Psychology. 48(1):37-42.

TECHCOM.
1974. Technical Committee of the Water Resources Research Centers of the Thirteen Western States. Water resources planning, social goals and indicators: Methodological development and empirical test. PRWG 131-1, Utah Water Res Lab., Utah State Univ. Logan, Utah.

U.S. FOREST SERVICE.
1973. National Forest landscape management. Vol. 1., Agriculture Handbook. No. 434, USDA, Washington, D.C.

ZUBE, H.
1974. Cross disciplining and intermode agreement on the evaluation of landscape resources. Environment and Man. 6(1):69-89.

APPENDIX 1
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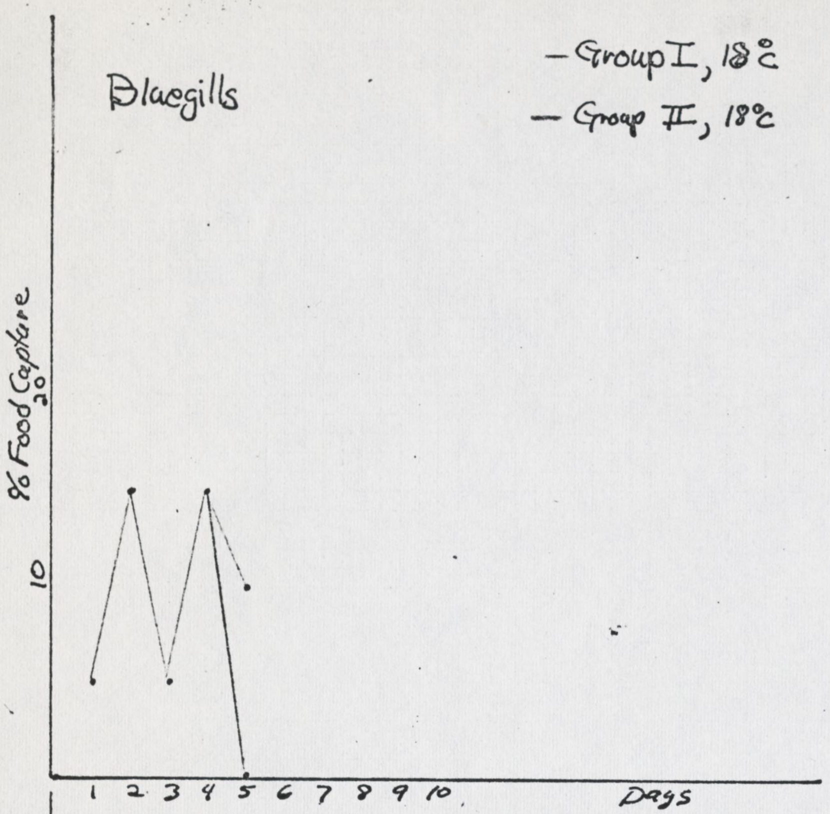
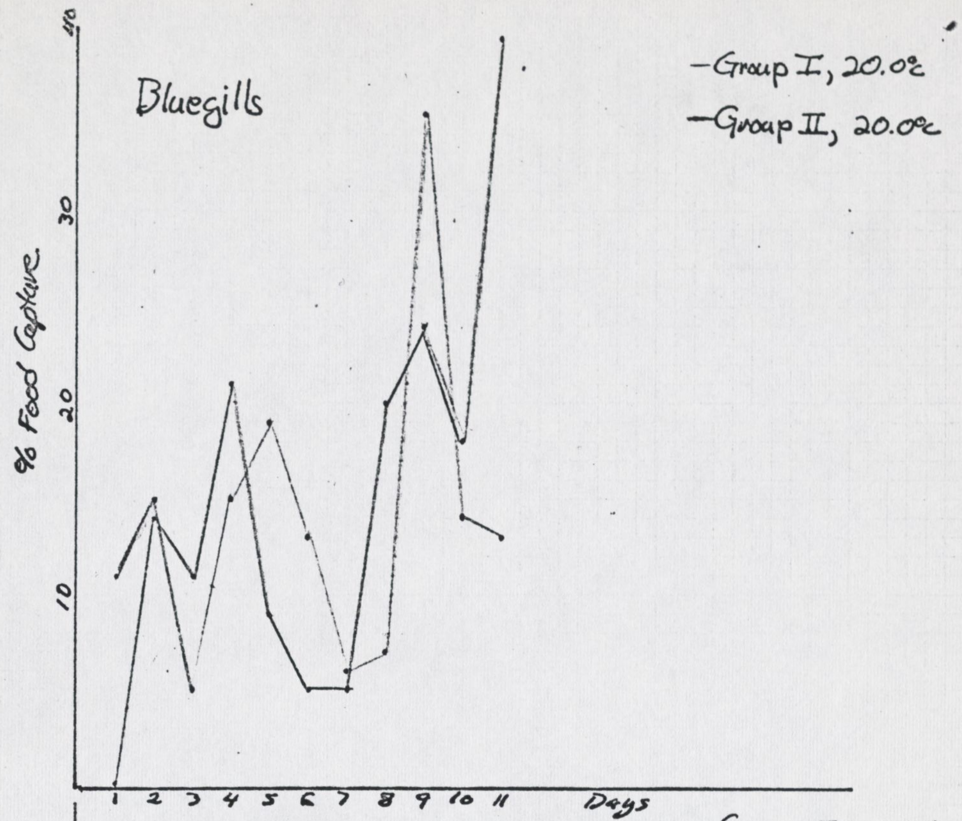
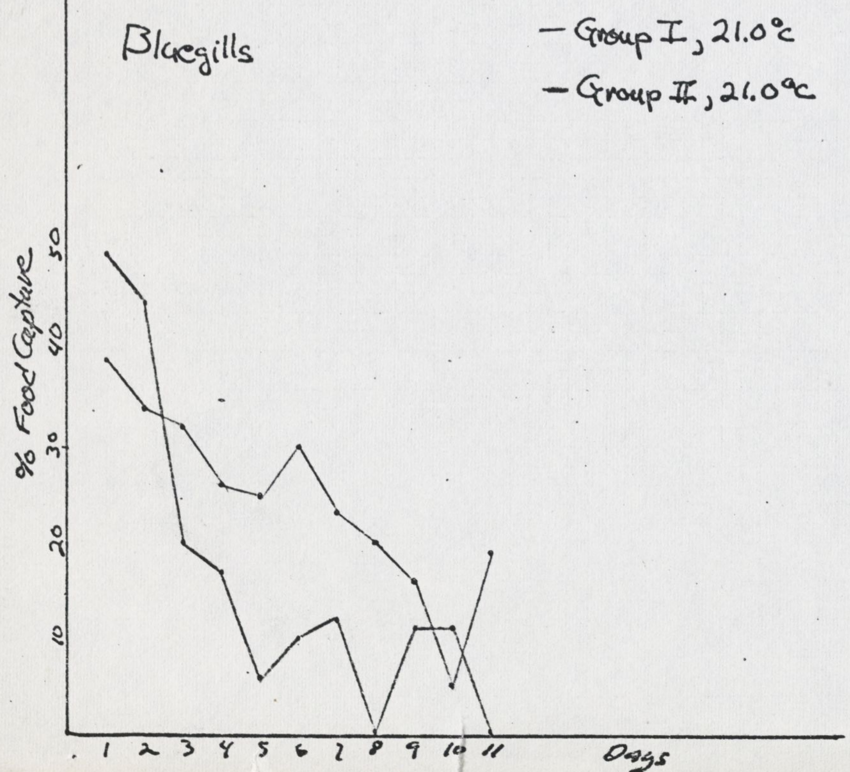


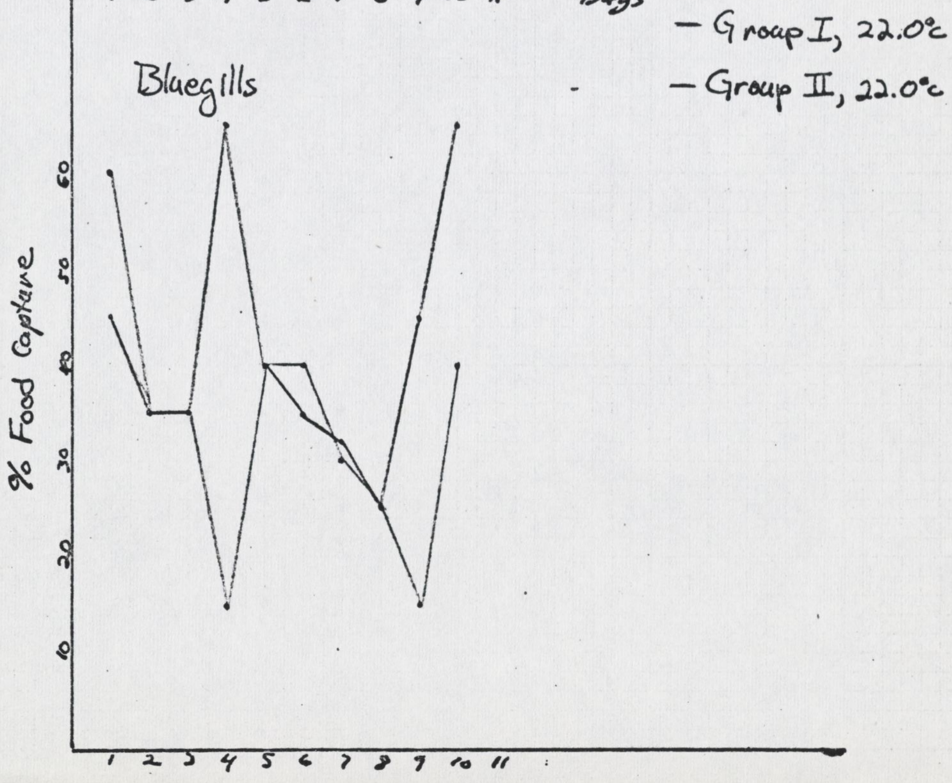
Bluegills
— Group I, 18°C
— Group II, 18°C
% Food Capture
10
20
1 2 3 4 5 6 7 8 9 10
Days



Bluegills
—Group I, 20.0°C
—Group II, 20.0°C
% Food Capture
10
20
30
40
1 2 3 4 5 6 7 8 9 10 11
Days



Bluegills
— Group I, 21.0°C
— Group II, 21.0°C
% Food Capture
10
20
30
40
50
1 2 3 4 5 6 7 8 9 10 11
Days



Bluegills
— Group I, 22.0°C
— Group II, 22.0°C
% Food Capture
10
20
30
40
50
60
1 2 3 4 5 6 7 8 9 10 11