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Analysis of Environmental Issues Related to Small-Scale Hydroelectric Development. V. Instream Flow Needs for Fishery Resources

James M. Lorr
Michael J. Sate

ENVIRONMENTAL SCIENCES DIVISION

Publication No. 1829

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A07 Microfiche: A01

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ORNL/TM-7861
Distribution Category UC-97e

Contract No. W-7405-eng-26

ANALYSIS OF ENVIRONMENTAL ISSUES
RELATED TO SMALL-SCALE HYDROELECTRIC DEVELOPMENT.
V. INSTREAM FLOW NEEDS FOR FISHERY RESOURCES

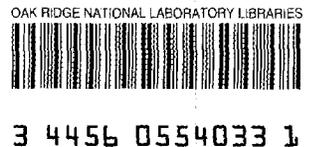
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ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1829

Prepared for U.S. Department of Energy, Assistant
Secretary for Conservation and Renewable Energy,
Division of Hydroelectric Resource Development

Date Published: October 1981

OAK RIDGE NATIONAL LABORATORY
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ACKNOWLEDGMENTS

We thank William Knapp (U.S. Fish and Wildlife Service, Region 5) and Mark Robinson (Federal Energy Regulatory Commission) for helpful discussions during the preparation of the report and for their constructive comments on the draft manuscript. Dale Huff, Jon Goyert, Stephen Hildebrand, and Webster Van Winkle (Oak Ridge National Laboratory) also reviewed the manuscript and provided many helpful comments and suggestions. Financial support for this activity was provided by the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Division of Hydroelectric Resource Development.

PREFACE

The purpose of this document is to provide guidance to developers of small-scale hydroelectric projects on the assessment of instream flow needs. While numerous methods have been developed to assess the effects of stream flow regulation on aquatic biota in coldwater streams in the West, no consensus has been reached regarding their general applicability, especially to streams in the eastern United States. Our presentation and review of these methods (Section 2.0) is intended to provide the reader with general background information that is the basis for the critical evaluation of the methods (Section 3.0). The strategy for instream flow assessment presented in Section 4.0 is, in turn, based on the implicit assumptions, data needs, costs, and decision-making capabilities of the various methods as discussed in Section 3.0.

We have restricted the scope of the document in several areas. Details on the specific procedures to be followed in applying the methods are not given but are available in the literature cited in Section 5.0. Moreover, the document is not intended to be a review of all the literature related to the issue of instream flow. Because determination of the instream flow needs for fishery resources is the most difficult and controversial aspect of the instream flow issue, we have only included those methods that are related to this aspect of the issue. Consequently, methods developed to assess recreational or aesthetic needs are not addressed in the document. Finally, the legal and institutional aspects of the instream flow issue (e.g., negotiation strategies) are not discussed.

This document is the fifth in a series of reports addressing environmental issues and small-scale hydroelectric technology that are being prepared by the Oak Ridge National Laboratory for the U.S. Department of Energy. The other reports in this series are listed below and are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

1. Loar, J. M., L. L. Dye, R. R. Turner, and S. G. Hildebrand. 1980. Analysis of environmental issues related to small-scale hydroelectric development. I. Dredging. ORNL/TM-7228. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 134 pp.
2. Hildebrand, S. G. [Ed.]. 1980. Analysis of environmental issues related to small-scale hydroelectric development. II. Design considerations for passing fish upstream around dams. ORNL/TM-7396. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 78 pp.
3. Hildebrand, S. G. [Ed.]. 1980. Analysis of environmental issues related to small-scale hydroelectric development. III. Water level fluctuation. ORNL/TM-7453. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 78 pp. plus Appendix.
4. Turbak, S. C., D. R. Reichle, and C. R. Shriner. 1981. Analysis of environmental issues related to small-scale hydroelectric development. IV. Mortality resulting from turbine passage. ORNL/TM-7521. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 112 pp.

ABSTRACT

Protection of instream uses of water, such as fish and wildlife habitat, recreation, and aesthetics, has been identified as a significant environmental issue, especially in the West where water supplies are limited and offstream uses (e.g., irrigation) are well-defined by law. The growing recognition nationwide of the importance of protecting these instream uses of water has coincided with the recent emphasis on the development of small-scale hydropower resources. The issue of instream flow maintenance in hydropower development is essentially a problem of evaluating the effects of planned modifications in hydrologic patterns. Because hydroelectric projects can alter natural flow regimes on both spatial and temporal scales, downstream water users and the aquatic ecosystem can be adversely affected. Assessment of the instream flow needs of aquatic biota (primarily fishes) has been the most difficult and controversial aspect of the instream flow issue.

Numerous methods have been developed to assess the effects of stream flow regulation on aquatic biota and to provide instream flow recommendations. The methods differ in their use of hydrologic records, hydraulic simulation techniques, and habitat rating criteria and in their capability to provide seasonal or species-specific recommendations. Because of these differences in data requirements, application costs and the level of resolution associated with the instream flow recommendations vary greatly. Consequently, guidance is needed to ensure that the most appropriate methods are selected for instream flow assessments at small-scale hydroelectric sites. To provide this guidance to developers of small hydropower projects, the methods were reviewed and evaluated to determine their applicability in the assessment of instream flow needs for fishery resources at small hydropower sites. The methods were grouped into three categories based on (1) level of resolution associated with the instream flow recommendation, (2) data needs, and (3) costs of

application. The categories correspond to different levels of assessment that might be required at a given hydropower site. To select the most appropriate level of analysis, criteria related to both the design and operation of the project and the aquatic resources at the site were identified.

Establishment of an instream flow regime may significantly affect the economic feasibility of many small hydropower projects, since water needed to maintain instream flows is often unavailable for power production. To minimize conflicts between these two uses of water, assessment of instream flow needs must be conducted in the early stages of project planning and development. Final resolution of potential conflicts, however, may require negotiations and, ultimately, some tradeoffs between hydropower requirements and the instream flow needs of the fishery.

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1. INTRODUCTION

The value of instream uses of water (e.g., fish and wildlife habitat, recreation, and aesthetics) is increasing as greater demands are placed on our water resources to meet various industrial, agricultural, and domestic needs (offstream uses). Although the problem of inadequate surface water supply is or will be severe by the year 2000 in many regions of the Midwest and Southwest, some regions of the East may also have water supply problems during low-flow months. The competition between offstream and instream uses will also intensify as a result of the estimated 27% increase in consumptive water use by the year 2000 (U.S. Water Resources Council 1978). Resolution of the conflict between the various uses of water raises important questions regarding the quantity of water that should remain in a stream or river to protect existing instream (nonconsumptive) uses. Because the value of these instream uses has only recently been recognized within a legal/institutional framework, many of the methods* that have been developed to assess instream flow requirements are relatively new.

Instream flow requirements (or needs) refer to the amount of flowing water within a natural stream channel that is needed to sustain the instream values (or uses made of water in the stream channel) at an acceptable level. Such a requirement identifies the flow regime that will maintain all uses of water within the channel, including fish and wildlife populations, recreation, aesthetics, water quality, hydropower generation, navigation, and ecosystem maintenance which includes freshwater inflow to estuaries, riparian vegetation, and floodplain wetlands (Bayha 1978, Wassenberg et al. 1979). Methods have been developed to assess the instream flow requirements

*The term 'methodology,' defined as a group of related methods, is often found in the literature on instream flow needs. Because the connotation is frequently ambiguous, we have intentionally avoided use of the term in this report.

associated with many of these uses. For example, mathematical modeling has been an important component in determining instream flow needs related to water quality (e.g., Mar 1973 and 1975 as cited in Wyoming Water Resources Research Institute 1978a; Grenney et al. 1976; Grenney and Porcella 1976; Porcella and Grenney 1976). Methods have also been developed to assess instream flow needs for recreation (Andrews and Madsen 1976; Andrews et al. 1976; Morris 1976; Cortell and Associates, Inc. 1977a,b; Hyra 1978; Wyoming Water Resources Research Institute 1978a) and aesthetics (Andrews and Madsen 1976; Masteller et al. 1976; Mittman 1976; Wyoming Water Resources Research Institute 1978a). The effects of water level changes on riparian and wetland communities have been described (e.g., Teskey and Hinckley 1977), and methods for assessing the effects of water management practices upon riparian vegetation and wildlife are available (Kadlec 1976a,b; Wyoming Water Resources Research Institute 1978b).

Assessment of the instream flow needs of aquatic biota, however, has been the most difficult and controversial aspect of the instream flow issue and is the subject of this report. Numerous methods have been developed to assess the effects of flow regulation on aquatic biota and to provide a basis for the determination of a suitable stream flow recommendation. Although all components of lotic ecosystems are affected by flow regulation (Sect. 1.1.1), the assessment of instream flow needs of aquatic biota has focused primarily on fish species. Only recently have studies of benthic macroinvertebrates been initiated, and these were limited to (1) development of new techniques for assessing instream flow requirements (Gore 1978, Railsback 1981), and (2) compilation and evaluation of habitat suitability data from existing literature (Herricks and Furnish 1980).

Because no consensus has been reached on the site-specific applicability of these methods, especially in the eastern United States, developers of small hydroelectric projects, which, depending upon their design and operation, can alter the natural flow regime

(Sect. 1.3), lack the necessary guidance for assessing the biological effects which might result from such modifications in stream flow. This report has been prepared to provide the guidance that does not currently exist for assessing instream flow needs for fishery resources below hydroelectric projects. The various methods are reviewed (Sect. 2.0) and evaluated (Sect. 3.0), and strategies are presented (Sect. 4.0) for selecting the most appropriate method based on (1) project design and operation, and (2) nature of the aquatic resources. Before discussing specific methods, however, additional background information is provided on the instream flow issue from an historical (Sect. 1.1), regulatory (Sect. 1.2), and hydropower (Sect. 1.3) perspective.

1.1 Historical Background on the Instream Flow Issue

1.1.1 Development in the West

Significant conflicts between offstream and instream uses of water first developed in the West where water supplies are limited and offstream uses (e.g., irrigation) are well-defined by law. Western water law is based on the appropriation doctrine which has two fundamental principles: (1) first in time is first in right and (2) beneficial use of the water is the basis of the right (Gould 1977). Because of the scarcity of water in many regions of the West, water development has been equated with growth, prosperity, and success (Lamb and Bayha 1978). In short, beneficial use was defined in economic terms. In many states, permitting water to remain in the stream (e.g., for the protection of fish and wildlife habitat or recreation and aesthetic values) was not recognized as a beneficial use. Now, however, most western states recognize the need to protect instream values and, in some cases, have been able to acquire protection through legislative changes (e.g., Dewsnup and Jensen 1977; Lamb and Bayha 1978).

The intense competition for water and the growing recognition that instream uses of water must be protected led to the development of numerous methods for assessing instream flow needs. Most of these methods focused on the protection of indigenous fish populations, particularly salmonids, because of their recreational and commercial importance. Some of the earliest studies to determine instream flow needs were conducted below large hydroelectric facilities located on coastal rivers of northern California (e.g., Curtis 1959, Delisle and Eliason 1961, review by Fraser 1972a). After legislation that recognized the importance of maintaining suitable stream flows had been passed in Oregon, field studies were initiated in 1961 to determine specific flow requirements of salmonids at different times of the year (Sams and Pearson 1963, Thompson 1972). In 1962, the U.S. Forest Service developed a transect line, cluster sampling procedure for use on trout streams in Utah and Idaho (Dunham 1972). A few years later, work on the now well-known Tennant or Montana Method (Elser 1972, Tennant 1976) was initiated in Montana.

Beginning in the early 1970's, several workshops were held in the Northwest to discuss the various methods that had been developed. As a result of this communication, methods were compared and modified to incorporate the new information that was being collected on the habitat requirements of salmonids. Several reviews of the methods available for assessing instream flow needs were also published during this period (Fraser 1972a, Giger 1973, Hooper 1973).

At the same time that methods were being developed to assess the instream flow needs of fish species, site-specific studies were conducted to examine the biological consequences of stream flow regulation. Results of these studies showed that the primary impact of reduced flows on fishes was a reduction in usable habitat (Holden 1979). A trans-basin diversion project on the Trinity River in northern California, for example, resulted in a significant reduction in salmonid spawning habitat below the point of diversion (Smith 1976).

In most regulated streams and rivers, major alterations were also observed in the composition of benthic macroinvertebrate communities (see review by Ward and Stanford 1979a). The important factors controlling macroinvertebrates (temperature, flow, and substrate) were also found to affect lower trophic levels (e.g., primary producers such as benthic algae). However, the limited data available on the flora of regulated streams were secondary information obtained during studies of the macroinvertebrate and fish communities (Lowe 1979).

Three of the most significant events in the evolution of instream flow methods in the West occurred within a four-month period in 1976. In April, the results of a study to document and evaluate existing methods for fisheries, wildlife, water quality, recreation and aesthetics were published (Stalnaker and Arnette 1976). This document, an early product of the Western Water Allocation Project in the Office of Biological Services of the U.S. Fish and Wildlife Service, represented the first attempt to compile detailed information on the various fisheries methods and to critically examine them. The next month, a symposium and specialty conference on instream flow needs sponsored by the Western Division of the American Fisheries Society was held in Boise, Idaho. The proceedings of the conference, which addressed the legal, social, and biological aspects of the instream flow issue, were published in a two-volume series (Orsborn and Allman 1976a,b) that "may prove to be a landmark in the history of the subject" (White 1979). Finally, in July 1976, the multidisciplinary Cooperative Instream Flow Service Group (IFG)* in the Office of Biological Services of the U.S. Fish and Wildlife Service was established in Ft. Collins, Colorado. The purpose of the IFG was to advance the "state-of-the-art" and become the center of activity related to instream flow assessments (U.S. Fish and Wildlife Service 1977). Within a short period of time after formation of the

*The IFG is now known as the Instream Flow and Aquatic Systems Group.

IFG, the Incremental Methodology (Section 2.8) was developed (Bovee and Cochnauer 1977; Bovee and Milhous 1978; Stalnaker 1978, 1979b; Trihey 1979; Wegner 1979).

The use of comparative field studies to evaluate various fisheries methods is a recent development in the West (R. Giger, personal communication). These studies were funded in 12 western states as part of the Western Water Allocation Project. This comparative approach represents a logical step in the sequence of events that will hopefully lead to insights on the applicability of the various methods. Although many gaps still exist in our knowledge of the relationship between stream flow and fish production, these shortcomings should not prevent users from applying or modifying existing methods. The successful development of adequate methods for assessing instream flow needs will require applications on a wide range of watersheds throughout the country. Although no consensus has yet been reached regarding the "best" method to use in a given situation, additional information acquired from continued application in the field will eventually lead to a better understanding of the applicability of the various methods.

1.1.2 Development in the East

Unlike in the West where instream flow methods evolved over the past 20 years in response to the growing demand for limited water supplies, in the East instream flow needs are just beginning to develop as an issue. With the exception of the method developed by Robinson (1969) for the Connecticut River basin, no formal methods to assess instream flow needs have been documented from the eastern United States until recently (U.S. Fish and Wildlife Service 1981). Eastern initiatives in formulating instream flow policies were largely in response to an increase in the development of small hydropower resources in the Northeast. Because water is more abundant in the East than in the West, conflicts to date have been highly localized. Moreover, water law in most states east of the Mississippi River is

based on the riparian doctrine (Table A-1 in Lamb and Bayha 1978). The doctrine equates the existence of a water right with ownership of the land adjacent to the stream (riparian ownership), and each owner has an equal right to reasonable use of the water in the stream (Gould 1977). Depletions of both supply and quality of the water must not prevent downstream users from exercising their reasonable rights to use of the water (Lamb and Bayha 1978). The riparian doctrine is substantially different from the appropriation doctrine of most western states which accommodates offstream uses of water to promote economic development. Both the abundance of water (and, consequently, the absence of significant offstream use for irrigation) and the existence of the riparian doctrine account for the relatively brief history of the instream flow issue in the East.

As in the West, assessment of instream flow requirements in the East was initially associated with controlling the operation of hydroelectric facilities, and, until recently, these assessments were most likely based on historical discharge records and the judgment of biologists. In the late 1970's, methods developed in the West, particularly the Incremental Methodology, were used to assess instream flow needs below dams on the lower Susquehanna River in Pennsylvania (Jackson 1980) and in the upper Delaware River Basin in New York (Sheppard 1980). The Incremental Methodology has also been used on streams in West Virginia, Ohio, Indiana, Kentucky, Tennessee (Bayha and Hardin 1980), and North Carolina (Bain 1980). It is currently being used to survey instream flow requirements on a statewide basis in Illinois (Bayha and Hardin 1980, Herricks et al. 1980). At the same time that formal methods were being exported to the East, instream flow workshops were held. Two workshops sponsored by the Ohio River Basin Commission were held in 1979 and 1980, and an instream flow session was included in the program of the Annual Northeast Fish and Wildlife Conference in 1980 and 1981. A similar session was also included in Waterpower '81, an international conference on small hydropower held in June 1981 in Washington, D.C.

Assessment of the instream flow needs of fishery resources in the eastern United States is confronted by two major problems. First, the only site-specific methods currently being used to assess instream flow needs in the East were developed for salmonid populations in coldwater streams in the West; their applicability to eastern streams that may be water quality- or food-limited has not been rigorously examined. The numerous other methods that were also developed in the West have, with few exceptions, never been used in the East. Second, the concern for instream values over the past 20 years produced a wealth of information on the habitat requirements of salmonids, but a comparable data base for warmwater species, the predominant fishery resource in much of the East, does not exist. As a result, resolution of conflicts among various uses of water, especially instream use for hydroelectric generation versus protection of fish and wildlife habitat, may be more difficult in the East.

1.2 Environmental Regulations Related to Instream Flow

Major federal legislation provides a framework for evaluating the environmental impacts associated with water resource development projects, including the alteration of natural flow regimes below hydroelectric facilities. The Fish and Wildlife Coordination Act of 1934 and 1958 requires the Federal Energy Regulatory Commission (FERC), the agency responsible for the regulation of nonfederal hydroelectric dams under the Federal Power Act of 1920, as amended, to consult with the U.S. Fish and Wildlife Service and the appropriate state agencies to ensure that fish and wildlife conservation needs are adequately considered. Such consultation may result in an instream flow recommendation to protect fish and wildlife habitat. The FERC is also required to consult with the Council on Environmental Quality and the Environmental Protection Agency under the Public Utility Regulatory Policies Act (PURPA) of 1978 (Corso 1979).

Other legislation that relates directly to the environmental impacts of development projects (and indirectly to the instream flow issue) includes the National Environmental Policy Act of 1969, the Wild and Scenic Rivers Act of 1968, the Clean Water Act of 1972 and 1977, the Endangered Species Act of 1973, and the Anadromous Fish Conservation Act of 1965. Obviously, the instream flow issue can be significant if the alteration in stream flow will affect species included under either of the latter two laws. Instream flow needs related to water quality can be considered when application is made for a water quality certificate required under Section 401 of the Clean Water Act.

In addition to these environmental regulations, other legislation has been passed which provides a framework for the regulation and development of small hydropower. Section 10(a) of the Federal Power Act of 1920, as amended in 1935, requires FERC to assure that the proposed development and operation of a project will be best adapted to a comprehensive plan that includes other water uses in addition to hydroelectric generation. Protection of fish and wildlife is considered elsewhere in the Act, particularly Section 30(c). More recent legislation related to small-scale hydropower development was passed as Title IV of the Energy Security Act of 1980 which established incentives for the use of renewable energy resources. Section 408 of Title IV amended Section 405 of PURPA which outlined the granting of exemptions to licensing requirements.

Recognition of the importance of instream uses of water in the planning, development, and management of our water resources recently occurred at the national level. In 1973, the U.S. Water Resources Council issued Principles and Standards for Planning Water and Land Resources which required multiobjective planning for environmental quality as well as national economic development (Schamberger and Farmer 1978). Cooperative resource planning among state, federal, and private groups is emphasized. Among other requirements, information must be obtained about the needs and problems of the project area,

including the identification and inventory of the water resource base of the area (Wassenberg et al. 1979). In 1974, the Second National Water Assessment was undertaken by the U.S. Water Resources Council and represented "the first nationwide examination of instream flow conditions and the implications of accelerated offstream uses" (Bayha 1978). In his Water Resources Policy Reform Message of June 6, 1978, President Carter identified water conservation and instream flows as national goals. On July 12, 1978, he issued a directive to federal agencies to improve, where possible and in cooperation with the states (which have principal responsibility for protection of instream flows), the operation and management of existing water resources projects to protect instream uses. Although protection of the instream use of water is now recognized as a national concern, the most difficult aspect of this issue, the assessment of instream flow needs, remains a challenge.

1.3 Effects of Hydroelectric Generation on Instream Flow

The issue of instream flow maintenance in hydropower development is essentially a problem of evaluating the effects of planned modifications in hydrologic patterns. Both large and small-scale hydropower projects can alter natural flow regimes, often with adverse effects on downstream water users and the aquatic ecosystem. The effects of dams on downstream (tailwater) biotic communities were reviewed previously (e.g., Fraser 1972b; Ward and Stanford 1979b; Hildebrand 1980; Loar and Hildebrand, in press) and need not be reiterated. However, it should be noted that while the effects may be relatively well documented, the underlying mechanisms or causal factors responsible for these changes are, with few exceptions, poorly understood.

Alterations in flow regimes below hydroelectric dams can include both spatial and temporal changes in the amount of water moving through a natural stream channel. Large-scale spatial changes occur

when water is exported completely out of a watershed and all downstream reaches are affected. Localized changes in stream flow, on the other hand, are characteristic of many small-scale hydropower projects where water is diverted through a flume or conduit to a generator at a lower elevation before being returned to the original stream channel.

Similarly, temporal changes in stream flow can be either long-term or short-term, depending upon the design and operation of the facility. Flood control projects with large storage capacities can retain high flows, which typically occur during the winter and spring, for release during low-flow periods in the summer and early fall. Such modification of pre-project stream flow is on the order of months or even years. By retaining peak flows and augmenting low flows, nonhydroelectric uses (e.g., flood control, irrigation) of impounded streams often reduce the natural amplitude of water level fluctuations in tailwaters (Turner 1980).

Short-term temporal changes, on the other hand, occur over the span of several minutes or hours and are characteristic of hydroelectric projects that are operated in a peaking mode. Because the demand for electricity varies over a 24-h period, water is stored during off-peak hours for generation during the period of greatest demand (e.g., during the late afternoon and evenings on weekdays; Fig. 1-1). The amplitude of the water level fluctuations below peaking projects may be equivalent to that observed in unregulated (e.g., unimpounded) streams which can be subject to enormous natural fluctuations in water level in response to rainfall and subsequent runoff from the watershed (Turner 1980). However, peaking operations often result in a dramatic increase in the frequency and rate of change of major water level fluctuations and a reduction in the duration of a given water level (stage height) in the downstream channel.

Thus, the degree to which spatial and temporal flow patterns are altered is directly related to the design and operation of the

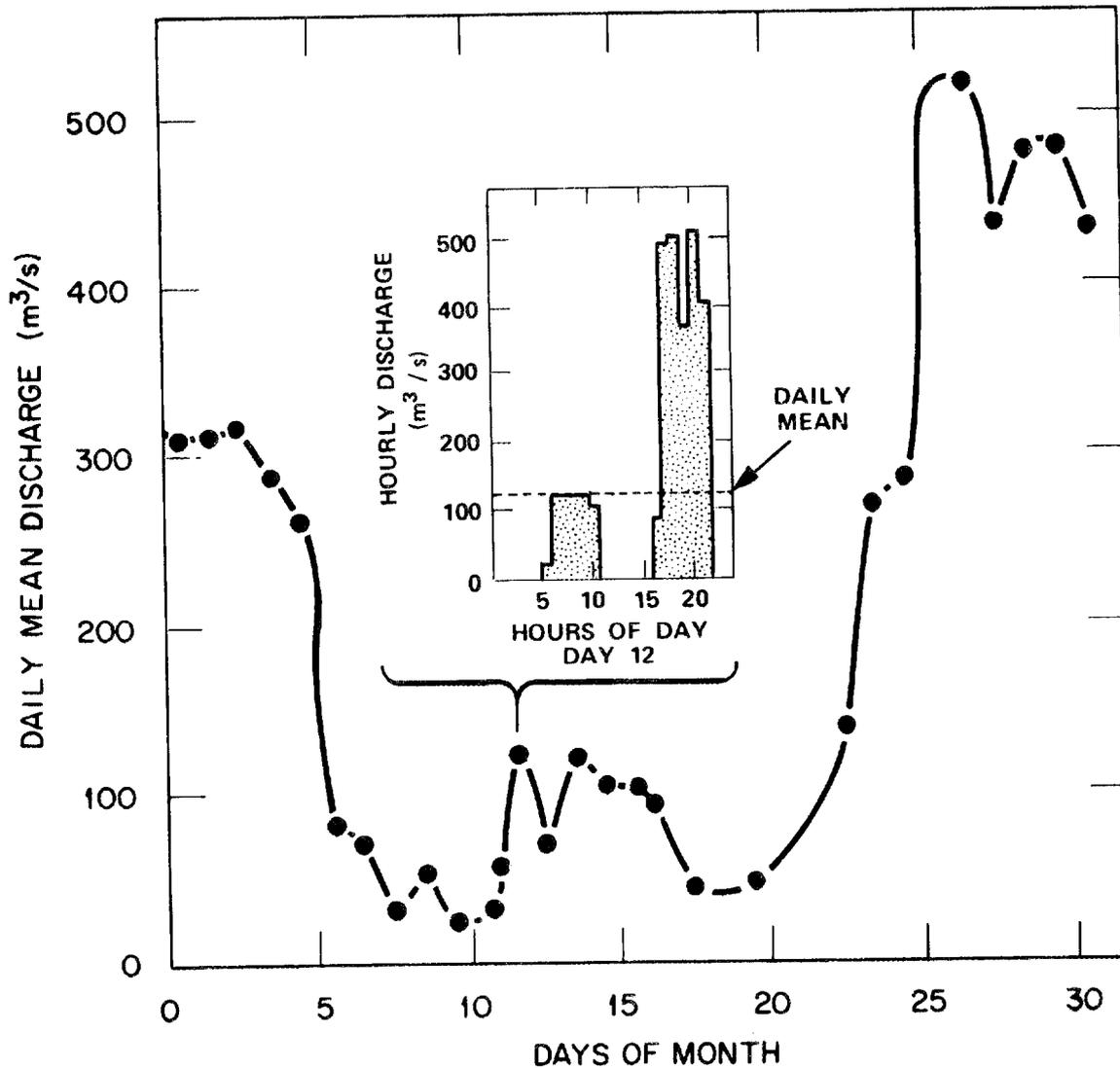


Fig. 1-1. Variation in daily mean discharge from a TVA reservoir during a one-month period of the flood season (approximately mid-October through mid-April). Typical hourly fluctuations about the daily mean are shown for day 12. (Modified from Shane 1981).

facility. Reservoir storage and releases from a dam are related to each other, as shown in the following equation (see also Fig. 1-2):

$$\Delta S = Q_i - Q_g - Q_n - W - E, \quad (1-1)$$

where ΔS = change in storage volume of the reservoir over a fixed time interval,

Q_i = reservoir inflow, over the same interval,

Q_g = generating releases passing through the turbines,

Q_n = non-generating releases (e.g., spillage, leakage, or instream releases),

W = consumptive withdrawal from the reservoir, and

E = net evaporative losses from the reservoir.

As described previously, store-and-release facilities rely on available storage to operate in a peaking mode ($\Delta S \neq 0$; Eq. 1-1). Hydroelectric projects can also be operated in a run-of-river mode. As defined in this report, run-of-river facilities are those projects that are operated with no change in reservoir storage ($\Delta S = 0$; Eq. 1-1). In reality, a gradation of project types exists in which the amount of peaking or seasonal storage is constrained by the acceptable water elevation changes within the reservoir (Hildebrand 1980, Szluha et al. 1981).

Another important aspect related to the design of hydroelectric projects is the location of the powerhouse. In the simplest case, the powerhouse is located at the base of the dam, and the distance between the dam and the confluence of the tailrace with the river is minimal ($L \cong 0$; Fig. 1-2). Many small hydropower projects, however, especially those in New England (U.S. Department of Energy 1981), utilize long penstocks or canals to gain additional head. For example, about one-half of all the New England sites under review by FERC since 1979 would require diversions greater than 150 m (Knapp

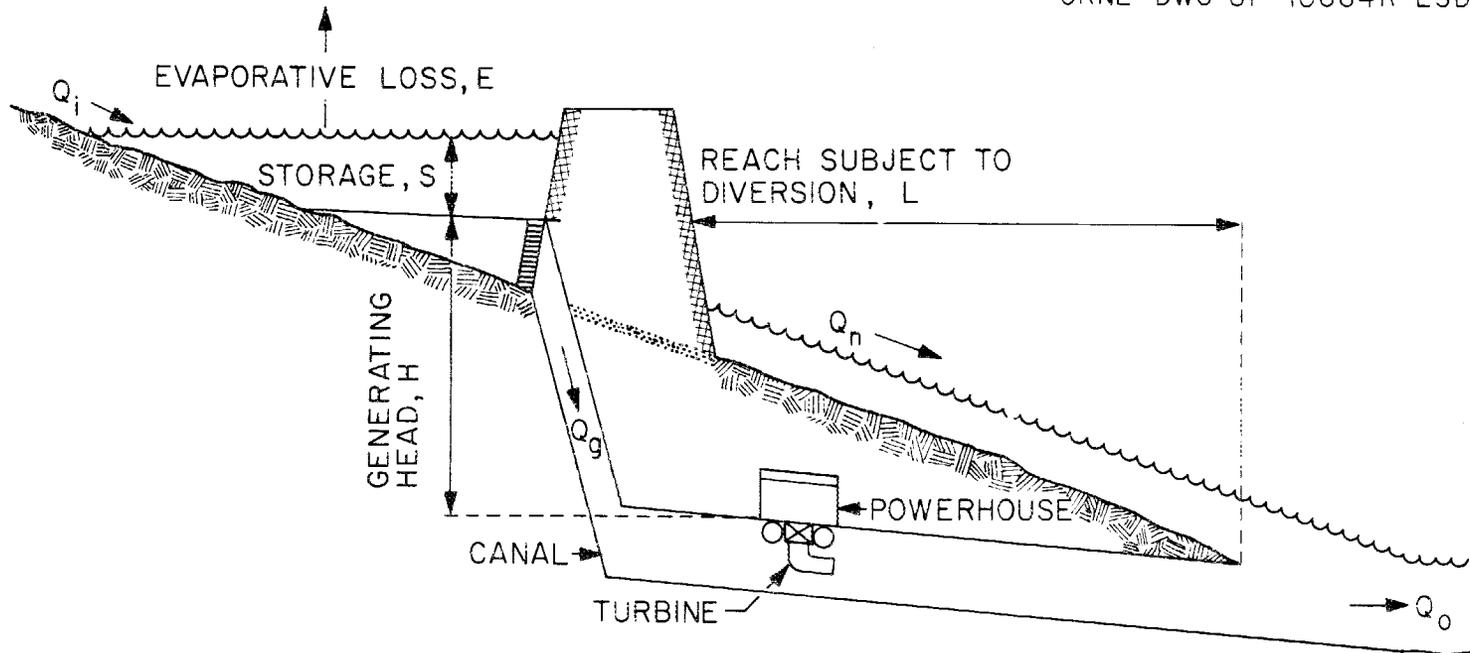


Fig. 1-2. Diagram of a generalized, small-scale hydroelectric project showing the important project characteristics. Total outflow (Q_0) = $Q_g + Q_n$, as defined in Eq. 1-1.

1981). In these cases, the powerhouse is located below the dam, and that reach of the river between the dam and powerhouse may be subjected to very low flows depending upon the amount of water that is diverted ($L \gg 0$ and $Q_n/Q_g \ll 1$). Such a design can be incorporated in projects that operate in both the store-and-release and run-of-river modes.

In most cases, large-scale spatial changes (e.g., transbasin diversions) and/or long-term temporal changes in stream discharge patterns will not be associated with the development of small hydropower resources, defined as those projects with a potential generating capacity of ≤ 30 MW. Currently, this development is focused on retrofitting existing dams for hydroelectric generation, and at most of these sites, reservoir storage capacity is limited. Consequently, modifications in the natural flow regime will likely consist of short-term (e.g., $\Delta S/Q_i < 24\text{h}$; Eq. 1-1) rather than long-term temporal changes if the facility is operated in a peaking mode. If, instead, it is operated in a run-of-river mode, no changes in temporal flow patterns would be expected. Both peaking and run-of-river facilities can, depending upon their design, result in localized spatial changes in stream flow.

In summary, instream flow may be the most significant issue associated with small hydropower development. Unlike the other issues which are either very site-specific (e.g., fish passage, dredging) or related only to projects operated in a particular mode (e.g., water level fluctuations at peaking facilities), the instream flow issue can affect both peaking and those run-of-river projects that utilize long penstocks or canals. Moreover, maintenance of an instream flow regime may reduce the potential energy that can be produced, because water used to maintain instream flows is usually not available for power production (U.S. Department of Energy 1981). In most regions of the United States, hydroelectric generating systems are characterized by the seasonal mismatch between energy demand and stream flow. For example, in some basins like the Columbia River, which is fed by the

melting snowpack in late spring and summer, the lowest flows occur in the winter when energy demand is high (Schultz 1979 as cited in Shane 1981). Because the low flow period in many regions of the country, especially the East, typically occurs in late summer, it too coincides with a peak demand period.

In some cases, hydropower development can benefit the fishery resources in the stream or river. Where natural flows provide a suboptimal environment for fish growth and development (e.g., extended periods of low flow), stream flow regulation can enhance production. Storage capacity of reservoirs can be used to augment flows during periods of low stream discharge. The beneficial aspects of a proposed hydropower project in Alaska are described briefly in Section 4.2.3 (Case 2).

Finally, the instream flow issue is related to other ecological issues associated with hydroelectric development. For example, fish passage requires not only bypass facilities at the dam but also adequate stream flows below the dam. At peaking facilities, maintenance of an instream flow regime below the dam is obviously related to changes in reservoir levels above the dam (the water level fluctuation issue). The assessment of instream flow needs must be integrated with these and other relevant environmental considerations; the assessment cannot be conducted in an ecological vacuum.

2.0 EXISTING METHODS FOR INSTREAM FLOW ASSESSMENT

Resolution of the conflict between the instream use of water for hydroelectric generation and other instream uses, such as the maintenance of aquatic habitats, will require information on the flow regimes needed to preserve these habitats. Because numerous methods have been proposed to assess the instream flow needs for fishery resources, it is the purpose of this document to review and evaluate these methods and to recommend a strategy that can be used to assess instream flow needs at small-scale hydroelectric sites. In this way, small-scale hydroelectric developers will have greater access to the existing methods, and assessment studies can be conducted in a more cost-effective manner.

A variety of assessment methods were developed in response to the relatively recent emphasis that was placed on evaluating the biological effects of flow regulation. Our review is not meant to be totally comprehensive but rather is intended to provide a representative summary of approaches which are currently available for quantifying instream flow requirements. This information provides the background for later comparisons and recommendations. For more detailed information on individual techniques, the reader is referred to the list of references (Sect. 5.0). Other reviews of assessment methods for instream flow needs can be found in Stalnaker and Arnette (1976) and in Wesche and Rechar (1980).

Listed below are several general characteristics which are important in distinguishing among the various instream flow assessment methods:

- Use of existing stream flow records,
- Application of hydraulic simulation techniques,
- Use of habitat rating procedures to measure the physical condition of the lotic environment,

- Dimensionality used in mapping the instream habitat, and
- Ability to provide seasonal or species-specific instream flow recommendations.

These characteristics provide a focus for the information presented in this section and are discussed in detail in the comparative analysis presented in Section 3.0.

2.1 Fixed Percentage

The best known of the fixed percentage methods is the Montana Method developed by Tennant (1975, 1976). Because of its relative simplicity and minimal data requirements, the Montana Method is one of the most frequently used methods for determining instream flow needs. The procedure involves calculation of the mean annual flow rate (MAF) at a proposed development site and expression of the instream flow needs in terms of a fixed percentage of the mean annual flow (Tennant 1976). Various levels of flow needs, or what Tennant called "recommended base flow regimens," were identified, including flushing flows (200% MAF), optimum flows for all instream water uses (100 to 60% MAF), and a gradation of lesser conditions ranging from excellent (60 to 40%) to severe degradation (less than 10% MAF). The minimum instantaneous flow recommended to sustain short-term survival habitat for most aquatic biota is 10% MAF. At this flow, channel width, velocity, and depth are significantly reduced and the aquatic habitat is degraded.

The basis for the Montana Method consists of an extensive set of observations on streams in the states north of the Mason-Dixon Line between the Atlantic Ocean and the Rocky Mountains (Tennant 1976). The percentages established for flow needs reflect what has been interpreted to be a consistent relationship between watershed hydrology and physical habitat conditions within the stream channel.

Although the original guidelines include a recommendation that the proposed flow requirements be supported by field data, such as photographs of the proposed development site at critical flows, the method has often been applied with no field work.

Data required to apply a fixed percentage method such as the Montana Method are easily obtained from the published stream gaging records of the U.S. Geological Survey (USGS). Good techniques are available for extrapolating the MAF statistic upstream or downstream from existing gaging stations or estimating MAF on ungaged watersheds (e.g., Chow 1964, Linsley and Franzini 1972). However, because of the skewed nature of stream flow events (floods are relatively rare in occurrence but very significant in terms of their effect on mean flow values), a sound argument can be made for the fact that the median flow statistic is a more appropriate measure of central tendencies in hydrologic data than the mean flow. The median statistic has been used in other approaches to instream flow assessment (Sect. 2.2).

2.2 Constant Yield

The U.S. Fish and Wildlife Service (USFWS) in Region 5 recently issued guidelines (the New England Flow Recommendation Policy or NEFRP) that establish a process for formulating minimum flow recommendations by using a combination of the median flow and a constant yield statistic to represent watershed hydrology (U.S. Fish and Wildlife Service 1981, Knapp 1980). For unregulated streams with a drainage area greater than 130 km² (50 sq miles) and good historical flow records (>25 years and ±10% accuracy of gage), the median monthly flow (MMF) serves as the datum for evaluation of instream flow needs in the NEFRP. For streams that do not meet these criteria, a constant yield factor, runoff per watershed area, was calculated for the entire New England region and is applied to a specific site to estimate actual flow conditions (Table 2-1). The instream flow recommendation based on this policy is called the Aquatic Base Flow (ABF) and is

Table 2-1. Seasonal instream flow recommendations (= Aquatic Base Flows) for rivers in New England with different flow records. Values are expressed as $m^3/s/km^2$ and $ft^3/s/sq\ mile$ (in parentheses); MMF = median monthly flow. Source: U.S. Fish and Wildlife Service (1981).

Season	Availability of historical flow records	
	<25 years	>25 years ^a
Spring ^b (April - mid June)	0.29 (4.0)	100% MMF ^c
Summer (mid June - September)	0.04 (1.0)	100% MMF ^c
Fall/winter ^b (October - March)	0.07 (0.5)	100% MMF ^c

^aOther criteria, in addition to record length, that are used to decide whether to accept/reject the gaging record include: (1) $\pm 10\%$ accuracy, or better; (2) drainage basin is $>130\ km^2$ (50 sq miles); (3) river is unregulated.

^bSpawning/incubation periods.

^cIf reservoir inflow is $< MMF$, then outflow = inflow.

equal to the August MMF or $0.015 \text{ m}^3/\text{s}/\text{km}^2$ (cmsk). The ABF is assumed to be adequate for all periods of the year, unless additional releases are necessary for fish spawning and incubation (U.S. Fish and Wildlife Service 1981). Instream flow releases recommended during the spawning and incubation periods are presented in Table 2-1. Like the Montana Method, the NEFRP relies on flow statistics which can be obtained without extensive field surveys.

The ABF which is calculated by this procedure is recommended as the minimum instantaneous discharge immediately below the dam during normal runoff conditions. During low-flow periods when inflow to the reservoir is less than the ABF, minimum releases equal to the inflow are requested. The NEFRP is unique in that alternative proposals for the flow release locations, schedules, and supplies can be submitted by the developer. Provided that such proposals are supported by biological justification and are found to afford adequate protection to aquatic biota, USFWS personnel may incorporate all or part of such proposals into their recommendations (U.S. Fish and Wildlife Service 1981). Thus, the NEFRP supports the ABF as sufficient to maintain aquatic life but does not preclude the same maintenance (or level of protection) at lower flows (W. Knapp, personal communication).

Other variations of methods that use a constant yield factor as the basis for determining instream flow needs have been proposed by Robinson (1969) for the Connecticut River and by Chiang and Johnson (1976) for streams in Pennsylvania. Robinson's recommendations were somewhat lower than the present New England Flow Recommendation Policy: $0.091 \text{ m}^3/\text{s}/\text{km}^2$ (cmsk) or $1.24 \text{ ft}^3/\text{s}/\text{sq mile}$ (cfsm) for maximum fishery values and 0.026 cmsk (0.36 cfsm) for moderate fishery values. The recommendations of Chiang and Johnson (1976) were based on an even lower set of stream flow statistics, either the 7Q10 (minimum flow which persists for seven days once every ten years) or a yield factor of 0.011 cmsk (0.15 cfsm). These differences in minimum flow requirements reflect the lack of a general consensus on what flows satisfy the needs of aquatic ecosystems as well as differences in basin runoff characteristics.

2.3 Flow Duration Curves

Another approach that has been proposed for deriving instream flow recommendations from historical stream flow records uses flow duration analysis (Fig. 2-1). The concept of flow duration in descriptive hydrology is somewhat of a misnomer. It refers to the discharge level which is equaled or exceeded in a certain percentage of all stream flow observations (i.e., a cumulative probability density function of flow events), but incorporates no direct measure of how long the flow persists. When discussing low flows, the 90 percentile annual flow (calculated from the data set of mean daily flows) would be the stream flow which would be expected to be equaled or exceeded nine out of every ten days of the year. Given a data set of historical flow records, the calculation of percentile flows is a relatively simple procedure common to many applications of descriptive hydrology, including dam and reservoir design.

The Northern Great Plains Resource Program (NGPRP) proposed a method that utilizes stream flow records and flow duration analysis (Anonymous 1974). With this procedure, which requires at least 20 years of daily flow records, a flow recommendation is made for each month of the year to protect all aquatic resources potentially affected by stream flow regulation. Although this method was presented as being applicable to both warm and coldwater rivers in the Midwest, a caution was added that it will not necessarily protect against degradation of aquatic habitats which might occur from high temperatures or low dissolved oxygen during low flows in warm lowland streams.

The NGPRP method includes a step in which flow records are modified by using Student's t distribution to identify and eliminate abnormal events (floods and droughts). After high and low observations are removed from the record for each month, the instream flow recommendation is the flow that is equaled or exceeded by 90% of the observations remaining in the record. This same procedure is

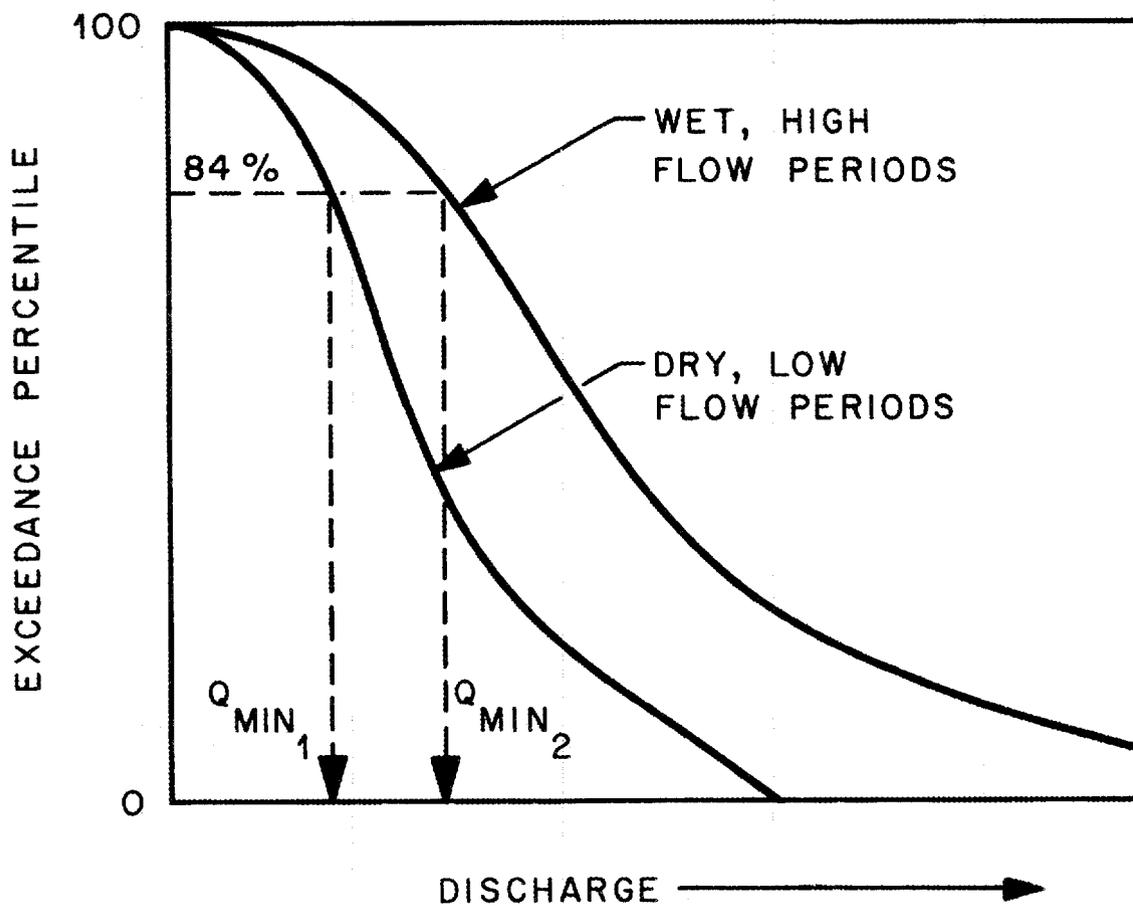


Fig. 2-1. Example of instream flow requirements (Q_{min}) based on flow duration data for two seasons with different hydrologic patterns.

repeated for all months except those in which high flows occur (i.e., the spring months). During high-flow months, the instream flow recommendation was set at the median flow of record (50 percentile).

The flow duration approach was developed for use on midwestern streams to satisfy assessment requirements in which extensive field data collection was not possible. However, it can be applied only where a relatively long historical flow record is available. The state of Iowa currently uses an instream flow policy based on the 84 percentile, annual low-flow statistic (Dougal 1979). Hoppe and Finnell (1970) also used a flow duration analysis on the Frying Pan River in Colorado, but they included equations to extrapolate flows to sites above or below USGS gaging stations based on watershed area.

2.4 U.S. Forest Service Habitat Evaluation

Several offices of the U.S. Forest Service (Regions 1, 2, and 4) developed assessment methods which examine the relationship between stream flow and physical parameters of the aquatic environment (Bartschi 1976, Cooper 1976, Isaacson 1976). All are used primarily in the mountainous, western United States on small, wadable streams (<50 m wide) with relatively low gradients. Site-specific field data (i.e., depth, velocity, and substrate type) are collected at one or more flows along transects across a stream channel and are used to describe the aquatic habitat. Transects are selected to be representative of specific types of stream habitat (e.g., riffles, pools, runs, etc.) which might be affected by alterations in flow. The eventual recommendations for instream flows are based on the actual habitat conditions at a site rather than on stream flow statistics, which were the basis of the three methods discussed previously.

Among the various regional approaches used by the U.S. Forest Service, there are differences in the way in which physical data are obtained and used to describe aquatic habitat. Transect data can be

collected either at several different discharges covering the entire range of conditions to be analyzed or at one discharge and then used to calibrate a simulation model which can predict conditions at other discharges. The second approach using hydraulic simulation requires significantly less field work to construct a habitat-discharge curve (see Sect. 2.4.3). Other regional differences are associated with the specific attributes that are used to represent instream habitat conditions.

2.4.1 Habitat-Discharge Curves

Several physical parameters were suggested as the flow-dependent variable to be used in developing habitat-discharge relationships (Bartschi 1976). These attributes can include such hydraulic parameters as stream surface width, wetted perimeter, average water velocity, maximum depth, or cross-sectional area at each transect. Presentation of the data is then made in a graphic format with discharge represented on the "x" axis and the habitat parameter on the "y" axis. For example, in situations where a fisheries biologist is concerned about instream flow needs for fish growth and rearing, wetted perimeter might be chosen to represent habitat condition, under the assumption that food production is proportional to bottom surface area. The habitat-discharge relationship can then be represented as relative changes from some reference flow (Fig. 2-2a) or in absolute terms (Fig. 2-2b).

Two different approaches were used to derive instream flow recommendations from the habitat response curves. The minimum discharge can be set at the flow which produces a fixed percentage reduction from a reference flow in a particular habitat attribute (e.g., 20% reduction in wetted perimeter is maximum degradation allowable; Bartschi 1976). This approach is called a habitat retention criterion. The second approach, which is also included in several other assessment methods, relies on determination of the "inflection point" on a habitat-discharge response curve (e.g., point

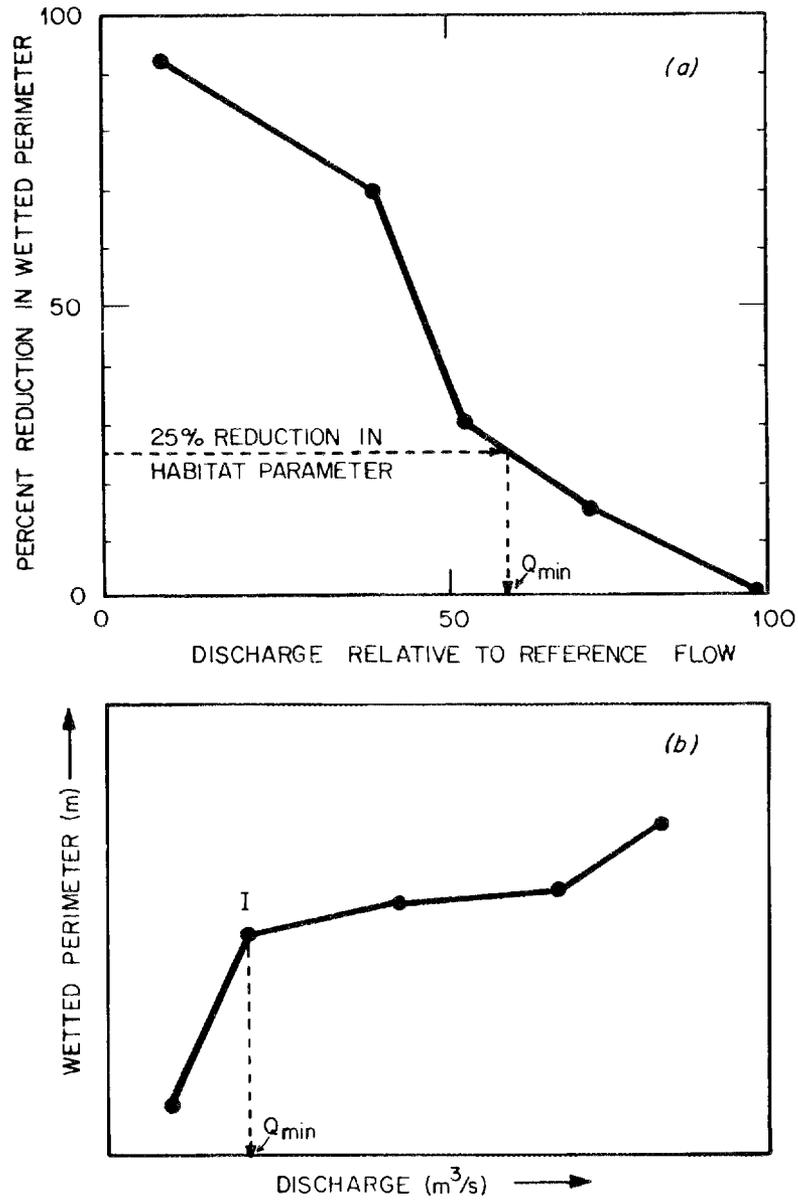


Fig. 2-2. Examples of habitat-discharge relationships developed from U.S. Forest Service procedures: (a) habitat retention criterion, and (b) inflection point (I) criterion.

'I' in Fig. 2-2b). The interpretation of the inflection point on a habitat-discharge curve is somewhat different from the formal definition; it is defined simply as the point where a major change in slope occurs. This approach represents an attempt to use the rate of change in a physical habitat attribute (e.g., meters of wetted perimeter per unit flow) to identify a threshold below which conditions are most rapidly degraded (see Sect. 3.4).

In addition to methods that measure single attributes of habitat condition, U.S. Forest Service personnel developed aggregative indices of habitat quality that incorporate multiple aspects of the aquatic environment (Dunham and Collotzi 1975, Cooper 1976). These procedures are also oriented toward transect-type data sets, but rely on the assignment of nonparametric ratings to "quantify" subjective evaluations by field personnel. Each of four components of habitat, pool measure (percentage of stream width with pool-type habitat), pool structure (quality of pool habitat based on depth, cover, etc.), substrate type, and riparian environment, is rated by assignment of an integer value between 1 and 4. The average of these four variables represents the habitat value index. This procedure is repeated for several different flow conditions, and a graph similar to that shown in Fig. 2-2a is constructed. The instream flow requirement is the discharge that results in 80% of the habitat index at a bank-full reference flow.

2.4.2 Simplified Staff-Gage Analysis

Efforts to develop a relatively simple field method for quantifying the relationship between habitat condition and stream flow led to what can be called staff-gage analyses. This approach is based on a stage-discharge curve similar to that used at USGS stream gaging stations, but a slightly different emphasis is placed on transect location. In contrast to the USGS hydraulic criteria for selecting a transect site, ecological criteria are used, preferably by a qualified fisheries biologist, to identify critical habitat for a target species

or life stage in the affected stream. The staff gage, a graduated stick set vertically into the water column, is established at a location representative of this critical habitat. The stage (water surface elevation) is read from the staff gage at several known flows.

An instream flow requirement can be determined by applying a specified habitat criterion (e.g., minimum depth threshold) at the gage location. If upstream control of the stream flow is available and flow rates are known, this analysis can be as simple as raising or lowering the flow until the habitat threshold is satisfied. However, in many other situations, upstream controls will not be available or flow rates will not be known. In these cases, data consisting of discharge measurements and stage heights must be collected. To extrapolate to an unobserved flow which satisfies the habitat threshold, an empirical stage-discharge relationship is derived, either graphically or by calibrating a power function equation:

$$H = a Q^b, \quad (2-1)$$

where H = stage (water surface elevation read from staff gage),

Q = discharge, and

a, b = regression coefficients fitted to field data.

Wesche and Rechard (1980) reported that this type of staff-gage analysis was used by the Bureau of Land Management. Personnel of the U.S. Fish and Wildlife Service also experimented with this technique at small hydroelectric sites in New England (G. Beckett, personal communication).

2.4.3 R-2 Cross

The Region 2 office of the U.S. Forest Service in Lakeland, Colorado, originally developed this analytical procedure for predicting the hydraulic conditions which could be expected at unobserved discharges. All calculations are based on the Manning

Equation (Eq. 2-2) for open channel flow and are used to describe the conditions at a single transect (Stalnaker and Arnette 1976).

$$Q = \frac{1}{n} \cdot A \cdot R^{2/3} \cdot S^{1/2}, \quad (2-2)$$

where Q = discharge (m^3/s),
 n = roughness coefficient,
 A = cross-sectional area (m^2),
 R = hydraulic radius (m) = A /wetted perimeter, and
 S = energy slope.

The Manning Equation can also be written as

$$V = \frac{1}{n} \cdot R^{2/3} \cdot S^{1/2}, \quad (2-3)$$

where V = mean velocity across transect (m/s).

Field data consisting of cross-sectional profiles (transverse distance and elevation), velocity measurements, and water surface slope in the vicinity of a transect are used to calculate the roughness coefficient, n , in Eq. 2-2. Assuming the values of n and S are independent of flow, an iterative computer program can then be applied to find values for average velocity, wetted perimeter, cross-sectional area, maximum depth, or hydraulic radius at discharges other than that observed in the calibration data set. These data are then used to derive a habitat-discharge curve (Sect. 2.4.1) with a minimum of field work. The identification of critical areas along a stream reach and proper transect placement remain important prerequisites with this method. Also, significant errors can result from using R-2 Cross to predict hydraulic conditions at flows greater than 250% or less than 40% of the calibration flow (Bovee and Milhous 1978).

Modifications to the original R-2 Cross model were made to relax some of the simplifying assumptions involved in applying Eq. 2-2 (Wesche and Rechar 1980). The Manning Equation was developed as an empirical description of uniform flows in open channels. In the original model, slope and roughness coefficients are assumed to be independent of stream discharge. However, both of these parameters change as a function of discharge at most locations in natural stream channels. To use this model in a more realistic manner, empirical equations have been proposed which make roughness and slope functions of hydraulic parameters such as Q or R (see Sect. 3.1).

Development of instream flow recommendations with R-2 Cross is essentially the same as that with other habitat evaluation methods. Habitat-discharge curves are drawn, and either a habitat retention criterion [e.g., 25% reduction (or 75% retention) of a habitat attribute from optimum or reference conditions] or an inflection point criterion is applied. The use of this method is restricted to narrow, wadable streams with low roughness (uniform or gradually varied flow).

2.5 WSP Hydraulic Simulation

This method is based on a step-backwater, hydraulic simulation model, Water Surface Profile (WSP), developed by the Bureau of Reclamation. The original purpose of the WSP model was to predict water surface elevations for flood routing problems (the HEC-2 model developed by the U.S. Army Corps of Engineers and PSEUDO developed by the Bureau of Land Management are other examples of this type of simulation model). It has been adapted to instream flow management problems in many of the same ways that R-2 Cross has been used; i.e., to predict changes in physical habitat parameters such as depths, velocities, and wetted perimeter with varying stream discharge (White 1976, Cochnauer 1976, Dooley 1976, Elser 1976, Workman 1976, Bovee and Milhous 1978). The advantage of using this method instead of R-2 Cross is that it uses a more sophisticated approach in modeling open

channel flows and can develop a more detailed, multitransect map of the stream environment.

The WSP model employs three basic equations to represent hydraulic dynamics: (1) continuity or conservation of discharge between transects, (2) Manning's Equation (Eq. 2-2), and (3) Bernoulli Energy Equation (Eq. 2-4).

$$H = z + d + v^2/2g, \quad (2-4)$$

where H = total energy head (m),
 z = elevation of the stream bed,
 d = average depth (m),
 v = average velocity (m/s), and
 g = force of gravity on water.

These three equations are used to link transect data together to predict depths and velocities longitudinally through a stream reach (Bovee and Milhous 1978). The Bernoulli Equation is used to calculate the change in energy head between transects and the energy slope, S (change in H per longitudinal distance downstream) that is required in the Manning Equation. A "step-backwater" procedure is used to balance energy losses in an iterative process that predicts water surface elevations beginning at the downstream transect and proceeding upstream. The adaptation of the WSP hydraulic simulation method to instream flow analysis may include an additional step of predicting mean water column velocities for multiple subsections of each transect. The use of the step-backwater procedure to predict velocity distributions is the most significant new aspect of WSP applications and requires careful calibration to assure accuracy (Bovee and Milhous 1978). The limitations of this modeling approach are discussed in greater detail in Sect. 3.1.1.

The generation of instream flow recommendations from WSP simulations involves the same type of habitat-discharge curve

development described in Sect. 2.4.1. This method has been found to be particularly desirable in modeling large, unwadable rivers without historical flow records (White 1976).

2.6 Usable Width

The terms 'usable width' and 'weighted usable width' originated from assessment methods developed for coldwater, salmonid streams in Oregon (Thompson 1972, 1974; Sams and Pearson 1963). The usable width method is oriented to single transects across critical locations in the stream channel where limiting habitat (e.g., spawning beds) occurs. Instream habitat condition is quantified as the percentage of the total stream width which is "usable," as determined by target fish species, life stage-specific criteria, and field survey data. Habitat-discharge relationships are obtained by repeating transect surveys at several discharges. Originally, the method did not include simulation techniques.

This type of approach is used for assessing flow requirements for fish passage, spawning, incubation, and rearing (i.e., growth and feeding). Applications are limited primarily to salmonid species. Habitat criteria consist of velocities and depths that are associated with the presence of fish. The difference between the usable width (UW) and weighted usable width (WUW) methods lies with the type of criteria used to define habitat usability. The former employs a binary criterion (usable or unusable); for example, portions of the transect that are less than a minimum depth criterion and exceed some maximum velocity criterion have no habitat value. Examples of these criteria for several salmonid species are given in Table 2-2.

Table 2-2. Binary habitat criteria for salmonid passage (from Thompson 1972)

Species	Habitat criteria	
	Minimum depth (m)	Maximum velocity (m/s)
Chinook salmon	0.24	2.44
Coho and chum salmon, steelhead and large trout	0.18	2.44
Other trout	0.12	1.22

To calculate WUW, on the other hand, the stream transect is uniformly divided into sections, each with a width, average depth, and average velocity. The width of each section of the transect is then multiplied by velocity and depth weighting factors which quantify, in relative terms, the habitat value of each subsection and can vary between 0.0 and 1.0 (Fig. 2-3). This product is summed for each section to compute the WUW for the transect:

$$WUW = \sum_{i=1}^n W(v_i) \cdot W(d_i) \cdot l_i, \quad (2-5)$$

where $W(v_i)$ = weighting factor for mean velocity
in the i^{th} section,

$W(d_i)$ = weighting factor for mean depth
in the i^{th} section,

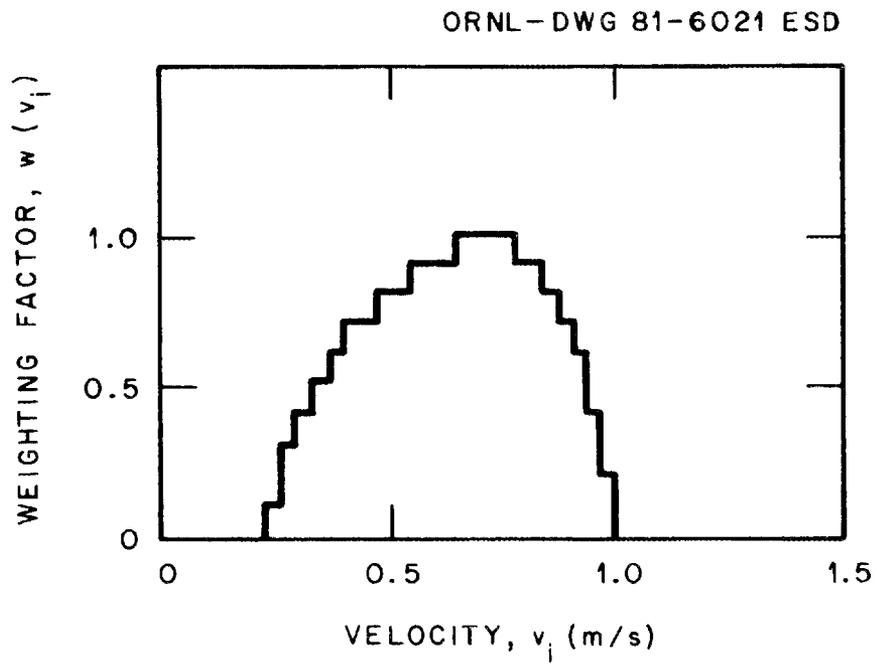


Fig. 2-3. Example of variable weighting factors used in calculating Weighted Usable Width (from Waters 1976).

l_i = width of the i^{th} section, and
 n = total number of sections along the transect.

It should be noted that if both weighting factors are given values of one or if one or both are equal to zero, then WUW is equivalent to UW. The techniques used to specify weighting factors have ranged from quantitative expressions based on the opinion of fisheries experts to a probabilistic function of fish presence (e.g., Bovee and Cochnauer 1977). In all applications of habitat weighting criteria, however, care should be taken to ensure that the site-specific preferences of fish are addressed as accurately as possible. If existing weighting functions originally developed in other geographic areas are used in an instream flow study, justification for their applicability to local fish populations should be provided.

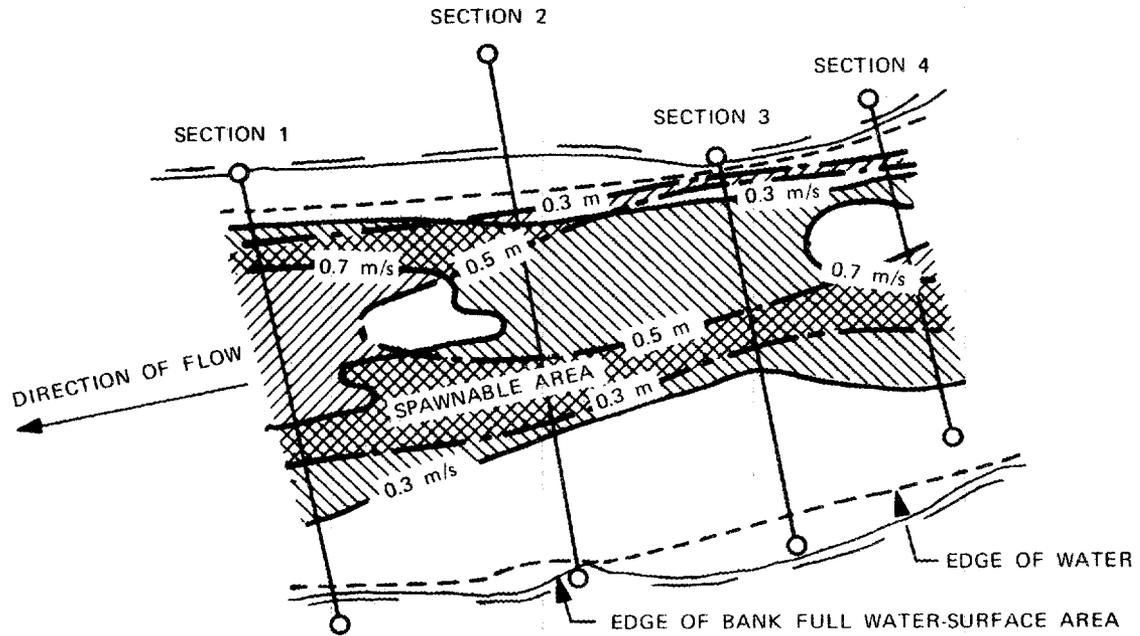
Instream flow recommendations derived from usable width methods are made by examination of the UW vs discharge curves. The minimum acceptable flow for salmonid migration (passage) is that flow which meets the minimum depth and maximum velocity criteria on at least 25% of the total transect width and on a continuous portion equalling at least 10% of the total width (Thompson 1972). An optimum spawning flow provides suitable flow conditions, with respect to the selected depth and velocity criteria, over the most gravel at critical spawning transects. The discharge that provides suitable flow conditions over 80% of the gravel available at the optimum flow is the minimum requirement for spawning. A major strength of the usable width approaches is that flow recommendations can be made on a seasonal basis with time-variable life stage requirements. An important component of this type of instream flow assessment is the construction of a periodicity chart which indicates the life stages present in each season.

2.7 Preferred Area

Two methods that quantify physical habitat in terms of preferred areas have contributed significantly to the development of instream flow assessment. Both increase the dimensionality of analysis compared to the usable width approaches by using multiple transect data and measuring habitat in units of area rather than of width.

The Washington Department of Fisheries, in cooperation with the USGS, applied a two-dimensional mapping technique, referred to as the Washington Method, to quantify the area of streambed available for salmon spawning (Collings 1972, 1974). Biological criteria for spawning consist of upper and lower bounds on preferred depths and velocities. Depth and velocity measurements are taken across four transects at a potential spawning site, and isopleth maps of the streambed are constructed to show the distribution of hydraulic parameters at a fixed discharge (Fig. 2-4). Areas satisfying both the velocity and depth criteria are designated as spawnable portions of the stream. This procedure is repeated for a minimum of five different stream flow conditions to develop a response curve of spawnable area vs discharge over the range of flows of interest. No hydraulic modeling is used in predicting depths or velocities. The preferred spawning flow is defined as the flow with the maximum spawnable area. Instream flow requirements are set at the flow which maintains 75% of the maximum spawning area. This type of flow recommendation is another example of a habitat retention criterion.

A second approach to quantifying instream habitat on an areal basis was developed by fisheries biologists of the Pacific Gas and Electric Company (Waters 1976). This work, which was initiated in the 1950's in California, predates all of the methods discussed previously. Like the Washington Method, two-dimensional maps of the stream environment are developed from transect data, but continuous weighting criteria for velocity and depth are used to calculate habitat values. Again, no hydraulic simulation modeling is used to



PREFERRED AREA FOR SALMON SPAWNING

- 1.) DISCHARGE = $2.7 \text{ m}^3/\text{s}$
- 2.) PREFERRED SPAWNING DEPTH (0.3 - 0.5m) = 97.1m^2
- 3.) PREFERRED SPAWNING VELOCITY (0.3 - 0.7m/s) = 158.5m^2
- 4.) TOTAL PREFERRED SPAWNING AREA WITH COMBINED DEPTH-VELOCITY CRITERIA = 67.4m^2

Fig. 2-4. Example of preferred area calculations using the Washington Method (modified from Collings 1972).

predict conditions at flows other than those observed. The habitat quality index used with this method is referred to as Net Preferred Habitat (NPH) and is calculated as:

$$\text{NPH} = \sum_{i=1}^n v_i \cdot d_i \cdot \Delta a_i, \quad (2-6)$$

where v_i = velocity weighting factor between 0 and 1,
 d_i = depth weighting factor between 0 and 1,
 Δa_i = bottom surface area of i^{th} element of stream reach, and
 n = number of elements in stream reach.

2.8 IFG Incremental Methodology

The Cooperative Instream Flow Service Group (IFG) of the U.S. Fish and Wildlife Service developed a set of habitat evaluation procedures known as the Incremental Methodology (Stalnaker 1978, 1979b; Trihey 1979). A package of computer programs, collectively called PHABSIM (Physical HABitat SIMulation system), is used to implement this analysis of instream flow needs (Fig. 2-5). The overall approach combines (1) multiple-transect field data from a representative and/or critical river reach, (2) hydraulic simulation models to predict physical habitat parameters such as mean velocity (\bar{v}), depth (\bar{d}), and substrate (\bar{s}), and (3) species-specific suitability functions (S_v , S_d , S_s) similar to those first described by Waters (1976). Suitability functions are used to calculate weighting coefficients representing the habitat preferences of various life stages of target fish species. Finally, measures of habitat suitability and availability (as wetted surface area, \bar{a}_i) are used in the computation of Weighted Usable Area (WUA), an index of habitat condition. This index is computed for each life stage [e.g., spawning (S), fry (F), juvenile (J), and adult (A)] and can be plotted against discharge (Fig. 2-5). The intent in developing the Incremental

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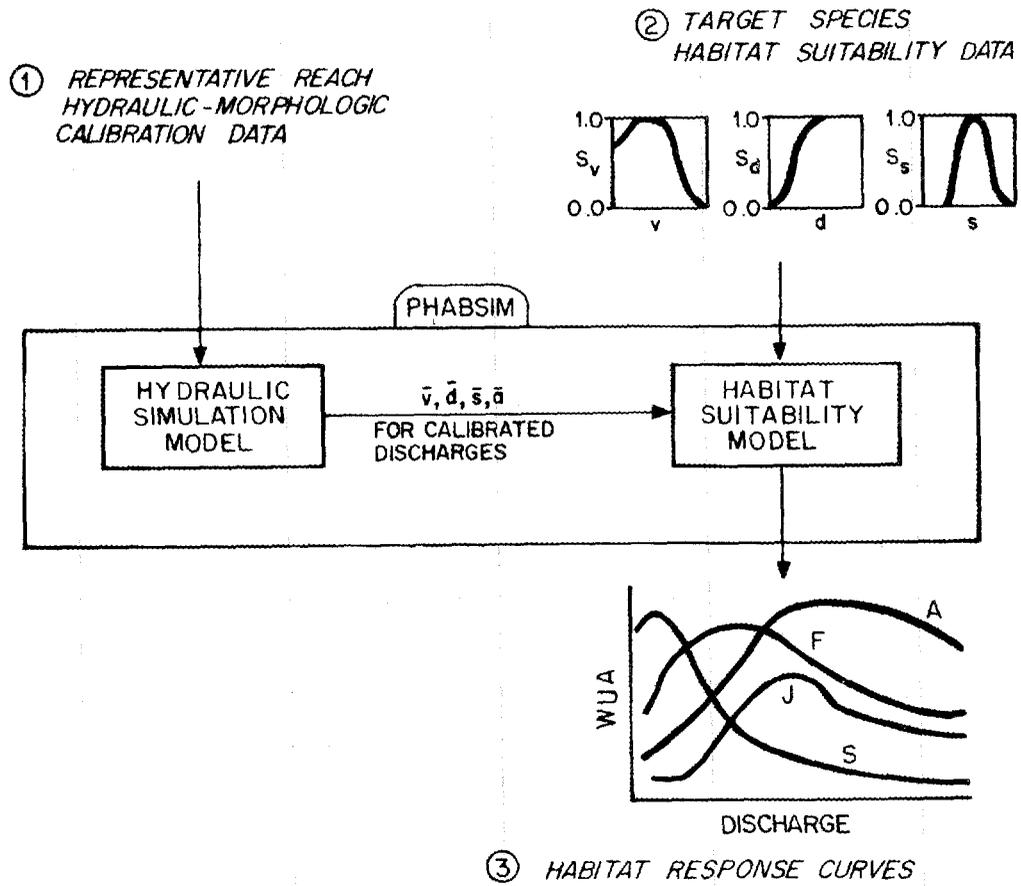


Fig. 2-5. Organization and information processing in the Incremental Methodology for instream flow assessment (from Sale 1980).

Methodology was to create a "state-of-the-art" analytical tool for addressing instream flow questions. Therefore, it incorporates many of the aspects of the methods developed earlier and described in Sections 2.1 to 2.7.

Hydraulic simulation in PHABSIM applications can be carried out using one of two different modeling techniques (Bovee and Milhous 1978, Wegner 1980). The first model of open channel flow, IFG-2, is a step-backwater procedure similar to the WSP model described in Section 2.5. Calibration can be accomplished using one set of velocity/depth transect data if limitations are placed on the range of flows that can be simulated (Bovee and Milhous 1978). Additional calibration steps are necessary beyond normal WSP procedures to maximize the accuracy of velocity predictions in individual cells of each transect (Bovee and Milhous 1978, Wegner 1980).

The second option for hydraulic simulation is IFG-4, a modified stage-discharge regression procedure (Wegner 1980). This model requires two or more (optimally three or more) sets of transect data from distinctly different discharge conditions to achieve good model calibrations (Bovee and Milhous 1978). Individual rating curves are calculated for the stage-discharge and velocity-discharge relationships in each cell along each transect of the representative reach. Although more field data are needed with this approach, the IFG-4 model is relatively less complicated to calibrate and more flexible than WSP in handling more difficult flow conditions (i.e., unsteady or nonuniform flows).

The attribute used to quantify bottom substrate in the Incremental Methodology is a relative index related to Wentworth particle size (Bovee and Cochnauer 1977; Trihey 1979). A coding system is usually established in which substrate types are assigned integer values ranging from 1 to 9; for example, plant detritus, mud, silt, sand, gravel, rubble, boulder, and bedrock bottom types are assigned values of 1 to 8, respectively. Substrate suitability curves are based on this system. Many variations are possible in coding

substrate type, including combinations where integer values represent dominant particle size in each mapping cell, and decimal values represent either characteristics of the matrix of smaller sediments in which larger substrate elements are embedded or cover characteristics in each mapping cell (i.e., overhanging vegetation, depth cover, proximity to large boulders, etc.; Bovee 1980). A great deal of flexibility can be incorporated into the substrate index, but as more complexity is included (e.g., addition of substrate and cover), more detailed transect surveys are required. Water temperature is another physical habitat parameter which has been included in calculating WUA indices (Bovee and Cochnauer 1977, Sheppard 1980).

The final output of PHABSIM is usually in the form of either a tabular or graphic relationship between stream flow and Weighted Usable Area (WUA). The calculation of WUA combines a measure of the quality of the physical instream habitat with a quantification of habitat availability by subdividing a stream reach into a matrix of rectangular cells (Fig. 2-6, Eq. 2-7).

$$WUA = \sum_i \hat{S}_i \cdot a_i, \quad (2-7)$$

where \hat{S}_i = composite habitat suitability of the *i*th mapping cell,
and
 a_i = surface area of the *i*th mapping cell.

A computer program, HABTAT (or IFG-3), calculates WUA values based on the mean velocity, depth, and substrate data (\bar{v} , \bar{d} , \bar{s}) predicted from hydraulic simulations. Composite habitat suitability, which is the measure of habitat quality, is a multivariate function of the physical parameters of each cell (Eq. 2-8). Several different techniques for calculating \hat{S}_i have been proposed (Orth 1980, Wegner 1980, Voos et al. 1981). The most frequently used composite suitability equation assumes independence among physical parameters and has the following form:

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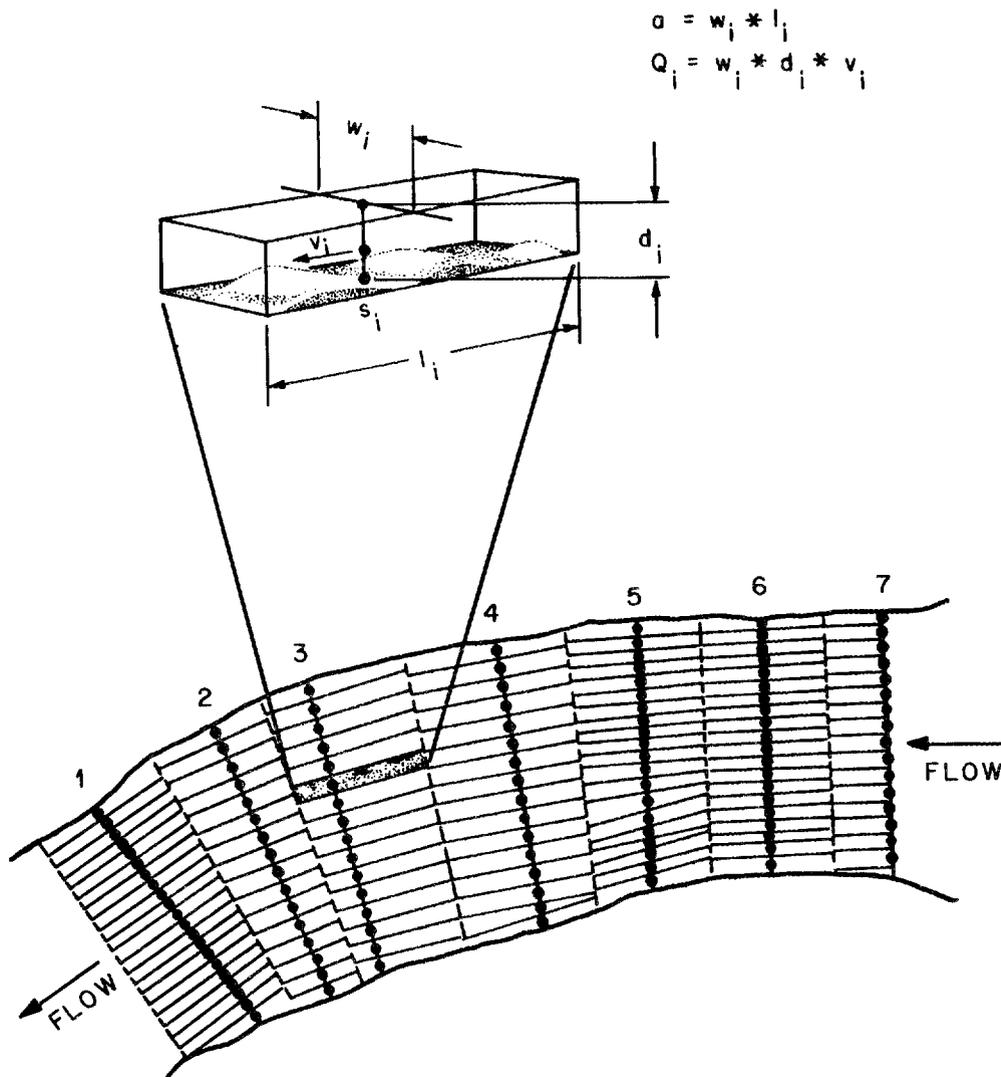


Fig. 2-6. Subdivision of a stream reach into transects and mapping cells for computational purposes with the Incremental Methodology (modified from Bovee and Cochnauer 1977 and Hilgert 1981).

$$\hat{S}_i = S_V(v_i) \cdot S_d(d_i) \cdot S_s(s_i), \quad (2-8)$$

where $S_V(\cdot)$, $S_d(\cdot)$, and $S_s(\cdot)$ = univariate suitability functions predetermined for each target fish species and life stage.

All suitability functions have values between 0.0 and 1.0 (Fig. 2-7). The univariate suitability functions used in calculating WUA can be developed in a variety of ways (Bovee and Cochnauer 1977, Voos et al. 1980). These include the use of field observations, literature sources, and ad hoc or Delphi-type procedures (e.g., Dakley and Helmer 1963). A source file of suitability functions for more than 50 warmwater and coldwater fish species (up to five life stages for each), some families of aquatic insects, and recreational activities such as boating and fishing is maintained by the IFG. Quality ratings (called evaluation criteria by IFG; Bovee and Cochnauer 1977) for all suitability curves in the IFG data base indicate the information source used to construct the curves and provide an excellent way to document the confidence to be placed on analyses made with their use. However, access to the IFG data base is limited to encourage the development of site-specific habitat preference data.

Two alternative methods were proposed for utilizing the WUA information to develop instream flow recommendations. The first method, which was developed by IFG and U.S. Fish and Wildlife Service users, is essentially an examination of the relative change in WUA from optimal conditions with respect to discharge (K. Bovee, personal communication). The discharge level between the monthly median flow and the 90 percentile monthly flow that results in the smallest reduction in WUA relative to the optimum is set as the instream flow requirement for each life stage of a target species. This analysis is

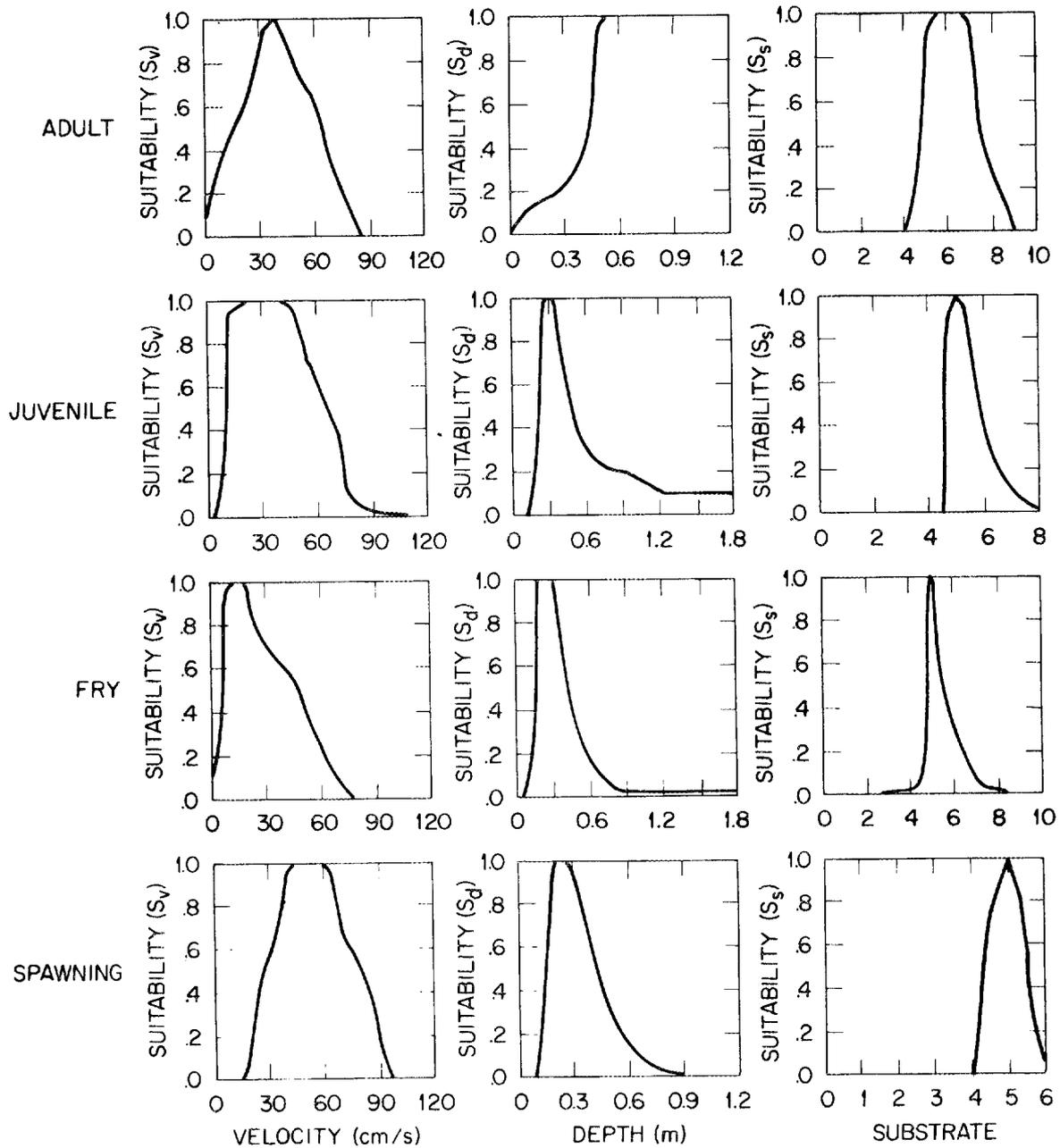


Fig. 2-7. Univariate suitability curves for rainbow trout (*Salmo gairdneri*) (modified from Bovee 1978).

repeated for each month that a life stage is present and for each target species and life stage of interest. The discharge level which results in the lowest relative change for all species and life stages is often used as the overall minimum flow recommendation for each month. An instream flow regime can be generated by using this procedure for each month of the year. No computer programs have been developed to aid in these computations.

A second application of the WUA-discharge curves was used to provide instream flow recommendations for Illinois streams (Herricks et al. 1980) and to analyze the impacts of reservoir operation schedules (Milhous and Bovee 1978). This approach is analogous to the flow-duration calculations common in descriptive hydrology. A daily flow record is first obtained for the representative stream reach, either from historical, pre-project data or from modification of those data by hypothetical storage and release specifications at a proposed reservoir. Next, the daily flow record is converted to a record of daily WUA values by using the habitat-discharge response curves produced by the Incremental Methodology. This procedure is carried out for different life stages of target species for only those seasons in which they are present. Habitat duration, the percentage of days in which WUA equals or exceeds various levels, is then calculated on either a weekly, monthly, or annual basis.

An instream flow recommendation can also be set at the discharge level which provides a fixed percentile habitat quality (e.g., the minimum monthly flow is the flow which provides the 80 percentile WUA value based on historical records). This habitat-duration approach provides the best available quantification of baseline or preproject habitat conditions against which instream flow recommendations can be made. This type of analysis can be organized into a nomographic calculation by plotting the habitat-discharge response curve and habitat-duration curve on the same set of axes (Fig. 2-8).

The Incremental Methodology is often described as "state-of-the-art" with regard to instream flow assessment methods. However, it

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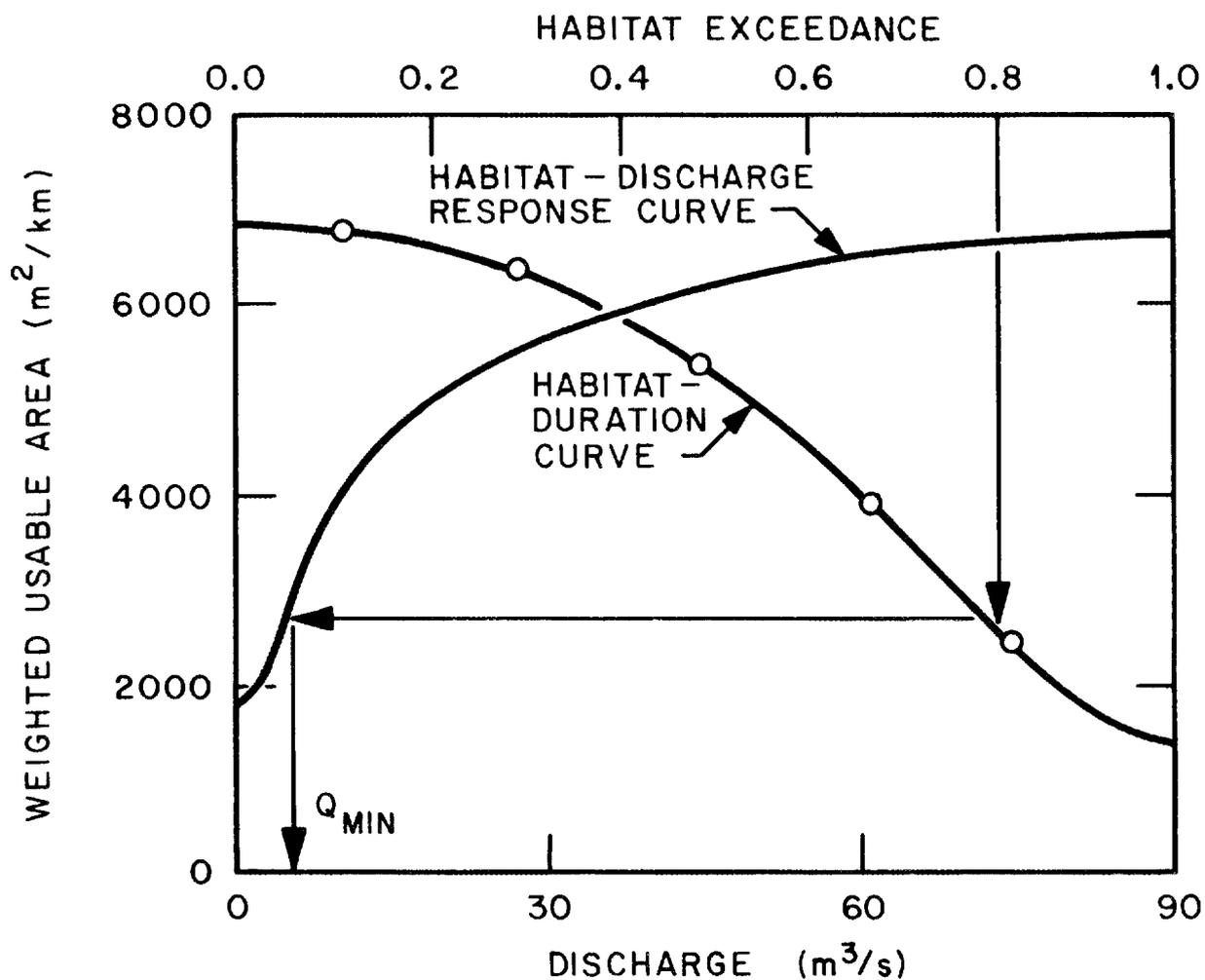


Fig. 2-8. Nomograph calculation of an instream flow recommendation using habitat-duration data and assuming a decision criterion to retain the 80 percentile habitat condition.

also may carry the connotation of being an excessively complex and time-consuming analysis. This latter point of view overlooks the fact that, where appropriate, components of PHABSIM and other software developed by the IFG can be used in more simplistic assessments. For instance, the IFG-4 hydraulic simulation package includes an option to output channel widths with depths equaling or exceeding specified habitat criteria in a manner analogous to the Usable Width method developed in Oregon. The IFG-4 model can also be used on single-transect data with or without the HABTAT program. A computer program called IFG-1 is available which is a slightly modified version of R-2 Cross. Therefore, for an experienced user, the computer packages which have been developed by the IFG provide a truly flexible set of assessment tools for instream flow assessment problems.

2.9 Summary of Available Methods

The five characteristics listed at the beginning of this section can be used to summarize the instream flow assessment methods currently available (Table 2-3). Distinct differences exist in the capabilities of the various methods. For instance, the first three approaches listed in Table 2-3 can be grouped into a category called discharge methods because decisions concerning instream flow needs are based only on historical flow records. The most detailed and the preferred approach in this group would be one based on flow duration data, because this statistic is the most realistic representation of natural stream flow variability at a given site (Stalnaker and Arnette 1976).

A second category of instream flow methods, hydraulic rating methods, includes all the procedures that examine hydraulic parameters for the purpose of developing generalized habitat-discharge relationships. Both single and multiple transect methods can be included in this group if species-specific habitat preferences are not

Table 2-3. Summary of existing instream flow assessment methods

Method	Characteristics				
	Stream flow records	Hydraulic simulation	Habitat rating	Transect data ^a	Species or seasonal specificity
Fixed Percentage (e.g., Montana)	Yes	No	No	None	Little or none
Constant Yield (e.g., NEFRP)	Yes	No	No	None	Some seasonal
Flow Duration	Yes	No	No	None	Some seasonal
USFWS Habitat Evaluation	No	No	Some indirect	Single or multiple	Some species
Stage-discharge Analysis (e.g., R-2 Cross)	No	Yes (Manning's Eq.)	Indirect	Single v/d	No
WSP Simulation (Idaho)	No	Yes (WSP)	Indirect (wetted perimeter)	Multiple v/d	No
Usable Width (Oregon and modifications)	No	No	Yes	Single v/d	Yes
Preferred Area (California and Washington)	No	No	Yes	Multiple v/d/s	Yes
PHABSIM (IFG's Incremental Methodology and modifications)	Some	Yes (WSP or IFG4)	Yes	Multiple v/d/s/c/t	Yes

^av = velocity; d = depth; s = substrate; c = cover; t = temperature

evaluated. This group does not involve as much field work as the most data-intensive approaches (e.g., the Incremental Methodology), nor does it utilize stream flow records directly to quantify baseline conditions. The most significant capabilities of this group are (1) introduction of simplified prediction techniques to reduce field survey needs and (2) ability to examine site-specific aspects of streambed morphology. Methods based on stage-discharge, hydraulic rating curves and the Manning Equation, when used within the limits of extrapolation to unobserved flow conditions, are probably the best examples from this group.

The third category includes those methods that apply species-specific habitat criteria in evaluating the condition of a stream environment. The Incremental Methodology is the best example of this group because it combines the habitat weighting concepts first developed in California, Oregon, and Washington with detailed hydraulic simulation models. When stream flow records are used to derive instream flow recommendations from the Incremental Methodology, all five characteristics can be included in the assessment.

These three categories do not include all the methods developed to assess instream flow needs for fishery resources. For example, in some western streams where water quality has been identified as a limiting factor for incubation of salmonid eggs, specialized methods were developed to measure interstitial dissolved oxygen concentrations (Stalnaker and Arnette 1976). The three-tiered categorization, suggested here for purposes of simplification, provides a framework for discussing those methods that will be most useful in assessments of instream flow requirements at small-scale hydroelectric projects.

3. CRITICAL EVALUATION OF EXISTING METHODS FOR INSTREAM FLOW ASSESSMENT

The purpose of this section is to compare and contrast existing instream flow assessment methods. The material presented in Section 2.0, combined with more detailed information available in appropriate references, provides the basis for this evaluation. The recommendations made in Section 4.0 are a reflection of the conclusions presented in this section.

Environmental impacts which result from flow regulation at hydroelectric facilities can be represented in a simplified chain of effects that includes three stages: (1) initial changes in the discharge regime due to project operation, (2) alteration of the physical habitat in the downstream lotic environment, and (3) biological response of the affected aquatic ecosystem (Fig. 3-1). This conceptual model may be oversimplified to some degree, but it provides a useful perspective for describing the capabilities of various assessment methods. Methods used to develop instream flow recommendations which do not analyze the entire impact chain must rely on implicit assumptions about the behavior of regulated stream ecosystems. These assumptions are described more completely in Section 3.1.

Other characteristics that are important in the selection of an appropriate method for a specific application include data requirements for implementation (Sect. 3.2), dollar costs (Sect. 3.3), and decision-making capabilities (Sect. 3.4). For the sake of clarity, discussions of these various characteristics emphasize a three-way classification of methods whenever practical. The three principle types of methods are (1) discharge methods, (2) single-transect methods which develop some type of hydraulic rating analysis (i.e., depth vs discharge or wetted perimeter vs discharge) but stop short of a more detailed analysis, and (3) multiple-transect, habitat rating methods.

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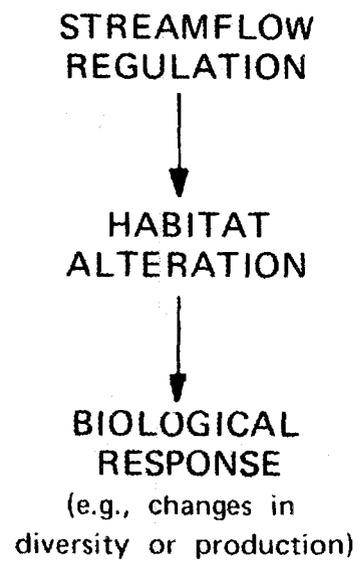


Fig. 3-1. Conceptual basis for instream flow assessment.

3.1 Implicit Assumptions

All of the assessment methods discussed in Section 2.0 involve certain assumptions about stream environments and the behavior of riverine (lotic) ecosystems. A clear understanding of these assumptions is an important prerequisite to selection and application of these methods. In a general sense, the assumptions to be examined fall into one of two categories: those related to the physical behavior of the river system, including its hydraulics and channel morphology, and those associated with prediction of the biological response to alterations in stream flow and habitat condition.

3.1.1 Hydraulics and Channel Morphology

Assumptions related to stream hydraulics or channel morphology are important in two situations: (1) specification of thresholds to be used in developing instream flow recommendations and (2) selection of hydraulic simulation models to predict depth and velocity at unobserved stream flows. The definition of thresholds is most obvious in the discharge approaches (e.g., Montana Method, New England Flow Recommendation Policy, or flow-duration analysis). When Tennant (1976) established 10% MAF as a minimum acceptable flow, it was based on the hypothesis that the amount of water will fill the stream channel to a width and depth adequate to assure short-term survival of aquatic biota. This empirical threshold was determined from observations on a large number of watersheds across the United States.

Hydrologic analyses that described the natural variability in stream flow were the basis of early attempts to establish instream flow requirements. From these analyses arose the concept of the 7Q10 (Sect. 2.2), a statistic that has been used as a criterion to design waste treatment facilities and one that has been offered as a "rule of thumb" for the minimum flow that would assure adequate water quality (Stalnaker 1979a). Although it was developed for water quality purposes and has no ecological basis, it, nevertheless, is still often

used to determine instream releases below hydroelectric projects. Use of the 7Q10 statistic in this manner ignores the dynamic nature of fishery requirements and the long-term recovery that is necessary after such a severe low-flow period (Stalnaker 1979a, 1981). While it may be very conservative for designing water treatment facilities, it is not conservative for protecting fishery resources (K. Bovee, personal communication). Use of a single "minimum" flow, such as the 7Q10 statistic, as the instream requirement needed to protect fish and wildlife habitat is not recommended.

The understanding of relationships between the shape of stream channels (i.e., hydraulic geometry) and flow frequency and magnitude has developed out of the combined disciplines of geology and hydrology (Leopold et al. 1964, Schumm 1977). Although most of this work predates concern over instream flow issues, it has direct bearing on the validity of certain assessment methods described in Section 2.0. The power function equations originally proposed by Leopold and Maddock (1953) have been successfully expanded to include flow-frequency parameters (Stall and Fok 1968, Stall and Yang 1970). Watershed area and stream order (e.g., Strahler 1957) have also been incorporated into equations which are widely used to predict hydraulic geometries of stream channels (depths, widths, velocities, etc.) at various locations in a watershed. These types of equations are based on logarithmic regressions of actual field data; for instance:

$$\ln D = \alpha + \beta F + \gamma \ln A, \quad (3-1)$$

where D = average depth,
 F = frequency of occurrence,
 A = watershed area upstream from site, and
 α, β, γ = regression coefficients for specific watersheds.

The regression coefficients reflect the influence of factors related to watershed geology, slope, and the aging process of water

courses. The coefficients in hydraulic geometry equations such as Eq. 3-1 vary by as much as a factor of three among the watersheds in the State of Illinois (Stall and Fok 1968). Greater variation can be expected among rivers in different states (Stall and Yang 1970). These equations suggest that for maintenance of fixed depth thresholds (Section 2.6) on watersheds with equal areas, different natural flow frequencies would constitute the instream flow requirement. None of the discharge methods discussed in Section 2.0 address this aspect of fluvial geometry. The existing flow-duration methods could be improved by incorporating more geomorphological variables as independent determinants of instream flow requirements.

The Montana Method uses an average flow statistic only and ignores completely the importance of flow variability characteristics of individual watersheds. Both the hydraulic geometry and affected aquatic biota of a stream are adapted to a past flow regime (i.e., a temporal pattern in both magnitude and frequency of occurrence). Using the same percentage of the average stream flow to determine instream flow requirements on different watersheds implies that equivalent flow regimes exist among watersheds. This assumption is not valid and overlooks the fact that local aquatic populations are adapted to natural variations in stream flow. Because temporal patterns are an important determinant in structuring stream fish communities (Horwitz 1978), it is only realistic to set instream flow requirements in reference to flow variability on a watershed-specific basis.

The New England Flow Recommendation Policy (NEFRP) method, which is based on median historical stream flows, incorporates flow variability to a limited extent in that it defines the Aquatic Base Flow (ABF) required to protect aquatic biota as equal to the median monthly flow (MMF) for August. The ABF applies to all times of the year unless superceded by spawning and incubation flow recommendations (100% MMF in the spring and fall). Although the policy recognizes the importance of higher flows at other times of the year, the additional

flow variability provided by supercedence flows is not characteristic of all sites (see Table 9 in Cunningham and Knapp, in press).

Even methods that are based on flow duration data and that set the instream flow recommendation equal to a percentile flow do not properly address known properties of hydraulic geometry. A constant percentile instream flow can only supply the same environmental conditions over regions with watershed characteristics that are relatively homogeneous.

Assessment methods other than the discharge methods avoid, at least partially, the problem of unique site-specific influences because they measure directly the physical parameters at actual flow events. Instream flow requirements should still incorporate the influences of natural flow availability, but many assumptions about what physical conditions are provided by specific flow levels can be eliminated with site-specific field surveys.

Methods that use hydraulic simulation models or analytical equations to predict depth and velocity conditions at observed flows often involve significant assumptions about the type of open channel flow that is being modeled. For example, the Manning Equation (Eq. 2-2) was originally developed to predict the relationships among discharge, velocity, hydraulic radius, channel roughness, and energy slope for uniform flow conditions (e.g., Olson 1973). Therefore, methods which rely on this empirically based equation, such as R-2 Cross or the WSP simulation model, may not be valid when applied to streams which deviate strongly from uniform flow (uniform flow is defined as conditions in which velocity, depth, and energy gradients are constant over relatively long distances). Methods employing Manning's Equation can be used with care under gradually varied flow conditions but should not be used under conditions of rapidly varied flow, such as the hydraulic jumps in rapids or stream reaches where the energy slope exceeds 10% (K. Bovee, personal communication).

When uniform or gradually varied flow conditions are satisfied, other assumptions should be examined to ensure the validity of

hydraulic simulations. Single-transect methods that are used to develop stage-discharge rating curves all involve assumptions about flow-dependent changes in bottom roughness, n , or slope, S . The original R-2 Cross method used only one set of field data to calibrate the variables n and S in Eq. 2-2, then assumed these values remained constant over a wide range of stream flows. More recent modifications to the single-transect approach have relaxed this assumption somewhat by making roughness a function of other hydraulic parameters such as R , the hydraulic radius. Wesche and Rechar (1980) report that one empirical technique proposed in Colorado to adjust roughness uses the relationship:

$$n_2 = n_1 \cdot \sqrt{R_1/R_2}. \quad (3-2)$$

The validity of Eq. 3-2 must be verified for each site-specific application. The best technique for verifying the predictions of changes in n and S is to collect three or more observations of river stages and to plot the slope-roughness factor, $n/S^{1/2} = AR^{2/3}/Q$, vs discharge to determine the influence of Q . Extrapolations based on data collected at each transect for three or more flows will be the most accurate in modeling the physical stream environment (e.g., Bovee and Milhous 1978).

Other limiting assumptions are important to step-backwater modeling applications such as WSP. The calibration data required for input to the WSP model assume steady flow conditions (i.e., the data from each transect were taken under constant discharge conditions). Also, each set of calibration data is good for simulating only a finite range of discharges. The IFG recommends that WSP predictions can be used over a range of conditions, from 250% above the calibration discharge down to 40% below the calibration discharge (Bovee and Milhous 1978; Wegner 1980). For example, the use of WSP simulations calibrated with data collected at 15 m³/s (530 cfs) should

be limited to a range of 6 to 38 m³/s (212-1325 cfs). Predictions of hydraulic or habitat conditions outside those ranges require an additional set of calibration data.

All hydraulic simulation models used to date ignore the interactions between bottom substrate (and therefore roughness) and discharge. The assumptions related to these interactions are discussed in detail by Bovee and Milhous (1978). Although this interaction is by no means trivial and is currently under study by the IFG, there are no reliable predictive models which can determine substrate conditions as a function of discharge regimes accurately enough to be useful in developing the habitat-discharge relationships needed in a detailed instream flow analysis.

None of the methods address short-term rapid fluctuations in flow that often occur below peaking projects. The hydraulic simulation models that were developed to predict depth and velocity at unobserved flows assume uniform or gradually varied flow conditions. Thus, the critical assumption is that these same models can be used to assess instream flow needs in riverine environments characterized by rapid fluctuations in flow. In these cases, the rate of change in water levels as well as the interval between major fluctuations are important considerations. Because of the assumption that flows must be uniform or gradually varied, none of the existing models (or methods) may be capable of addressing, in a meaningful way, the ecological implications of rapidly varied flows below peaking projects.

Finally, the concept of a representative reach, which is used in the habitat modeling approaches (e.g., the Incremental Methodology), is assumed to be sufficient to represent long sections of rivers and streams (Bovee and Milhous 1978; Trihey 1979). Although this concept was supported by numerous reviewers of the methodology (e.g., Patten et al. 1979), any application of the Incremental Methodology should include careful placement of one or more representative reaches to ensure that local instream resources are included in the analysis.

3.1.2 Biological Response

The conceptual impact chain of the effects of flow regulation (Fig. 3-1) is important because it indicates what is not explicitly covered by the various assessment methods. Approaches which use only discharge records to determine instream flow recommendations cannot analyze incremental, site-specific habitat alteration or biological responses to flow regulation. Single-transect methods which make decisions based on changes in such hydraulic parameters as wetted perimeter or maximum depth address habitat alteration only in a general sense and usually do not directly consider the needs of specific fish species or life stages. Habitat rating methods such as PHABSIM carry out a relatively detailed analysis of the habitat alteration caused by regulated discharges. In addition, habitat alteration is placed in a biological perspective by including species and life-stage specific preferences for physical parameters in their environment. However, even PHABSIM has limited predictive capability as far as productivity or standing crops of aquatic biota are concerned.

All of the methods that were developed to assess instream flow needs for fishery resources are based on the assumption that habitat is the factor limiting population size. Because many western streams are characterized by very low flows at certain periods of the year, the assumption is made that the decrease in available habitat during these low-flow periods is the key factor. In some cases, however, high flows might be limiting. In eastern streams, fish production is often limited by the available food resources (Patten et al. 1979). Water quality problems are also more significant in the East, and this factor may also be limiting in some streams. In short, the assumption that fish populations are physically limited is critical, because the existing methods have reduced utility when other factors are limiting or controlling population size or production. However, water quality or food limitations should not preclude all instream flow management for physical habitat, especially when future improvements in these

limiting factors can be expected. While the Incremental Methodology also assumes that physical habitat is limiting, the IFG emphasizes the importance of evaluating other factors, such as watershed equilibrium and water quality, prior to using the method.

Two important biological assumptions involved in using any of the discharge approaches are (1) affected aquatic resources are a function of past hydrologic conditions which, in turn, can be accurately represented by a particular stream flow statistic, and (2) acceptable management of extant aquatic resources is directed at conserving those past conditions. While these assumptions are reasonable in many situations, they may not always apply due to unique, site-specific opportunities, management objectives, or project characteristics. Aquatic species do adapt to local environmental conditions. However, both the variability and magnitude of stream flow events are important in determining the composition and structure of riverine fish communities (Horwitz 1978).

One situation where aquatic resource management might not be based on conserving past hydrologic conditions occurs when the fisheries resource is dominated by nonindigenous fish species (e.g., stocked salmonids). In this case, fish populations will not be adapted to past conditions, so historical stream flow records may have little value in determining instream flow needs. To accurately determine the benefits of stream flow patterns or release schedules to introduced fish species, a method with more species-specific resolution should be used.

Single-transect hydraulic rating methods that develop relationships between descriptive physical parameters and stream flow eliminate some of the implicit assumptions regarding thresholds of habitat alteration inherent in discharge methods. However, the selection of critical transects and specific hydraulic parameters can again include important assumptions about biological responses. The single-transect methods usually assume that the factors limiting aquatic resources (e.g., fish populations) can be represented by a

single hydraulic parameter and that one critical transect accurately represents the influence of that hydraulic parameter throughout a heterogeneous stream reach. Furthermore, these types of analyses often imply that the same limiting factor is active for all seasons and all species.

For single-transect hydraulic rating methods, the choice of parameters and associated limiting factors include the following types of assumptions: spawning and egg incubation are proportional to maximum depth or velocity; cover is proportional to pool depth or exposure of undercut banks; rearing and food production is proportional to wetted perimeter. Whenever a habitat retention or inflection point criterion based on any of these parameters is used, the implication is that a linear relationship exists between the hydraulic parameter and fish production or standing crop (Sect. 3.4).

Of the methods currently available, the Incremental Methodology, PHABSIM, permits the most detailed analysis of the habitat alteration effects caused by changes in stream flow. However, the method has been criticized because of its incomplete representation of biological responses (Patten et al. 1979). The dynamics of aquatic ecosystems are a complex function of a number of different physicochemical and biological factors (Table 3-1). PHABSIM provides a quantitative tool which can be used to examine only two of the general categories of factors, habitat structure and flow regime, that are determinants of biological responses. Therefore, even if Weighted Usable Area (WUA) were a perfect index of habitat condition and its response to changes in stream flow, at least two other factors, water quality and trophic community structure, would be necessary to fully model the biological response. Therefore, WUA is a necessary but not sufficient indicator of ecosystem integrity (Patten et al. 1979). Only in situations where water quality or food resources are not limiting (e.g., coldwater trout streams) can WUA be assumed to be a good predictor (i.e., necessary and sufficient) of parameters such as biomass or production. Validation studies of the Incremental Methodology in western trout streams tend to support this assumption (Stalnaker 1979b).

Table 3-1. Determinants of aquatic ecosystem integrity and productivity as viewed by various investigators

Karr and Dudley (1981)	Pennak (1971)	Patten et al. (1979)	Binns and Eiserman (1979)
Water quality	Summer temperature Winter temperature Dissolved oxygen Turbidity Hardness Total dissolved inorganic matter Total dissolved organic matter	Temperature Dissolved oxygen Sediment load Nutrients	Maximum summer temperature Bank erosion NO ₃ -N
Habitat structure	Width Velocity Substrate	Depth Velocity Substrate Stream morphology	Width Velocity Cover
Flow regime	Flow		Annual variation in flow Late summer flow
Trophic community Structure		Food supply Predation	Food supply

The IFG describes its index of instream habitat condition as a measure of habitat usability where usability is the product of two environmental variables, habitat suitability and habitat availability (Voos et al. 1981). Habitat suitability is an index that can range from 0.0 to 1.0. It is a multivariate function of an "organism's voluntary or involuntary preference for combinations of environmental attribute values" (Voos et al. 1981). In other words, a suitability coefficient represents the behavioral tolerances of a specific life stage of a target species to a set of environmental parameters. The calculation of WUA using Eq. 2-7 has the effect of equating an area of suboptimal habitat to a smaller area of optimal habitat. This computation implies that a fish or other aquatic organism can make the same use of 100 m² of optimal habitat as it can of 1000 m² of available but marginal habitat with a suitability of 0.10. The validity of this assumption will be highly species-specific and is largely untested.

In the version of PHABSIM currently available, the calculation of composite habitat suitability, \hat{S}_i in Eq. 2-8, assumes independence among the influences of depth, velocity, and substrate on composite habitat suitability. This implies, for example, that a fish will have the same preference for various combinations of velocities and substrates at a depth of 0.2 m as it will at 2.0 m. Tests of this assumption of independence have shown that in many cases the influence of the physical habitat dimensions are not independent of each other (Orth 1980, Stein et al. 1980, Voos et al. 1981). Multivariate suitability functions incorporating interaction terms between depth and velocity have been developed for brown trout in Colorado and Wyoming streams (Voos et al. 1981; Voos 1981), but much more work remains to be done in developing, testing, and validating habitat suitability models.

Despite what appears to be significant simplifications in the way the Incremental Methodology represents habitat utilization, some success was reported in using WUA to predict fish standing crops.

Stalnaker (1979b) reported a strong correlation between WUA and standing crop of brown trout in Wyoming streams. Orth (1980) also found significant correlations, especially during summer low-flow conditions, between the standing crop of freckled madtom, stonerollers, and orangebelly darters and WUA in a small warmwater stream in Oklahoma. However, the same type of relationship could not be demonstrated with juvenile or adult smallmouth bass in the same stream.

The assumption that WUA is a limiting factor to fish populations may be valid only during very low or very high flow conditions. At other times, when WUA takes on high values, other factors such as water quality or food resources may be more important than physical habitat in controlling population dynamics. The time series of WUA values created by long sequences of flow events are probably more important than instantaneous discrete WUA values in determining actual biological responses.

Finally, habitat indices, such as WUA and NPH (Sect. 2.7), are composite descriptions of the physical environment and can be linked to the design and operation of dams and reservoirs. How aquatic biota respond to changes in habitat (as measured by some habitat index), however, is largely unknown. To develop methods capable of quantifying or predicting biological responses to flow regulation, including rapid fluctuations in flow, more emphasis must be placed on evaluating the influence of stream flow and habitat regimes on aquatic biota.

3.2 Data Requirements

One or more of three types of data may be required in the application of the assessment methods described in Section 2.0, including:

- stream flow records and/or watershed description
- transect data (depth, velocity, substrate and/or cover)
- target species habitat criteria.

Under certain circumstances it will also be necessary to obtain information on the design and operation of the hydroelectric project in question to determine the significance of the instream flow issue (see Sect. 4.2).

3.2.1 Hydrologic Data

At most sites information on historical flows will be among the easiest data to obtain due to the excellent monitoring system of the USGS throughout the country and the "state-of-the-art" of descriptive hydrology. A large amount of data on surface water is available from the USGS through annual publications of state water resources data, other statistical summaries, and two computerized data processing systems, NAWDEX and WATSTORE. The National Water Data Exchange (NAWDEX) provides a comprehensive list of federal, state, local, academic, and private agencies that collect water data as well as a list of the sites at which those data are available. The National Water Data Storage and Retrieval System (WATSTORE) provides access for subscribers to USGS records describing active stream gaging sites and tapes of daily flow values. Other computerized data bases, such as the U.S. Environmental Protection Agency's STORET system, can provide useful information on historical stream flows. Customized statistical summaries of stream flow records are also often available through regional USGS offices at minimal charge. The types of hydrologic data required for some instream flow assessments are often similar to those required for the design of reservoirs and hydroelectric facilities.

The choice of an appropriate statistic for describing the flow regime at a potential hydropower site is very important to instream

flow assessment. Because of the skewed nature of stream flow events, the mean discharge is an unreliable measure of central tendency, especially for the purposes of representing the environment of aquatic biota. The median is a better measure of central tendency with frequency estimates and percentile flows being preferable for describing the natural variation in stream flows. However, the procedures used to calculate flow duration curves can also have a significant effect on instream flow analyses and final recommendations.

Flow duration curves exhibit a consistent trend of becoming flatter (more uniform) as the interval over which flow data are collected becomes longer (e.g., Linsley and Franzini 1972; Fig. 3-2). Consequently, if long intervals are used (e.g., flow duration calculated on mean annual flows), relatively less variation in flow conditions will be obvious and higher instream flow recommendations may result. Flow duration curves used for instream flow recommendations should be based on stream flow data derived over monthly or shorter intervals to represent the type of environmental variation to which fish populations respond and are adapted. In highly regulated streams, daily or even hourly records may be necessary to construct an accurate representation of flow variations. The size of the upstream watershed, which strongly influences flow variability (i.e., large basins have more stable flow patterns, so longer averages may be acceptable), is also important in selecting an appropriate time interval.

Variability in stream flow occurs naturally both between and within annual cycles. The seasonal variation at a project site can be accounted for by separating instream flow recommendations into seasonal intervals. This approach leads to a regimen of instream flow recommendations that will protect complete life cycles of aquatic biota (see Sect. 4.1, item 3).

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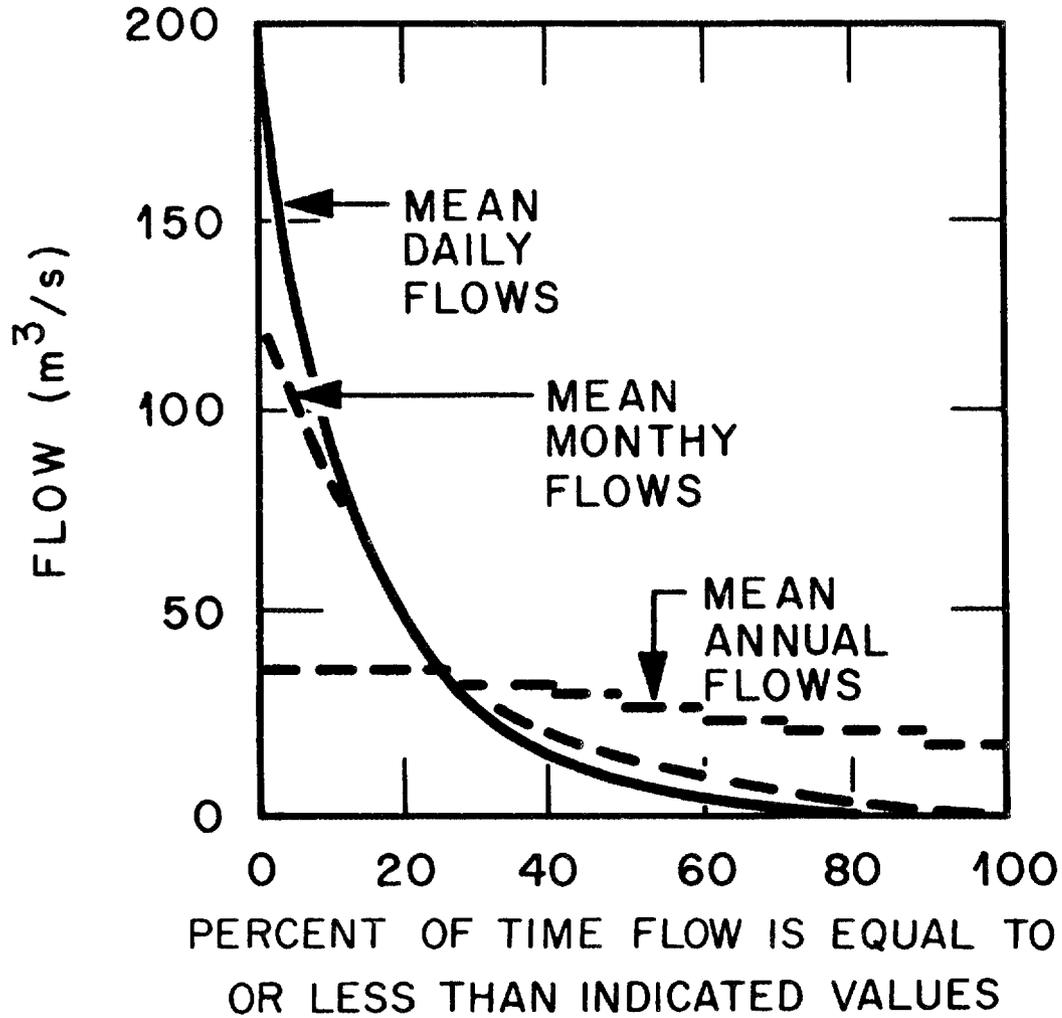


Fig. 3-2. Flow-duration curves calculated on different flow statistics for Cherry Creek near Hetch Hetchy, California, 1941-1950 (Redrawn from Linsley and Franzini 1972, with permission from McGraw-Hill, Inc.).

3.2.2 Transect Data

With the exception of the discharge approaches, all assessment methods will require some level of field survey work. This site-specific description of the physical stream environment can range from a single site visit in which a critical transect is identified and a transverse depth/velocity profile is taken (i.e., R-2 Cross or some other stage-discharge rating method) to multiple site visits involving detailed field surveying and discharge measurements at many transects. The manpower costs of these different levels of effort may differ by an order of magnitude or more (see Sect. 3.3.3). The skills and expertise of the personnel involved in collecting these data will also have to match or exceed the requirements of the particular method.

Assessment methods requiring the most intensive field surveys are those which develop two-dimensional maps of the streambed (i.e., WSP applications, preferred area methods, and PHABSIM). The data elements which must be collected prior to applying these methods are (1) location and elevation of headstakes marking the ends of each transect, (2) elevations and distances separating each set of headstakes, (3) water surface elevation at each transect throughout the reach (assuming steady flow), (4) cross-sectional profile of bed elevation across each transect, including the bank out of the water, (5) discharge measurement at each transect, and (6) bottom substrate and/or cover characterization across each transect (Bovee and Milhous 1978). The use of PHABSIM with the IFG-4 method of hydraulic simulation de-emphasizes the need to link transects and headstakes together but requires discharge measurements at two or more flow conditions (Sect. 2.8). A relatively high proficiency with surveying techniques is required to establish elevations and headstake locations within the necessary accuracy (± 0.3 cm for headstakes and water surface elevations; ± 3 cm for bed cross-sections). Results from a comparative study of instream flow methods in 12 western states indicate that acceptable proficiency of field crews was obtained after

two or three applications of PHABSIM (R. Giger, personal communication).

Procedures for discharge measurements have been well established by USGS and other federal agencies responsible for water resources management (Buchanan and Somers 1968, Bovee and Milhous 1978). A set of depth and velocity measurements are taken at intervals across a transect, and discharge is calculated as

$$Q = \sum_{i=1}^n q_i = \sum_{i=1}^n (v_i \cdot w_i \cdot d_i), \quad (3-3)$$

where Q = total discharge through the cross section,
 q_i = discharge through a partial section of the cross section,
 v_i = mean water column velocity in the i^{th} section,
 w_i = width of the i^{th} section,
 d_i = depth of the i^{th} section, and
 n = total number of subsections in the cross section.

Standard procedures have been established by the USGS determination of the maximum size of subsections, calculation of v_i , and care and use of current meters. For accurate discharge measurements, for example, the guideline of $q_i \leq 0.05 * Q$ for all i should be followed.

3.2.3 Habitat Criteria

The development of habitat criteria, usually in the form of suitability functions for depth, velocity, substrate, and cover, are associated primarily with high resolution methods such as the Incremental Methodology. This information is readily available for western, coldwater species (Giger 1973, Bovee 1978). With the increasing emphasis on instream flow needs in the eastern United States, habitat preference data are beginning to become available for

more warmwater species (Herricks and Klopke 1980, Orth 1980, Stein et al. 1980, Sheppard and Johnson 1981). Although standardized procedures have been developed for collection of field data and calculation of habitat suitability functions (Bovee and Cochnauer 1977, Voos et al. 1981), this work can be extremely time-consuming. When habitat suitability criteria are not available for indigenous fish species at a site, acceptable results might be obtained from PHABSIM by modifying curves developed in other watersheds (e.g., Hilgert 1981). However, considerable caution should be exercised whenever curves that have been developed in the West are modified and applied to other areas of the country, particularly the Northeast, Middle Atlantic, and Southeast regions.

3.3 Costs of Application

The actual dollar costs of applying any particular assessment method will be influenced by such project-specific factors as travel costs, experience and proficiency of personnel, and the availability of baseline data. However, certain generalities can be made regarding the relative costs of the various methods available for instream flow assessment. These costs will vary as a function of the specific requirements for office work, field data collection, and any computer analysis or other data processing costs with each method. Finally, selection of an appropriate method will depend, in part, on the target species (and life stages) of interest (Sect. 4.2.2), and some cost may be incurred in obtaining the "baseline" biological information needed to determine the target species and life stages present and their seasonal occurrence. The cost of obtaining this information, which is a key element in the initial stages of any assessment, regardless of the method that is ultimately chosen, is not included in the analysis that follows. In many cases, however, selection of target species and life stages might not require new site-specific data but rather would be based on existing data and/or on the expertise of local/regional fisheries biologists.

3.3.1 Discharge Approaches

Methods based on the examination of flow records (Sects. 2.1, 2.2., 2.3) are the least expensive to use because the analyses can be conducted without a site visit. For example, the Montana Method requires only that the mean annual flow at a project site be calculated and a fixed percentage of that statistic set as the instream flow recommendation (Sect. 2.1). These types of assessment methods will usually require less than one man-day (Wesche and Recharad 1980; R. Giger, personal communication).

Some variation in time requirements may result if flow duration calculations are required or if site visits are made to obtain photographs and other reconnaissance data to support the flow recommendation. Although it is recommended that some cursory field data be collected to substantiate instream flow requirements (Tennant 1976), the need for a site visit would eliminate some of the cost advantage of these methods. Requests to USGS for customized data analysis may cause some time delay but only minor dollar costs. In most cases, flow duration curves will have been developed as part of the design of a hydroelectric facility (e.g., Dixon 1979). Other complications in calculating an appropriate flow statistic may arise on regulated or ungaged watersheds. Techniques for handling these problems are available and are not excessively complex (Emmert and Heitz 1979).

3.3.2 Single-Transect, Hydraulic Rating Approaches

Methods that are based on single-transect data and that develop some type of hydraulic rating curve (e.g., depth vs discharge, or wetted perimeter vs discharge) are intermediate in cost. The analysis of historical flow records is replaced by site visits, some type of stream survey, and simplified analytical calculations. Although computer software, such as IFG-1, has been developed to aid in data analysis, hand calculators with programming capabilities and graph paper are usually sufficient for these types of methods.

Estimates of manpower requirements for single-transect methods are one to four man-days in the field, depending on the number of flows observed, and less than one to three man-days in the office (Wesche and Recharad 1980; R. Giger, personal communication). Travel time, which is not included in this estimate, can be more significant than the time actually spent in applying the method. Also, the ability to physically control stream flow (e.g., below existing dams) will reduce application time drastically. The past experience of personnel is a major factor in both the time requirements and the success of this approach as well as the next.

3.3.3 Habitat Modeling Approaches

As previously mentioned, application of multiple-transect methods with complete habitat rating is by far the most expensive approach for assessing instream flow needs. In general, it can be expected that an application of the Incremental Methodolgy will involve at least an order of magnitude more in terms of manpower requirements compared to the single-transect hydraulic rating approaches (Table 3-2). These cost estimates will again be highly variable depending on the project specifications and assessment needs (R. Giger, personal communication). Instream flow assessments of small slow-moving streams which are wadable and which approach uniform flow conditions will be among the easiest and least expensive.

The construction of suitability curves for target fish species may also be a major expense (Sect. 2.8). Development and testing of multivariate habitat suitability models is not within the scope of most environmental assessment work conducted at small-scale hydroelectric projects. Therefore, it is expected that application of the Incremental Methodology at these projects would have to rely on existing habitat suitability data that have been modified to represent local conditions, as necessary (see Hilgert 1981 for an example of modifying existing suitability curves; also Sect. 3.2.3).

Table 3-2. Approximate manpower requirements (man-days) for application of the Incremental Methodology, excluding travel costs. Field crews are assumed to have some experience. Requirements are for one representative reach consisting of eight transects (K. Bovee, personal communication).

Study phase	Wadable streams ^a	Large rivers ^b
Presurvey planning	0.5-1	1-2
Field survey ^c		
WSP data (1 flow)	6	12
IFG-4 data (3 flows)	15	30
Data preparation		
Organization of field notes	1	1
Computer input	0.5	0.5
Hydraulic model calibration		
WSP simulation	2	2
IFG-4 simulation	<1	<1
Habitat modeling		
Construction of suitability curves ^d	0.5-2	0.5-2
HABTAT execution	<1	<1
Flow recommendation	1	1
Range for total study	10-25	20-40

^aOptimal field crew size is 2 to 3 people.

^bOptimal field crew size is 3 to 4 people.

^cSurveying requirements increase by 50% if high precision is required or if cover is included as an element of physical habitat. WSP assumes only one set of transect data while IFG-4 requires data sets from three different discharges. WSP modeling may require more data sets to cover the entire range of flow conditions.

^dMinor modification of existing curves and/or consultation with fisheries experts. Creation of completely new suitability data can easily double study costs because of the extensive field work required.

Data processing costs associated with these habitat modeling approaches need not be excessive but do require some expertise in computer programming. Also, past experience has shown that some minimal level of proficiency in the use of PHABSIM is necessary to obtain good results (R. Giger, personal communication). For a five-transect reach with 20 cells per transect and six extrapolated flows, Wegner (1980) estimates that computing charges on the Colorado State University CYBER computer would average \$5.00 for IFG-4 hydraulic simulations, \$7.00 for WSP hydraulic simulations, and less than \$10.00 for a single-species HABITAT (IFG-3) run for five life stages. Access to the PHABSIM software is available commercially through the Boeing EKS-1 commercial computing system in more than 170 cities in the United States (Wegner 1980). Many government agencies can obtain access to PHABSIM through the computer system operated by the Water and Power Resources Service at Colorado State University. At the present time, this software is compatible only with Control Data Corporation NOS operating systems.

3.4 Decision-Making Capabilities

As referred to in this section, decision-making capabilities refer to the manner in which the data obtained from the application of a particular method are used to generate a final recommendation for instream flow regimes. Unfortunately, this capability is one of the most important, and most frequently neglected, aspects of the assessment of instream flow needs. For example, the only reference in the accessible literature that approaches an explicit set of directions for using the Incremental Methodology output to generate instream flow recommendations is a short example by Stalnaker (1979b). Reasons for this lack of guidance may include (1) unsettled legal status of instream water uses throughout the United States, (2) reluctance of water managers to fully integrate environmental quality into multiobjective water resource planning, and/or (3) hesitancy of

biologists to depend on tentative assumptions that may require further investigation.

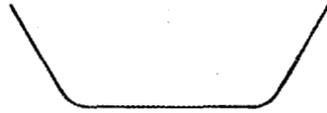
With the possible exception of the discharge approaches, all the methods develop some type of response relationship between a descriptive parameter of habitat condition and stream flow. With the Incremental Methodology, this habitat-response information is complicated by the need to consider multiple time periods and multiple target species and their life stages. Without some set of standardized information-processing procedures, it is very easy to reach a point at which the output becomes overwhelming and even obscures any final recommendation. Furthermore, an assessment method should be considered incomplete without these integrating procedures (Sale 1980).

Some of the techniques available for selecting minimum discharge points from habitat-response curves are clearly better than others. The "inflection point" techniques used with the R-2 Cross, WSP, and usable width methods are ill-defined and can lead to ambiguous analyses. The shape of a wetted perimeter vs discharge response curve and the presence of an inflection point is dependent upon the cross-sectional configuration of the stream channel (Fig. 3-3). Examination of these curves and the "inflection points" chosen to generate an instream flow recommendation often leaves an objective reviewer baffled by the criterion that was used (e.g., Nelson 1980, Prewitt and Carlson 1979, Pruitt and Nadeau 1978). Use of this technique can create rather than alleviate controversy over water allocation needs.

Habitat-retention criteria are much less ambiguous than inflection-point calculations and are preferable because the value judgments are clear and relatively more defensible. If methods that base habitat retention calculations on some reference stream flow are used, then justification should be provided concerning the significance of that datum point. Final recommendations will also have to be defensible from the point of view of why a specific

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CROSS SECTION PROFILE



P VS. Q RELATIONSHIP

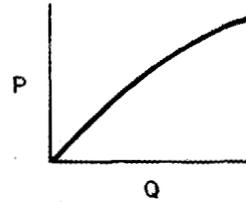
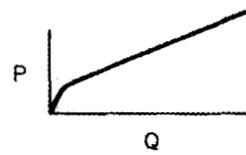
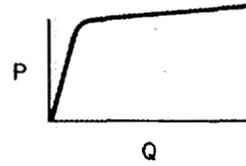


Fig. 3-3. Relationship between channel cross-sectional profile and the shape of the wetted perimeter (P) vs discharge (Q) curve (from Bovee and Milhous 1978).

percentage of the reference habitat condition is desirable. Given the present understanding of aquatic ecosystem dynamics, these habitat-retention criteria will usually have to be based on the subjective impressions of fisheries biologists.

In addition to their use in setting absolute minimum thresholds, habitat-discharge response curves can be used as value functions in either a formal or informal optimization procedure. The negotiation framework most commonly encountered in water allocation conflicts would be an example of an informal optimization procedure (Wassenberg et al. 1979, Lamb and Sweetman 1979, White et al. 1980). The IFG has a great deal of practical experience regarding the type of negotiations involved in obtaining instream flow allocations from federal water projects.

Formal optimization to obtain instream flow allocations refers to the application of water resource systems analysis models with the habitat-response functions (WUA vs discharge) used either as objectives or constraints. Optimization models have already been applied to the design and operation of water projects for the purposes of improving water yield, power generation, flood protection, and economic efficiency. Linear programming and dynamic programming models are highly efficient in analyzing the tradeoffs involved with water allocation issues. Sale (1980) demonstrated how the habitat-response curves could be utilized as objective functions in a nonlinear programming model to improve the performance of a multipurpose reservoir in central Illinois. This type of modeling approach, combined with multiobjective optimization techniques and further research, can be very useful in finding operating rules which protect instream values affected by water development systems, including hydroelectric facilities. Initiatives in these areas are currently being pursued both at ORNL and by the IFG.

4. CONCLUSIONS AND RECOMMENDATIONS

The need for water to generate electricity often conflicts with other instream flow needs, such as recreation, aesthetics, water quality, and fish and wildlife habitat. With the recent emphasis on the development of small hydropower resources, these conflicts may intensify. Resolution of the problem will likely focus on tradeoffs between water needed for hydroelectric generation and water required for the protection of fisheries. Although many methods have been developed in the West over the past 10 to 15 years to assess instream flow needs related to fishery resources, very little is known about their applicability to watersheds with different hydrologic characteristics. Our examination of the instream flow issue has been directed toward a review (Sect. 2.0) and evaluation (Sect. 3.0) of these existing methods. The results of this analysis have led to (1) several general conclusions regarding the instream flow issue (Sect. 4.1) and (2) a proposed strategy to assist developers of small-scale hydroelectric projects in assessing the issue at a given site (Sect. 4.2).

4.1 General Conclusions

1. The potential for conflict between water needed for hydroelectric generation and that required for other instream uses, especially maintenance of fish and wildlife habitat, must be assessed in the initial stages of project planning and development (i.e., in the feasibility study). Consultation with personnel in the appropriate local, state, and federal agencies or organizations is an important component in this assessment.

2. Using the methods currently available, it is difficult, if not impossible, to generate an absolute threshold for instream releases needed to protect instream resources. That is, all the methods have an element of subjectivity. Professional judgment must be exercised in formulating the actual recommendation (Sect. 3.4). The methods should be viewed as tools that assist in or provide a basis for decision-making.

3. The instream flow recommendation should be based on an annual discharge regime. Differences between seasons of the year are considered by varying the recommendation through the year. The variability in discharge between years, on the other hand, can be taken into account by establishing recommendations based on normal and dry years. In short, use of a single minimum flow value (the threshold concept) to represent the instream flow recommendation is not advisable because (1) the minimum flow becomes the average condition as additional water is appropriated out-of-stream (Stalnaker 1979a, b) and (2) the assumption that only flows below the minimum will be detrimental is often not valid (U.S. Fish and Wildlife Service 1979). Thus, the 7Q10 statistic should not be recommended as the single minimum flow needed to protect fish and wildlife habitat (Sect. 3.1.1).

4.2 Guidelines for Assessing Instream Flow Needs Related to Fishery Resources at Small-Scale Hydropower Sites

Based on the review and evaluation of existing instream flow assessment methods presented in Sections 2.0 and 3.0, respectively, a

strategy was developed for addressing instream flow issues at small hydropower sites. The strategy represents a hierarchical approach and is delineated in this section of the report by both explanation and example. The hierarchy consists of four classes of methods (or levels of analysis) that differ in the degree of resolution provided (Sect. 4.2.1). Consequently, selection of the most appropriate method is dependent upon the level of resolution required. Criteria are proposed to assist developers in this determination (Sect. 4.2.2). Finally, implementation of the hierarchical approach is examined by providing examples to illustrate the association between selected criteria and a given level of analysis (Sect. 4.2.3).

A similar analytical approach to that proposed for assessing instream flow needs was recommended by Cairns (1980) to assess the risk associated with chemical pollutants. In the latter case, sequential tests (e.g., LC_{50} determinations, chronic toxicity tests, life cycle studies, etc.) are performed in screening chemicals to evaluate their potential hazard in the environment. These tests are arranged into tiers for the purpose of progressively narrowing the confidence intervals around the concentration or exposure level associated with "no adverse biological effects." Unlike the field of water quality assessment where biological thresholds are often explicitly identified, water quantity or stream flow assessments are based on thresholds that have been implicitly identified; i.e., the existence of such a biological threshold associated with stream flow is implied whenever an assessment of instream flow needs is performed. Nevertheless, the basic approach in evaluating both water quality and quantity issues is similar and can be based on a hierarchical scheme that provides greater resolution at the higher tiers or levels of investigation. Such an analytical approach was also proposed for evaluating watershed processes, sedimentation, and water quality as part of the overall IFG Incremental Methodology (Mar et al. 1979, Simons et al. 1979).

4.2.1 Levels of Analysis

The hierarchical approach proposed for evaluating instream flow needs at small-scale hydropower sites includes four levels of analysis which differ in (1) data needs, (2) cost, and (3) level of resolution associated with instream flow recommendations (Fig. 4-1).

The first level (Level I) usually requires no site-specific field work (but see Sect. 3.3), only an evaluation of stream flow statistics. Because existing data are used, costs are very low. On the other hand, a relatively large possibility for error exists in the selection of the instream flow requirement (in either direction from the "optimum"), because site-specific factors related to habitat requirements are either ignored or considered only in very general terms. Level I-type analyses were used for reconnaissance purposes to assess instream flow needs at both the national (Bayha 1978) and regional levels (Washington State Department of Ecology 1979; U.S. Fish and Wildlife Service 1981). Flow duration analysis coupled with instream flow recommendations that are based on seasonal percentile flows is the preferred method at this level.

The next level of analysis requires a relatively modest amount of field work (transect surveying) at the proposed hydropower site. Consequently, costs are somewhat greater than for Level I, but the resolution is higher. A hydraulic rating method, such as R-2 Cross, IFG-1, or IFG-4 with only one transect and no habitat suitability (HABTAT) analyses, is the appropriate choice at this level. The dependent variable (plotted as a function of stream flow) would be a hydraulic parameter such as maximum depth or wetted perimeter. Although the level of resolution is higher than Level I, the instream flow recommendations produced at this level of analysis would not, in most cases, be based on a detailed knowledge of the habitat requirements of any species. Instead, Level II recommendations would be directed at preserving general hydraulic conditions in ecologically significant areas affected by flow regulation.

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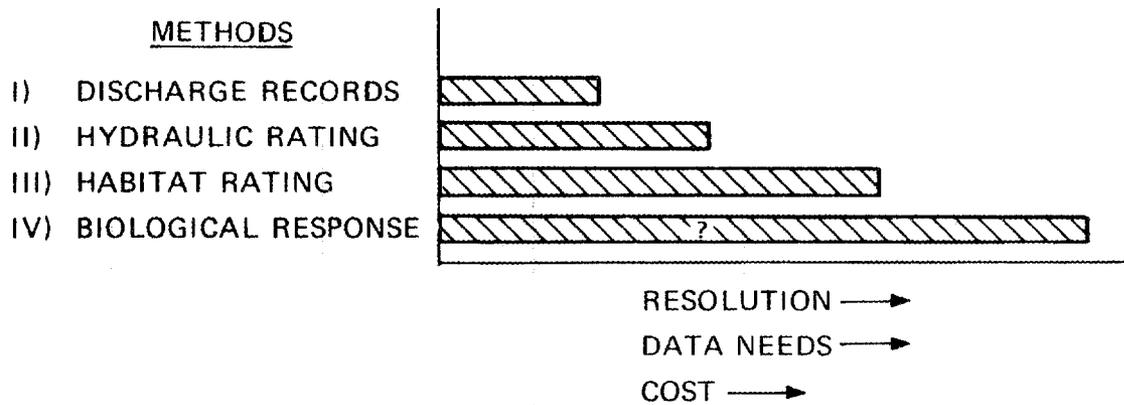


Fig. 4-1. Four levels of analysis for assessing instream flow needs at small-scale hydroelectric sites. Existing methods fall into a hierarchical arrangement with progressively greater resolution, data needs, and costs.

The third level of analysis requires habitat evaluations that are based on species-specific requirements (habitat suitability curves), representative reach mapping using multiple transects, and the development of habitat vs discharge response curves. The greater data needs associated with Level III analyses will significantly increase the cost compared with Levels I and II. Costs for Level III analyses can vary considerably, depending on (1) size and discharge characteristics of stream and river and (2) need for site-specific data to develop/modify habitat suitability curves (see Sect. 3.2).

The fourth level of analysis, which is currently in the research-and-development stage, would employ ecological modeling techniques to investigate and predict biological responses to flow regulation. Responses could be evaluated at any one of several levels of organization (e.g., survivorship or fecundity of individuals, production of a given species, alterations in fish community structure, changes in ecosystem structure and function). Efforts to develop a fish population model that includes parameters such as WUA (Sect. 2.8) were recently initiated by the Susquehanna River Basin Commission (Williams 1980). Patten et al. (1979) recommended that the Incremental Methodology include several parameters, in addition to the existing physical variables (e.g., v , d , s), that reflect chemical and biological processes of ecosystems, noting that the existence and status of fisheries is related to the status of stream ecosystems. Recognizing the present "state-of-the-art" in understanding and modeling stream ecosystems, and given the complexity and cost of modeling biological responses in general, Level IV analyses would be beyond the scope of the type of environmental assessment usually associated with small-scale hydroelectric projects. Until the tools needed to quantify/predict these responses can be developed, a Level III analysis provides the greatest level of resolution for identifying the instream flow needs of aquatic biota. Modeling coupled with the appropriate field experiments could, nevertheless, provide valuable insights to the biological consequences of flow regulation.

4.2.2 Criteria for Selecting Among Levels

Although numerous methods currently exist for assessing instream flow needs related to fishery resources, there is no general consensus regarding their applicability among watersheds with different physical and hydrologic characteristics. In spite of the comparative studies conducted by the U.S. Fish and Wildlife Service (R. Giger, personal communication), not enough experience has been obtained in evaluating several methods on the same stream at the same time. Consequently, our initial attempt to rigorously define limits on the applicability of the methods presented in Section 2.0 was unsuccessful. However, the methods can be categorized into three major groups according to the level of resolution associated with their instream flow recommendations. Given the "state-of-the-art" of the methods at each level of analysis (e.g., most have not been applied in the East where water quality problems are likely to be more significant than in the West), it is very difficult to specify exactly what level of resolution is associated with each of the methods discussed in Sections 2.0 and 3.0. Thus, we chose to identify several groups of methods that differ in the level of resolution provided. From this hierarchy, guidelines in the form of criteria can be established for determining the level of resolution required at a given site or project.

Instead of providing an exhaustive list of criteria that includes economic, institutional, and environmental factors, we focused on the nature and magnitude of the potential environmental impacts associated with changes in the existing hydrologic regime at small-scale hydroelectric sites. The degree of impact is influenced by the design and operation of the facility (the causative agent) and the nature of the ecological resources in the stream or river (the affected agent). Thus, the level of analysis (or the degree of precision associated with the estimate of instream flow needs) that is selected is a policy decision that should be based on an evaluation of several factors (criteria) that are the primary determinants of the nature and magnitude of the environmental impacts.

The design of small-scale hydroelectric facilities can affect stream flow if the powerhouse is not located at the dam. The use of long penstocks or canals to gain additional head can result in periods of very low or no flow in that reach of the stream between the dam and the confluence of the tailrace with the river (Sect. 1.3). The flow regime can be further altered if the facility is operated in a peaking mode. Projects operated strictly in a run-of-river mode, on the other hand, would not alter the flow regime downstream of the project because no change in reservoir storage would occur. Thus, the potential impacts on downstream aquatic ecosystems could range from negligible for run-of-river projects without canals or penstocks to potentially significant in the case of peaking facilities that are designed with long headraces.

In assessing the potential impacts of small-scale hydroelectric projects on instream uses (e.g., fish and wildlife habitat), the ecological characteristics of the stream or river must also be considered. Some of the most important aquatic resources are threatened or endangered species, or their critical habitat, and anadromous fish species which provide important commercial and sport fisheries (e.g., Pacific salmon in the Northwest) or are the focus of restoration programs (e.g., Atlantic salmon and American shad in the Northeast). Other migratory species, such as walleye or white bass, often utilize the tailwaters below dams and provide important recreational fisheries. The selection of target species should also include evaluation of their temporal (life-cycle) requirements; i.e., critical life stages should be considered. To identify the significant aquatic resources, which in some cases may be an entire stream or watershed rather than a particular fishery or species population, personnel in the appropriate local, state, and/or federal agencies and organizations should be consulted during the early stages of project planning and development.

4.2.3 Applications

To illustrate the application of the hierarchical approach in assessing instream flow needs at small hydropower sites, two case studies (Levels II and III) are described. While no specific examples of a Level I application are presented, this type of analysis has been used in various reconnaissance-type surveys (Sect. 4.2.1). This level of analysis can also be used to quickly evaluate the potential for conflict at a given site during the early stages of project planning, especially if the project is to be operated in a peaking mode. In these cases, a developer may not wish to conduct a detailed Level II or III assessment because of time constraints. Thus, a very cursory, early evaluation of the potential for conflict may be obtained by using a simple Level I-type analysis; a more detailed assessment would be conducted at a later stage (e.g., feasibility study). Finally, no examples of a Level IV application are available, although such an approach was recently initiated to assess instream flow needs in the Susquehanna River basin (Williams 1980).

Case 1: Level II analysis*

The Mystic Lake power project (FERC No. 2301) is an existing facility located on West Rosebud Creek in southcentral Montana. The project consists of a high-elevation storage reservoir (Mystic Lake) and a powerhouse located 3.2 km below the dam. The reach between the dam and powerhouse is a high gradient (difference in elevation between the reservoir and powerhouse is 343 m), coldwater stream with a drainage area of 135 km². Mean daily flow for the period of record is 0.96 m³/s and ranges from 5.97 m³/s in June during snowmelt runoff to 0.08 m³/s in the winter (January through April). Excess spillage over Mystic Dam normally occurs over a seven-week period in midsummer. Rainbow trout (Salmo gairdneri) and brown trout (S. trutta) spawn in

*Source of information: Montana Power Company (1979).

the 3.2-km reach, although the latter species is confined to a 500-m section just above the powerhouse. The recreational fishery in this reach is insignificant.

An instream flow study was conducted to determine the minimum releases required on West Rosebud Creek between the dam and powerhouse to "protect and enhance the fishery resource of the creek." The Oregon Method (Thompson 1972), or the Usable Width method as described in Section 2.6, was used to assess the flow requirements for fish passage at critical transects (those located in broad shallow reaches that were judged to be critical to the passage of large fish). The assumption was made that flows sufficient for fish passage would also satisfy other requirements (i.e., spawning, incubation, and rearing). Measurements of depth, velocity, and width were recorded on five occasions along each of three transects located in two general regions of the 3.2-km reach. The minimum flow for fish passage was defined as that flow which met the minimum depth criterion of 0.12 m on at least 25% of the total width and on a continuous portion equal to 10% of the total width. Total width was defined as the stream width corresponding to the mean daily flow.

Additional studies were also undertaken as part of the overall assessment of instream flow needs in West Rosebud Creek. The relationship between $s^{\frac{1}{2}}/n$ and cross-sectional area was examined by correlation analysis for each of the six transects. Manning's equation was then used to generate plots of Q vs width and to extrapolate to unobserved flows (e.g., wet width at the mean daily flow). The fisheries study conducted as part of the instream flow study included (1) estimates of standing crop in three stream reaches, (2) length-frequency analysis, (3) computation of length-weight relationships, and (4) evaluation of condition factors. Finally, it should be noted that the study was conducted with the cooperation of the Montana Department of Fish, Wildlife, and Parks and the U.S. Fish and Wildlife Service. Both agencies were requested to review the proposed study and were kept informed of the progress.

Case 2: Level III analysis*

The proposed Terror Lake hydroelectric project (FERC No. 2743) includes a 20-MW baseload facility that would be located in the northeastern portion of Kodiak Island, Alaska. The project would require the inundation of Terror Lake, a 109-ha natural lake, to create a 344-ha impoundment. Up to 90% of the discharge from Terror Lake would be diverted through a 9-km-long power tunnel/penstock to a powerhouse located in the Kizhuyak River basin about 5 km upstream from the head of Kizhuyak Bay. Diversion dams would also be constructed on four small tributary streams and the flow diverted to the power tunnel.

Pre-project mean monthly flows in the Kizhuyak River range from 0.68 m³/s in March to 15.72 m³/s in June; similar variability in flow exists in the Terror River at the lake outlet. During an average water year, operation of the project would reduce the mean annual discharge near the mouth of Terror River by about 35% and would increase the mean annual discharge of the Kizhuyak River at a point 2.5 km below the powerhouse by approximately 69%. Because of the diversion dams, flows in the river above the powerhouse would be reduced by about 41%.

The project will also significantly alter seasonal stream flow patterns. Although flows below Terror Lake would not be modified from December through April, flows during the remainder of the year would be significantly reduced. Peak flows during June and July, for example, would decrease by approximately 46%. The post-project flow in the Kizhuyak River below the powerhouse would be approximately 5.66 m³/s from November through April, compared to existing flows of 0 to 3.00 m³/s.

The primary fishery resources in both the lower Terror and Kizhuyak Rivers are pink and chum salmon (Oncorhynchus gorbuscha and

*Source of information: Federal Energy Regulation Commission (1981); Wilson et al. (1981).

O. keta, respectively). Both species contribute to an important commercial fishery and constitute a significant seasonal food resource of the Kodiak brown bear. These species enter the rivers in early July and spawn through August and early September. The primary spawning habitat exists in the lower (2.5-km) reaches of the mainstem and adjacent channels of both rivers, although the runs in the Kizhuyak River are smaller. The outmigration of fry occurs during April and May, soon after emergence. Other less abundant species that inhabit the two rivers include coho salmon (O. kisutch) and Dolly Varden (Salvelinus malma) which spawn from late summer through early fall. No fish occur in Terror Lake or the tributary streams where diversion dams will be constructed due to their precipitous nature.

The implications of the changes in post-project stream flows on fish habitat in the Terror and Kizhuyak Rivers were evaluated using the Incremental Methodology. Four reaches in each river were studied intensively using the IFG-4 (6 reaches) and the IFG-2 (2 reaches) hydraulic simulation models. Important life stages and target species included spawning (pink, chum, coho, Dolly Varden), fry (coho and Dolly Varden), and juveniles (coho and Dolly Varden). Interim suitability curves were initially developed based on discussions with state and federal fisheries biologists and a search of the relevant literature (from Alaska only). Important habitat parameters included depth, velocity, and substrate for spawning and depth and velocity for rearing (fry and juveniles). Suitability curves for temperature were not developed because the project would not significantly alter the thermal regimes of the rivers. Similarly, cover surveys indicated that adequate cover was available throughout the watersheds. Final site-specific suitability curves were developed later on the basis that the nature of the available habitat and the microhabitat preferences of a species in a particular river could vary significantly within the region.

To evaluate the effects of the proposed project on salmonid resources, the percent reduction in WUA from the optimum discharge

(defined as that discharge which optimizes WUA for more than one species and more than one life stage concurrently) was examined for average and 1-in-10 low water years under pre- and post-project conditions. In the primary spawning area of the lower Terror River, post-project 1-in-10 low water year conditions would result in a 10 to 15% reduction in optimal WUA during late summer. Instream releases of 4.25 m³/s, if required, would conserve approximately 95% of optimal WUA for spawning. The decrease in flow in the upper Kizhuyak River (above the powerhouse), where the gradient is steep and the substrate large, would result in an 18% increase in spawning WUA during an average water year and no change during a 1-in-10 low water year. A small decrease in WUA (1-2%) would occur in that portion of the river below the powerhouse. The higher post-project discharges in both the lower Kizhuyak and Terror Rivers during the normally low-flow period in winter could enhance the survival of salmon eggs and fry.

In both of the above examples, the level of analysis is commensurate with the degree of impact associated with alterations in the natural flow regime. Often the choice will be obvious; the presence of threatened or endangered species near the site dictates that the error bounds on the instream flow recommendation be as small as possible, so a Level III analysis would be required. However, this level of analysis is not required in every case involving potential conflicts over water use. Other approaches (e.g., R-2 Cross, Usable Width) that usually require considerably less time and money may be appropriate. The criteria presented in Section 4.2.2 should assist developers (or other users) in determining the required level of analysis. The importance of consultation with the appropriate local, state, and/or federal fishery agencies or groups during the initial stages of project planning when the instream flow issue is first addressed cannot be emphasized enough.

4.3 Planning for Instream Flow Assessments

As noted previously, instream flow needs must be assessed in the early stages of project development. Because stream flow characteristics are used in evaluating the size of the turbine(s) to be installed, any restrictions on the flow available for generation, such as that required to meet the instream needs of fisheries, must be identified prior to ordering the generating equipment. Consequently, the issue of instream flow is most appropriately addressed in the feasibility study. This initial assessment should be conducted in consultation with those state and/or federal agencies that have responsibility for establishing instream flow requirements. Failure to consult in the very early stages of project development will only result in costly delays later. The approach recommended in Section 4.2 is designed to provide the guidance necessary to assess instream flow needs during these early stages. If conflicts between hydropower generation and other instream uses are identified, sufficient time should still be available for resolving the conflicts before a license or exemption application is submitted to the Federal Energy Regulatory Commission. Resolution will likely involve tradeoffs among the various users which, in most cases, will involve negotiations between hydropower developers and fishery managers. For recent information on this aspect of the instream flow issue, see Knapp (1980), Sweetman (1980), and White et al. (1980).

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550. Frank J. Wobber, Office of Environmental Research, Division of Ecological Research, Department of Energy, Mail Stop E201, Washington, DC 20545
551. Robert W. Wood, Office of Health and Environmental Research, Department of Energy, Washington, DC 20545
552. William B. Wren, Tennessee Valley Authority, Athens, AL 35611
553. R. A. Wright, Manager, Hydraulic Plant Equipment, Ontario Hydro, 700 University Avenue, Toronto M5G 1Xb, Canada
554. Kathy Yergeau (MCFRU), 310 Holdsworth Hall, University of Massachusetts, Amherst, MA 01003
555. David Zoellner, National Electric Cooperative Association, 1800 Massachusetts Ave., NW, Washington, DC 20036
- 556-765. Given distribution as shown in DOE/TIC-4500 under category UC-97e, Hydroelectric Power Generation