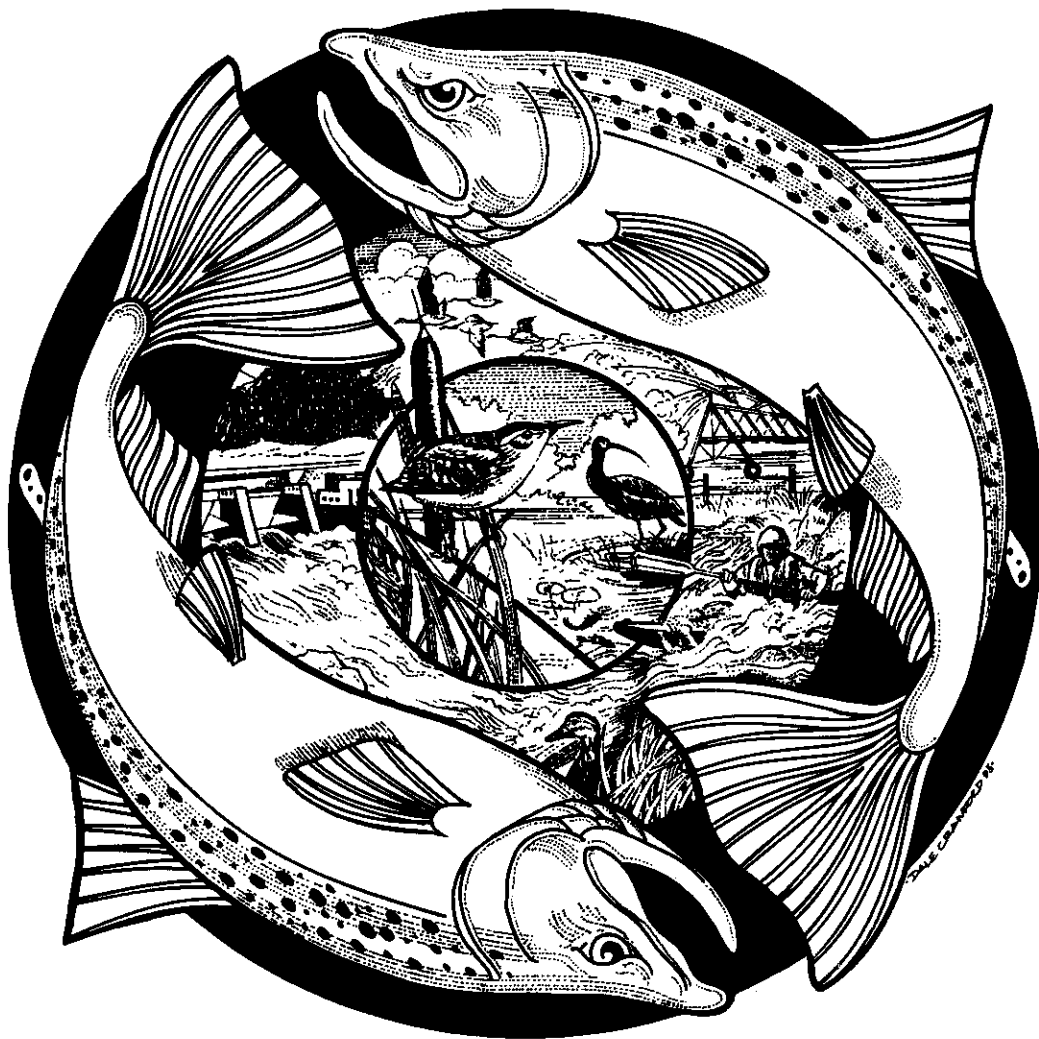

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The Instream Flow Incremental Methodology

A Primer for IFIM



National Biological Service
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by

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Preface

This booklet is a primer on the Instream Flow Incremental Methodology (IFIM). Our objective for this primer is to give you a short but comprehensive introduction to the background, philosophical and ecological underpinnings, individual components, and steps in applying IFIM. As a primer, we have tried to keep it simple. Scientific names and other technical details have been avoided, but the primer includes relevant definitions (with key words or phrases indicated in *italics* for their first use), summaries of the literature where you may wish to turn for further reading, and explanations to increase your understanding of what IFIM is all about and how it works. The primer should reinforce your growing knowledge and provide the necessary stepping stones into more advanced, certified training in IFIM methods.

This primer is divided into five more or less independent sections. The first section reviews the history of instream flow problems in the United States. Reading this section should provide you with an understanding of why IFIM emerged to solve certain complex water management problems and hint at future directions. The second section discusses the choice of instream flow methods and, more importantly, provides a framework for deciding whether IFIM is appropriate for the kind of problems you might be facing. The third section reviews the ecological underpinnings of IFIM from a historical perspective. This section is meant to show you the degree to which IFIM components, or models, represent the essence of the biological systems that we are attempting to understand. It is more detailed than the other sections and meant specifically to be of interest to biologists and ecologists. Section four delves into the broader philosophical, problem-solving approach embodied in IFIM. This perspective is important because the 'facts' alone rarely dictate good decisions; it is how we employ those facts to resolve instream flow problems in an interdisciplinary decision making arena that is important. The fifth section outlines the logical steps in applying IFIM and the information flow that holds them together. Here you will learn how to navigate through the IFIM process from tentative problem identification to problem resolution.

Our objectives for this primer do not stop at the last page. We hope that as you learn more about IFIM, you may be motivated to continue your learning by enrolling in one or more of several advanced courses dealing with IFIM. Please contact Conference Services at Colorado State University, Fort Collins, Colorado 80523, or call 303-491-7767 for more course information and a catalog of available National Biological Service courses sponsored by CSU. Technical questions should be directed to our office at the address below.

We encourage IFIM users to suggest improvements that may increase the utility and effectiveness of our products. Please use the comment form at the back of this booklet or send suggestions to:

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Chapter 1. The History of Instream Flow Problems and IFIM

Instream flow methods have been developed predominantly by biologists and hydrologists working for agencies having regulatory responsibility related to water development and management (Stalnaker and Arnette 1976). Such efforts over the last 30 years have provided the impetus for detailed ecological studies leading to a significant growth in the understanding of the relations between stream flow and aquatic habitats. Most of the empirical evidence gathered to date has focused on fish and benthic macro-invertebrate habitat requirements, with recent emphasis on the relation between stream flow and woody riparian vegetation and river-based recreation (Gore 1987; Orth 1987; Brown 1992; Shelby et al. 1992; Scott et al. 1993). Water management problem solving has matured from setting fixed *minimum flows* with no specific aquatic habitat benefit to *incremental methods* in which aquatic habitats are quantified as a function of stream discharge. Within this historical progression we also saw the application of a *water budget* which set the stage for having the fisheries manager be an integral part of an interdisciplinary decision-making system. This chapter will review the progression of circumstances and techniques leading to the development of IFIM and point toward what the future might hold.

Minimum Flow Standards Provide Minimal Protection

Following the large reservoir and water development era of the mid-twentieth century in North America, resource agencies became concerned over the loss of many miles of riverine fish and wildlife resources in the arid western United States. Consequently, several western states began issuing rules for protecting existing stream resources from future depletions caused by accelerated water development. Many assessment methods appeared during the 1960's and early 1970's. These techniques were based on hydrologic analysis of the water supply and hydraulic considerations of

critical stream channel segments, coupled with empirical observations of habitat quality and an understanding of riverine fish ecology, most notably the Pacific salmon and freshwater trouts. Collectively, the efforts led to a general class of instream flow assessment techniques (models) meant to help reserve a specific amount of water within the channel for the benefit of fish and other aquatic life (Wesche and Rechard 1980; Morhardt 1986; Stalnaker 1993). Application of these methods usually resulted in a single threshold or 'minimum' flow value for a specified stream reach below which water may not be withdrawn for consumptive water use. The minimum flow is almost always less than the optimal or pristine habitat condition, yet these 'reservations' of water form the current basis for issuing water permits in many states. See MacDonnell et al. (1989) and Lamb and Lord (1992) for recent discussions of the status of state recognition and protection of flowing water for instream flow.

Impact Analyses Lead to Increased Resource Protection

Following enactment of the National Environmental Policy Act (NEPA) of 1970, attention was shifted from minimum flows to the evaluation of alternative designs and operations of federally funded water projects. Methods capable of quantifying the effect of incremental changes in streamflow to evaluate a series of possible alternative development schemes were needed (Stalnaker 1993). This need led to the development of habitat versus discharge functions developed from life-stage-specific relations for selected species, that is, fish passage, spawning, and rearing habitat versus flow for trout or salmon. Corroborating research took the form of analyses correlating the general well-being of fish populations (usually in terms of measured standing crop) with various physical and chemical attributes of the stream flow regime and its interaction with the stream channel structure

(Binns and Eiserman 1979). A set of these variables consistently was shown to contribute significantly to the variation in fish population and production. These variables were water velocity, minimal water depths, instream objects such as cover, bottom substrate materials (with particular emphasis on the amount of fines in the interstitial spaces within coarse bed elements), water temperature, dissolved oxygen, total alkalinity, turbidity, and light penetration through the water column (Gosse and Helm 1981; Shirvell and Dungey 1983). These variables were integrated into methodologies for analyzing the consequences of proposed water withdrawal or storage-release activities and were applied to many federal water projects operated by the Bureau of Reclamation, Army Corps of Engineers, and Tennessee Valley Authority (Nestler et al. 1989).

During the late 1970's and early 1980's, an era of small hydropower development began. Hundreds of proposed hydropower sites in the Pacific Northwest and New England regions of the United States came under intensive examination by state and federal fishery management interests. During this transition period from evaluating large federal reservoirs to evaluating license applications for small hydropower, the Instream Flow Incremental Methodology (IFIM) was developed under the guidance of the U.S. Fish and Wildlife Service (Trihey and Stalnaker 1985). This methodology attempted to integrate the planning concepts of water supply, analytical models from hydraulic and water quality engineering, and empirically derived habitat versus flow functions. This methodology produced simulations of the quantity and quality of 'potential habitat' resulting from proposed water development, illustrated through a series of alternative flow regimes. Such efforts involving incremental methods and analyses of alternatives through time were further enhanced during the next 10 years, driven by several hundred relicensing applications submitted to the Federal Energy Regulatory Commission. Most of these applications involved reservoirs that had been in place for 30–50 years without any downstream instream flow considerations factored into their operating procedures.

Opportunities were seen by the natural resource agencies to restore riverine aquatic resources that had been impacted (occasionally eliminated) for many decades. Conversely, many hydropower companies wanted to shift their operating protocol toward hydropeaking and pump-storage to enhance the revenues at existing installations. Many of

these peaking projects operated by private power companies or public utilities were readily accessible for recreational use. The recreational interests seized on the relicensing opportunity as a means to enhance river recreational use by canoes, kayaks, and rafts. NEPA guidelines for examining alternatives and hydropower relicensing forced United States decision makers to balance potential conflicts among users of the riverine resources. Incremental methods became the tools of choice for quantitatively describing the consequences of alternative ways of managing flowing waters, setting the stage for negotiation among various interest groups and better informing the decision makers in their role in conflict resolution (Stalnaker 1993).

Water Budgets Establish Fisheries as a Legitimate Management Purpose

As the multiple-use ethic emerged over the last two decades, it became clear that simply allocating part of the water supply to various uses is not sufficient to resolve conflicts. The same water can be used many times if it is managed so that the timing of release serves instream purposes while still being delivered to downstream consumptive users. This multiple-use management philosophy, exemplified by the Pacific Northwest Electric Power Planning and Conservation Act of 1980 and subsequent efforts by the Bonneville Power Authority, allowed federal, state, and tribal fishery biologists to identify management prescriptions for restoration and enhancement of the anadromous salmon runs in the Columbia River basin. A minimum flow did not provide sufficient protection for stream resources during drought cycles, nor did it provide the opportunity for optimal fish production during wet years. Water budgets allocating a portion of water stored in upstream reservoirs for fishery benefits reserve flows that could be released when they were most needed (Waddle 1991). When downstream water users are not calling for delivery through critical spawning or rearing reaches, the 'fish water' can be released to relieve any habitat-induced *bottlenecks*.

A recent case study by the National Research Council (1992) recognized the value of reservoir release management in alleviating conflict and enhancing multiple uses (including instream) within arid western United States river basins. The

Yakima River basin in Washington, focusing on Pacific salmon restoration, and the Truckee-Carson River systems in Nevada, emphasizing endangered species and terminal wetland habitat recovery, were highlighted as examples of emerging multiple-use management. Assigning a reservoir water budget to the fisheries for downstream habitat management is now being seriously considered during the operations evaluation phase of many large federal water storage projects. The traditional water user groups (for example, irrigated agriculture, municipal, and industrial) may prefer such reservoir water budget management because the fish water is treated the same as other water in the system, and the call for water must be decided by the fishery manager, relieving the reservoir operator and other users in the system from having to decide how and when the instream flows are to be delivered.

The shift from a set of minimum flow constraints to a water budget set aside specifically for fisheries purposes changed the role of the fisheries manager in river systems in the United States. From now on, to be most effective, the fishery resource managers must become water and habitat managers. Thus, natural resource agencies need to acquire a more interdisciplinary mix among their employees. These contemporary agencies must be prepared to decide about the delivery of water on a daily basis during particular seasons and to decide what portion of the river basin fishery resource will be favored (and conversely what part sacrificed) during droughts. By adopting water budgets, a mutual 'sharing' of storage in federal water projects across all user groups during droughts is facilitated. Under the traditional diversionary allocation philosophy of 'first-in-time-first-in-right' practiced under Western water *appropriation doctrine*, the fishery may have first priority during a water-short year (if flows are reserved by appropriation) or last priority (if allocated a very junior water right). By gaining a 'seat at the management table' the instream-fishery interests get part of the water stored during high-flow periods for release when the most critical conditions occur downstream. Sharing the storage allows for delivery to relieve these critical conditions.

Multiple Use Implies Interdisciplinary Analyses

Multiple-use management of water at the river basin level is widely recognized as essential in the

United States. A recent study by the National Research Council (1992) points out that management of reservoirs for single purposes such as irrigation or hydro-electric production is no longer socially acceptable. Efficient use of water must incorporate a multitude of instream and consumptive uses throughout a river basin. This management will require an interdisciplinary group of professional water managers to establish procedures for evaluating the water supply, distributing the water, and sharing the consequences of low supply. Resolving conflicts among states and user groups sharing the same river system calls for interjurisdictional river boards or commissions to manage water stored in public reservoirs for instream and out-of-stream uses. Agency resource personnel will be asked to apply state-of-the-art tools, extensively tempered with judgement and experience, to day-to-day decision making. Fishery and recreation agency managers will make recommendations on seasonal and monthly bases, dependent on forecasted water supply and available storage. Stream ecologists have a substantial challenge before them to provide research data to enhance the ability of resource managers to make these decisions. Research is needed to improve and validate relations between fish, wildlife, and riparian vegetation and the stream flow regime. New research is needed for groups of organisms (guilds) and habitat variables that are not currently factored into the decisionmaking process.

Development of IFIM

IFIM unfolded against the backdrop of minimum flow standards, quantitative impact analyses, water budgets, and interdisciplinary analyses. The specific impetus was the National Environmental Policy Act, which mandated all federal water resource agencies to consider alternative water development and management schemes. This requirement placed increased responsibility on natural resource agencies for methods, evaluations, and recommendations related to reservoir storage and release and stream channel depletions. IFIM was developed by an interdisciplinary team and was founded on a basic understanding and description of the water supply and habitats within stream reaches of concern. Historical analysis of the flow regime using a monthly or weekly timestep to describe the reference or *baseline* hydrologic conditions was considered essential because this type of analysis was normal practice within the water re-

source engineering profession. Looking at stream-flow through time (by constructing a hydrologic *time series*) allows one to compare the frequency and duration of wet and dry periods, to examine the difference between snow-melt and rain-driven systems, and to determine the intensity and duration of short-term events such as cloud bursts and peaking cycles. To influence operating decisions within large-scale water development settings, a tool was needed that underscored conflicts and complementary water uses, considered and evaluated each user's needs, and was understandable, acceptable, and easy to use by a broad clientele. Such decision arenas involve a diversity of disciplines, including engineers, hydrologists, biologists, recreation planners, lawyers, and political scientists.

The U.S. Fish and Wildlife Service Directorate requested direct input from other agencies in the development of this special methodology. Water resource professionals were assigned to work on this cooperative effort for periods up to 4 years. Engineering, water quality modeling, and planning expertise came from the U.S. Bureau of Reclamation, Soil Conservation Service, Army Corps of Engineers, Environmental Protection Agency, and university scientists. Expertise in aquatic ecology, fishery biology, water law, institutional arrangements, and planning came from state agencies. The Intergovernmental Personnel Act provided the vehicle for these assignments from state organizations.

This interagency effort led to the conclusion that an analytical methodology should handle a variety of instream flow problems, from simple diversions from the stream channel to complex storage and

release schemes involving hydropeaking schedules, pump-storage, and a network of interconnected reservoirs. For such a methodology to be suitable for evaluating alternatives, it had to be useful in identifying, evaluating, and comparing potential solutions, be capable of being tailored to a specific stream reach, and be expandable such that reach information could be applied throughout a river basin. With this general charter, and building on historical planning practices using stream reach hydrology, IFIM has developed over a period of 15 years into a river network analysis that incorporates fish habitat, recreational opportunity, and woody vegetation response to alternative water management schemes (Bartholow and Waddle 1986; Milhous et al. 1989; Auble et al. 1991). Information is presented as a time series of flow and habitat at selected points within a river system (Milhous et al. 1990). Figure 1.1 illustrates the general information flow within IFIM; we will discuss the various components of IFIM throughout the remainder of this booklet.

Optimizing for any one use is contrary to the general philosophy of multiple use; efficiency of use is defined as the greatest return in the number and quantity of uses, with emphasis on simultaneous use. It is imprudent to use the simple, intermediate output (for example, flow/habitat or flow/recreation functions) to argue for a minimum release or flow standard chosen from the maximum value on a flow versus habitat graph. The timing of events across seasons is critical to the reproductive success and relative strength of year classes within fish populations. The temporal distribution of strong versus weak year classes shows the well-being of the fish

Overview of Incremental Methodology

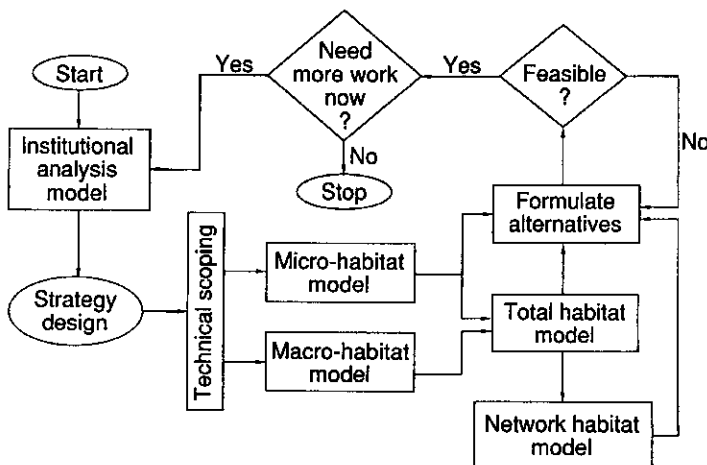


Fig. 1.1. Overview of the Instream Flow Incremental Methodology.

population and, more importantly, determines the number of adults available to the fishery on an annual basis. To illustrate this point, we must combine the habitat functions and hydrologic time series into a quasi population analysis by displaying habitat quality and quantity through time and space. The IFIM methodology translates the baseline hydrology into a description of the available or usable habitat present during that historical period. This description is often called the resource benchmark, from which fishery scientists identify enhancements and impacts resulting from proposed water delivery schedules.

By examining recent historical conditions (say the last 5–10 years) using the power of computer simulation, it is possible to calibrate a system model using historical data such as annual population indices and trend information, creel census information, computed year-class strength data from age and growth studies, or anecdotal information on the general well-being of fish populations in one year versus another. If the fishery manager can show that a simulated habitat analysis over a 10–20-year historical hydrologic regime agrees with historical information on good years versus poor years in the fishery, much more credence can be placed in those models for comparing various alternative futures.

IFIM has been designed for river system management by providing an organizational framework for evaluating and formulating alternative water management options. It has been built on the philosophical foundation of hydrological analyses to understand the limits of water supply. Analysis offers a description, evaluation, and comparative display of water use throughout a river system. Emphasis is placed on the display of usable habitat across several years to capture the variability in both water supply and habitat. Such comparative information enhances negotiations in the planning and management of the riverine resources. Sharing limited water during drought cycles and the management of timed releases contribute to compatibility between instream and out-of-stream user groups and allow for rapid recovery of aquatic populations during favorable conditions.

We are often asked to provide cost estimates for conducting an IFIM study. One might say that about 80% of IFIM studies for a single river segment could be conducted within a 12-month time frame and cost less than \$45,000. But "it depends" is probably the best answer. It depends on how many variables are included in the various

models, the sampling strategy, the standards for quality assurance and quality control, the size of the river and accessibility of the physical site, the experience of those performing the work, the number of alternatives to be analyzed, and the number of times Murphy meddled from start to finish. A careful scoping is always in order before proceeding.

Extending IFIM Into the Future

Reiser et al. (1989) surveyed IFIM users and found that the highest priority research needs are to (1) define the relation between flow, habitat, and fish production; (2) validate and test the relation of habitat measurements to fish production; and (3) develop new methods for determining flow requirements. Contemporary research (Hagar et al. 1988; Cheslak and Jacobson 1990; Auble et al. 1991; EA Engineering, Science and Technology 1991; Nehring and Anderson 1993; Williamson et al. 1993) is broadening the role of IFIM to provide fisheries management as well as habitat management capabilities.

The relation between flow, habitat, and fish production is based on work relating the amount and quality of habitat available to the fish population at critical stages in its life history (Burns 1971; Mundie and Traber 1983; Morhardt and Mesick 1988). In riverine systems the amount and quantity of suitable habitat can be highly variable within and among years. At any time, the observed population and biomass of fish may be influenced (depressed or stimulated) by many preceding habitat events. Long-term habitat reductions from reduced flows may also be important in determining the fish population and production (Bovee 1988). National Biological Service scientists are testing models of these new concepts on anadromous salmonid populations in California and resident trout populations in Colorado (Bartholow and Waddle 1994; Bartholow et al. 1993).

Goals of contemporary research are (1) development and validation of a dynamic fishery population model, including response to flow-related limiting events, specifically *physical habitat* and temperature; (2) testing of habitat bottleneck hypotheses; (3) development of processes for evaluating water management strategies to achieve fish population objectives; (4) testing of strategies for long-term population support including biotic interactions; and (5) improvement to those

existing components of the IFIM necessary to provide a smoothly working set of analytical tools for fish population analysis. Such efforts should expand the state of fisheries science and the art of water management by clarifying the effects of population-limiting habitat events and water temperatures on movement, growth, and mortality rates of fishes and should provide direct feedback between fish populations and reservoir op-

erations with water budgets for fishery management purposes.

Current emphasis in many federal agencies is on ecosystem planning and management. It is too early to tell how IFIM techniques may be utilized in this current push, but if utilized, applications must be broader in geographic scope and emphasize longer time horizons than have typically been employed in the past.

Chapter 2. Choosing the Appropriate Assessment Tools

Every water management decision that includes instream flow protection offers a unique challenge. Instream flow decisions may include a federal permit or license, an operating schedule for a water storage project, a state instream flow water right, or an element in a state water management plan. No matter which of these decisions is being addressed, each requires an understanding of several factors before an appropriate instream flow assessment technique can be chosen.

Several considerations guide the choice of technology for instream flow needs assessments, including statutory authority, history of water use, technical orientation, available fiscal resources, and time allowed to complete studies. In addition, there is an ongoing debate about the relative scientific merits of competing instream flow assessment technologies (Granholm et al. 1985; Mathur et al. 1985; Estes and Orsborn 1986). All factors heighten the challenge of selecting the right technology to guide establishment of stream flow protection. When choosing a technology, the analysts' concentration is often initially directed to the technical details of the procedures, such as measurement of stream transects or operation of computer models. However, experienced professional biologists and engineers responsible for assessments recognize that harder policy questions must first be answered. Analysts ultimately decide to use a technique as much because it fits the political and environmental problems they face as because the technology meets scientific standards (Lamb 1986).

A Dichotomy of Techniques

Political and environmental problems can be conveniently divided into two categories depending on the objectives of the decision process: standard-setting or incremental. In a standard-setting problem, the analyst is called on to recommend an instream flow requirement to guide general and, usually, low-intensity decisions setting a limit

below which water cannot be diverted (Trihey and Stalnaker 1985). This process might be called preliminary planning. An incremental problem refers to a high-intensity, high-stakes negotiation over a specific development project. The term incremental implies the need to answer the following question: What happens to the variable of interest (e.g., aquatic habitat, recreation value) when the flow changes?

Rather than a clear dichotomy, it may be appropriate to picture these two types of decisions on a continuum ranging from the setting of noncontroversial standards for overall planning to conflict over establishing incremental differences in flow levels. No matter where on the continuum a problem falls, there is an additional question: How many variables are important? The answer to this question may be as simple as saying the problem is one species of fish or one type of recreation. The answer may also be expressed as a flow regime that meets the needs of several decision variables. For example, a flow regime may be instituted to satisfy channel and riparian maintenance, fish habitat, and recreational uses of the water. Although it is most common for incremental problems to present themselves as multi-purpose questions, it is not uncommon for standard-setting questions to require answers for more than one decision variable.

Whether a problem falls under the category of standard-setting or incremental is not a question of scientific credibility; defensible scientific analysis is always required because answers to both types of questions must be trustworthy. Moreover, expert judgement is required in both standard-setting and incremental problems. This judgement comes into play in reaching conclusions based on the technology that is chosen, as well as in choosing the appropriate method. There is one other consideration. Standard-setting techniques are inappropriate for *brokered decisions* because brokered decisions require the exploration of alternatives. In other words, the standard that has

been set is, by definition, essentially non-negotiable. Standard-setting techniques might be appropriate for *arbitrated decisions* where the analyst feels safe that the standard-setting reflects the best evidence (or the most equitable position), that is, whenever there is a rebuttable presumption that the analyst is correct. The problem still arises in the mid-range situations when the analyst is forced to give a quick answer that will become the subject of negotiation or arbitration.

Different technical solutions are appropriate for each of the two poles on this continuum. On the one hand, inexpensive, straightforward, rule-of-thumb solutions are well-suited to standard-setting tasks. For these tasks, the considerations are certainty that the planning objectives will be met and that the recommendations will be easily communicated to policy makers. On the other hand, incremental problems are likely to require an in-depth knowledge of the flow requirements of fish and wildlife, recreation, water quality, and other instream uses, as well as the ability to integrate these concerns into plans for a specific project.

Much of the debate that surrounds instream flow technology is not about the approaches most suited to these extreme cases but about the best technology for problems that fall somewhere in between. In this mid-range, solutions may have long time-horizons while still leading to identifiable projects. Inevitably, a quick rule-of-thumb method will be found inadequate, followed by a more complicated analysis and demands for compromise.

The choice of an instream flow technique for mid-range cases is further hampered by the need for low cost and speed in making the first recommendation. That first recommendation precedes a period of wrangling over project benefits and then negotiation of more in-depth studies. Finally, these discussions conclude with an expensive technical analysis and hard bargaining over the professional judgements of those making and challenging the never-quite-final recommendations. Other situations can be found or imagined that would also fill this middle ground between long-range planning and specific project negotiations. The choice of initial and follow-up technologies in these types of disputes is a balancing act.

The first simple technology chosen will be linked through the study design to the final project negotiation. How well this linkage can be achieved depends on several factors, including statutory authority, fiscal resources, training of

Table 2.1. The opposite ends of the problem-solving spectrum.

Standard-setting	Incremental
Low controversy project Reconnaissance-level planning	High controversy project Project-specific
Few decision variables Inexpensive Fast	Many decision variables Expensive Lengthy
Rule-of-thumb Less scientifically accepted	In-depth knowledge required More scientifically accepted
Not well-suited for bargaining	Designed for bargaining
Based on historical water supply	Based on fish or habitat

personnel, and management support for the investigations. Most of all, success in moving from planning studies to hard bargaining depends on whether the analysts guessed correctly about what would happen to their first recommendations (Olive and Lamb 1984). The range of instream flow assessment techniques can be illustrated both with a summary of these ideas in Table 2.1 and with the example that follows.

Standard-Setting Techniques

Several techniques are available for the long-range planning of instream flows for fisheries. In a low-intensity situation, not much detail is required because the questions are straightforward. Thus, a quick, reconnaissance-level, office-type approach may be used.

Most standard-setting occurs in statutory state instream flow protection programs (Lamb and Doerksen 1990). As one analyst observed, "[i]n most statutes, it is difficult to either ascertain legislative intent or determine if a proposed instream flow regime would satisfy the legislative purpose" (Beecher 1990). An instream flow standard should include the following elements (Beecher 1990): (1) the goal (such as non-degradation), (2) resources (such as fish species), (3) unit of measurement (such as flows in cubic feet per second [*cfs*] or habitat in *weighted usable area* [*WUA*]), (4) benchmark period (such as a 10-year period of record), and (5) protection statistic (such as the median habitat value for July).

Hydrologic Records

Of the many techniques available for standard-setting related to fisheries, the easiest to use requires data on the hydrologic records of a stream. The use of stream gage records assumes that measured flows support aquatic resources at acceptable levels (Wesche and Rechar 1980). This assumption only applies where streams are essentially undeveloped or where the pattern of development has been stable for a long period.

Eastern states increasingly face planning problems associated with undeveloped streams, whereas most western states have streams already encumbered with sophisticated development projects. In situations where stream flow is depleted or regulated, the natural flow regime can be reconstructed from gage records to account for water diversions and stream modifications (an art discussed by Bayha (1978); see also other standard techniques in Riggs (1968)). This approach is satisfactory only if the analyst has information on, or is willing to make assumptions about, the condition of the fishery before development.

Even when pre-development data are available, it is difficult to predict future impacts on the aquatic resources. On some developed streams, channel structure and fish populations have adjusted to the new flow regime. Existing water developments may have dampened chronic low- or high-flow events, thus enhancing the fishery. Developing a knowledge of post-project conditions will require field investigations. In any case, selecting flows from historical records in the presence of existing development is a limited long-range planning technique.

Where it is possible to use historical records, several questions arise, for example: Is it best to recommend a flow based on natural or altered conditions? What percentage of the historical stream flow should be recommended? One solution is to use the 'aquatic base flow' (Larson 1981; Kulik 1990). This technique selects the median flow for the lowest flow month (typically August or September) as adequate throughout the year, unless additional flow releases are required to meet the needs for spawning and incubation. Another planning scheme involves the use of median monthly flows (Bovee 1982). This monthly flow level is a surrogate for the natural annual pattern of stream flows because it provides a flow that typifies historical flows for each month.

A hydrologic technique that is inappropriate for establishing instream flows for fish is the 7-day-

10-year low flow (expressed as 7Q10). This statistic was developed to ensure that water treatment plants did not violate water quality standards during droughts (Velz 1984). It establishes a very low flow that must not be diminished in quality if treated water is discharged into it. Thus, it requires a high level of sewage treatment but does not address the flow requirements of fish.

The Tennant Method

The most renowned of the long-range planning tools for fisheries is that of Tennant (1976). In its original form, the Tennant Method arrays flow levels for seasonal periods based on percentages of the mean annual flow. Tennant used 10 years of personal observations in Montana and the mid-west to categorize streams into varying quality trout habitat based on recorded flow. He also recommended that periodic high flows be provided to remove silt, sediment, and other bed material. The U.S.D.A. Forest Service has argued that an annual high flow event is needed to protect the channel structure in alluvial streams (U.S.D.A. Forest Service 1984). Because Tennant had in mind more of a scouring purpose, his approach was not based on these morphological considerations.

Table 2.2 shows Tennant's recommendations for stream flow to support varying qualities of fish habitat based on his observations of how to best mimic nature's hydrology. Some states recognize that they cannot apply Tennant's recommendations to their own streams without adjustments. In these cases, changes are made for the species of interest and the types of streams in a particular state.

Tennant's method and other desk-top tools anticipate that hydrologic records are available; when they are not, instream flows can still be recommended based on a surrogate indicator. Drainage area is an example of such an indicator for managed streams. In one drainage area technique, a minimum instream flow value, or base flow, of 0.5 cubic feet per second per square mile (cfs/m; 0.0055 cms/km²) of drainage area is recommended for the summer months. Higher flows in fall and spring are used to accommodate the spawning and incubation of anadromous species (Larson 1981). Use of this technique for non-anadromous species would, of course, require a different set of rules.

These simple, rule-of-thumb techniques are very useful in the development of long-range

Table 2.2. Instream flow analysis based on the Tennant method (Tennant 1976).

Health of habitat	Percent of mean annual flow	
	October–March	April–September
Flushing or maximum	200	200
Optimum	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	<10	<10

planning recommendations, though they may be criticized for technical reasons (Kulik 1990). A more difficult question arises when a problem is cast as long-range planning but is clearly destined to become an intense negotiation within a very short time. This change sometimes develops because decision makers do not understand instream flow analysis and believe that a simple one-time answer will accommodate a complex project. At other times, policy requires a level of analytic effort commensurate with some larger public purpose. While the call goes out for a speedy recommendation, the expectation is for a sophisticated answer.

Mid-Range Techniques: A Little More Than Basic Standard-Setting But Not Quite Incrementalism

Modified Tennant Approach

At the lower end of stream flow quantification problems for fisheries, where the controversy is not intense but time is nevertheless a constraint, a specially tailored Tennant approach might be applied. This approach calls for the repetition of all of Tennant's steps. The analyst would begin by observing habitats known to be important in the species' life history and by studying the stream during flows approximating various percentages of the mean annual flow. After collecting data on cross-sectional width, depth, and velocity of the stream at each flow, a set of recommendations could be made to resemble the set shown in Table 2.2. The difference would be that the new table would reflect the empirical observations of the

analyst, instead of Tennant, and would be tailored specifically to the species and stream of interest.

Wetted Perimeter Technique

The wetted perimeter technique (Nelson 1980) is another method frequently used with some success, in Montana and elsewhere. In this hydraulic approach, a desired low-flow value is chosen from a habitat index that incorporates stream channel characteristics (Trihey and Stalnaker 1985). The wetted perimeter technique selects the narrowest wetted bottom of the stream cross section that is estimated to protect the minimum habitat needs. The relation of wetted perimeter to cross section is shown in Fig. 2.1.

The analyst selects an area assumed to be critical for the stream's functioning (typically a riffle) as an index of habitat for the rest of the stream. When a riffle is used in the analysis, the assumption is that minimum flow satisfies the needs for food production, fish passage, and spawning. The usual procedure is to choose the break or 'point of diminishing returns' in the stream's wetted perimeter versus discharge relation as a surrogate for minimally acceptable habitat. This inflection point represents that flow above which the rate of wetted perimeter gain begins to slow. Once this level of flow is estimated, other habitat areas, such as pools and runs, are also assumed to be satisfactorily protected. Because the shape of the channel can influence the results of the analysis, this technique is usually applied to streams with cross sections that are wide, shallow, and relatively rectangular.

Other fisheries-related standard-setting methods in this middle ground include the Arkansas Method (Filipek et al. 1987), Hoppe Method (Hoppe 1975), and Texas Method (Mathews and

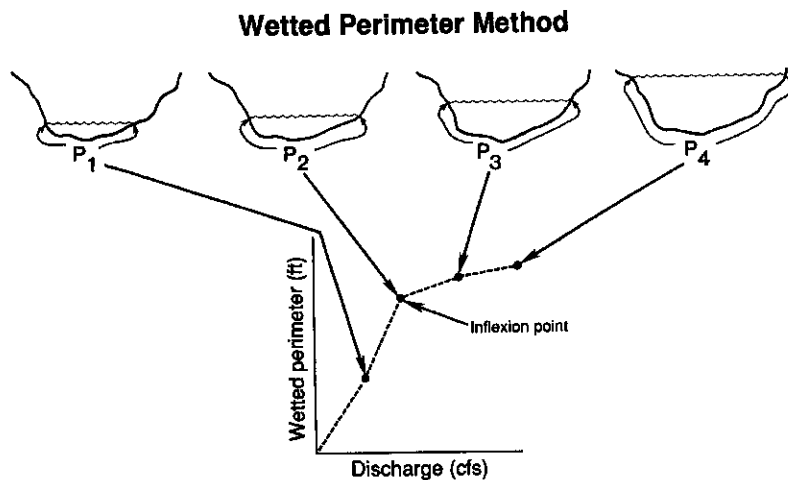


Fig. 2.1. Use of the wetted perimeter method to estimate instream flows.

Bao 1991). Additional methods are described by Wesche and Rechar (1980).

Multiple Attribute Standard-Setting Methods

All of the methods previously discussed result in a single stream flow value, recommended for a defined period in individual streams. These methods have given rise to the term 'minimum flow.' Such standard-setting recommendations are hard to use in negotiation because too little information is available to allow an informed compromise. Much more must be done to answer the hard questions during negotiation (Wilds 1985). Answering these hard questions requires moving away from tools leading only to minimum flows. Techniques need to show the relation between the amount of habitat and stream flow. Such approaches allow the analyst to display impacts on the resource of interest for any given flow.

Tools that can be used to achieve this result fall into two groups. The first uses statistical analyses to correlate environmental features of a stream with fish population size. An example of this type of analysis is Wyoming's Habitat Quality Index (HQI), described by Binns (1982). An HQI is developed by regressing several habitat variables against the standing crop of fish. This procedure is stream-specific, and the recommendations are related to critical low flows. The second group of tools link open channel hydraulics with known elements of fish behavior. Examples include the Physical Habitat Simulation System (*PHABSIM*), as first presented by Bovee and Milhous (1978) and discussed again by Bovee (1982; also see Milhous et al.

1984). An important explicit element of *PHABSIM* and HQI is an analysis of water supply. A water supply analysis should accompany any standard-setting technique to answer the question: What is the likelihood that water will be available to meet the standard?

Many people confuse IFIM with the Physical Habitat Simulation System (*PHABSIM*). Whereas IFIM is a general problem-solving approach employing systems analysis techniques, *PHABSIM* is a specific model designed to calculate an index to the amount of microhabitat available for different life stages at different flow levels. Developed from techniques used in the Pacific Northwest, *PHABSIM* requires the collection of field data on stream cross sections and habitat features, hydraulic simulation to evaluate habitat variables at different flows, and species *suitability criteria* to calculate stream characteristics with available habitat at alternate flows. Depending on the complexity of the proposed project and the complexity of the stream under study, the collection of field data ranges from inexpensive and quick to costly and time consuming.

Using *PHABSIM* enables the investigator to inform decision makers about the impacts on fish habitat of different flows for different life stages. Attention is typically given to the life stages of fish species that are of special concern for management or that are thought to be most sensitive to change. The resulting relation between flow and habitat, generated by linking species criteria with flow-dependent stream channel characteristics, aids in negotiation by more clearly depicting the effect that less-than-optimum flow will have on habitat (Geer 1980). Figure 2.2 is an example of a typical habitat

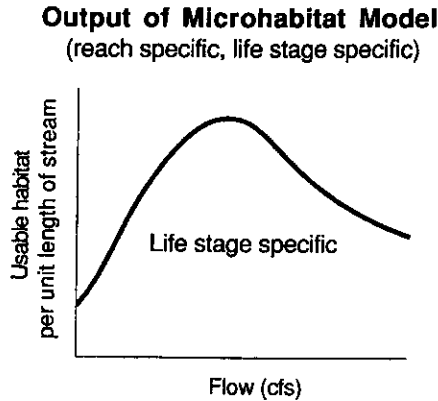


Fig. 2.2. Flow-habitat relation developed by using PHABSIM.

versus flow function showing how incremental changes in flow result in quantifiable changes in habitat value.

Even the best mid-range techniques leave the analyst open to criticism. There are two frequently challenged features of PHABSIM. First is the necessity for species suitability criteria (estimated species responses to stream variables, normalized onto a response curve). Figure 2.3 depicts example suitability criteria for two life stages of brown trout. The curves show that adults use deeper and faster water than do juveniles. These criteria may be established by several methods ranging from solicitation of expert opinion to site-specific collection and verification of field data (Bovee 1986; Modde and Hardy 1992, (Thomas and Bovee 1993). All of the criteria development methods have been challenged to some degree.

The second criticism concerns the requirement to analyze habitat species by species, which may not account for habitat selection affected by interspecies competition (Ross 1986; Hearn 1987; Modde et al. 1991). Note that the quality of habitat suitability data, along with the significance of PHABSIM's driving variables (e.g., depth, velocity, substrate material, and cover), forms the basis for most criticisms of this technique (Morhardt 1986). To satisfy such criticisms, more in-depth analysis is needed than is usually undertaken in simple PHABSIM or HQI studies. PHABSIM is an incremental method in the sense that it predicts changes in habitat resulting from changes in flow, but it focuses on only a few variables affecting localized fish behavior and ignores the dynamics of habitat through time. The use of PHABSIM alone also ignores many other biotic factors such as inter- and intra-specific interactions.

Incremental Techniques

The mid-range techniques essentially provide temporal snapshots of stream resources. When the imperatives of negotiation or court proceedings require a more dynamic look at the instream flow question, other techniques are needed. These project bargaining problems have been labeled 'incremental' (Trihey and Stalnaker 1985) because a deep knowledge of how aquatic habitat value changes as a function of incremental changes in streamflow is required. This detailed quantification must be developed to prepare for negotiations

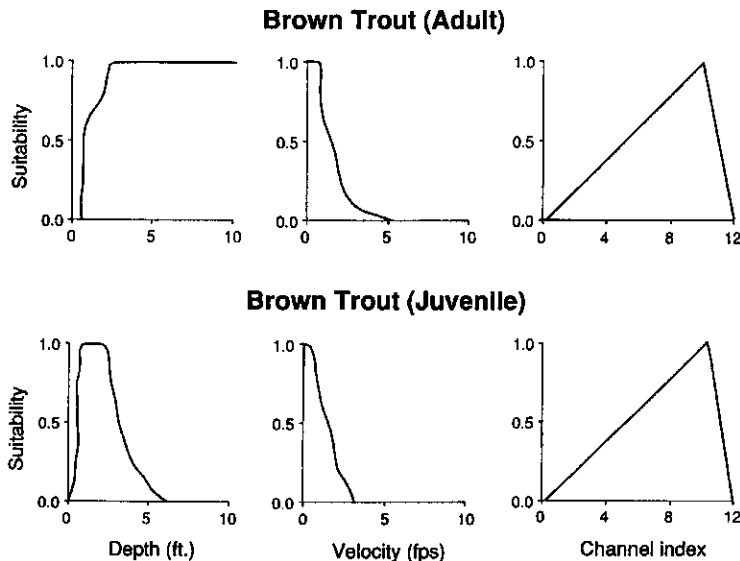


Fig. 2.3. Suitability-of-use curves for brown trout.

that involve assessment of the impacts of alternative project proposals.

Incremental problems often create a labyrinth of choices for the analyst who tries to anticipate questions and design stream flow research to accommodate likely needs. A simple PHABSIM or HQI analysis will not be sufficient in this setting. New steps, however, can sometimes be added to mid-range processes to help them fit more demanding problems. More often, as Olive and Lamb (1984) reported, a more comprehensive approach must be chosen. Although fish habitat is still the decision variable, when these more complex tools are used the analysis alone may require as long as 2 years to complete. Each study is preceded by negotiations covering study design and followed by negotiations in which results are debated. The total elapsed time for study design, data collection, and analysis may be more than 3 years. Replicate habitat sampling, biological sampling to develop habitat suitability criteria, and sediment and water routing studies, as well as physical habitat, temperature, and water quality simulations, may be necessary to accurately depict the effects of project operations (Sale 1985). These steps go far beyond what might be accomplished solely with PHABSIM.

The IFIM is one process designed to accomplish this intricate research based on knowledge of fish response to habitat features. Trihey and Stalnaker (1985) pointed out that processes like IFIM should be properly called methodologies rather than methods. Whereas 'method' connotes a single tool or concept, 'methodology' implies the linking of procedures, perhaps from several disciplines, to tackle a multi-faceted problem.

In IFIM, habitat suitability data come in two forms: *macrohabitat* and *microhabitat*. Macrohabitat suitability refers to variables that vary longitudinally downstream, such as water quality, channel morphology, discharge, and temperature. Microhabitat suitability refers to the same variables used in PHABSIM analysis: depth, velocity, substrate material, and cover. IFIM uses computer software to integrate these two measures of habitat into habitat units that are then related to flow over time, resulting in a Habitat Time Series. Figure 2.4 illustrates an example habitat time series and a population-size time series. Note that the population does not track the magnitude of the habitat trace, but rather is a function of the habitat capacity established by the minima.

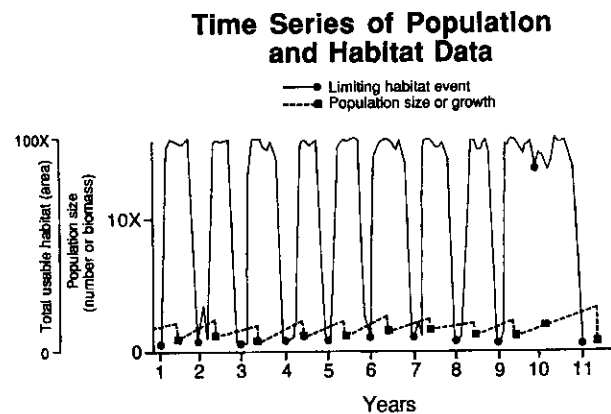


Fig. 2.4. Example fish population size related to usable habitat area using the IFIM.

The Habitat Time Series displays the availability of suitable habitat over a period of record. For example, if the period of record is 10 years (a good minimum number), the Habitat Time Series would display available habitat over that 10-year period. The time trace can be hourly, daily, or monthly. The analyst can answer many questions, such as What amount of habitat is available 90% of the time? What is the median habitat value? What would happen to the available habitat if the flow were reduced by 20% in high flow months? This information makes it possible to analyze the effects of changes in flow on each life stage of every species for which habitat suitability data are available. Where a standard-setting approach might result in a set of annual or seasonal minima below which flow could not fall, an incremental technique might result in a set of monthly or weekly flow envelopes, or windows, within which flow might vary depending on the water supply.

With a complex technique such as IFIM, an analyst must be able to document the scientific acceptance of all the technologies used and must be able to extrapolate from the data collected. Especially in intense negotiations, the assumptions of each method should be well understood, and careful planning should anticipate what special studies or modifications to a methodology are needed. The result should be the ability to predict changes in habitat over time, to make recommendations for wet and dry situations, and to quantify habitat *duration* phenomena similar to the *firm yield* concept in hydrology (Trihey 1981). Figure 2.5 illustrates the duration concept, which summarizes the availability of habitat values across time. For example, at least 15.5 habitat units are

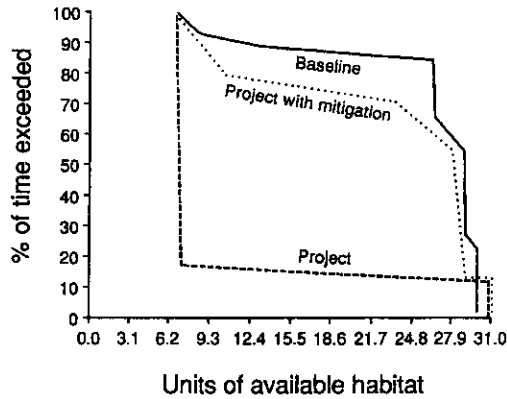


Fig. 2.5. Duration analysis of habitat available under baseline conditions, with-project, and after mitigation of project.

present about 90% of the time under the baseline condition, but only 15% of the time under the with-project condition.

An extension of these incremental, project-bargaining methodologies leads to predicting population responses to flow changes (Cheslak and Jacobson 1990; Bartholow et al. 1993). In an approach such as IFIM, these predictions will typically require hydrologic analyses, habitat models, sediment transport, water quality, and temperature analyses, as well as trophic level studies, validation of species criteria, studies of biomass, and population dynamics (Bovee 1982).

An alternative to combining these models into a predictive methodology would be long-term empirical observations of fish behavior. Such studies would document population responses to carefully controlled changes in flow over perhaps 20 years. Recent research on the South Platte River, Colorado, by Bovee (1988) demonstrated the rigorous analysis required to show the relation between flow and population. Bovee's work highlights that these relations can be established in theoretically sound, intuitively satisfying directions. We have already seen (Fig. 2.4) the form that these population responses to changes in flow over time are likely to take.

Conclusion

Several instream flow quantification procedures are commonly used. The Tennant Method and wetted perimeter technique are widely used in the

early stages of planning throughout the country. The wetted perimeter and conceptually similar approaches, concentrating on passage for upstream migrating salmon, are important first-cut analytical tools. The PHABSIM method is commonly used as a way to look at hydroelectric power projects (Bovee 1985), to set standards for controversial streams (Washington Department of Ecology 1987), and to develop conditions on federal permits and licenses (Cavendish and Duncan 1986). The PHABSIM method is sometimes used in very complex problems (Olive and Lamb 1984), but care must be taken to consider several intervening variables. IFIM is appropriate for the most controversial project assessments (Fig. 2.6; Trihey and Stalaker 1985).

Naturally, all of this experience with instream flow technology has led to a literature of evaluation and criticism. In particular, useful insights into choosing and employing instream flow assessment technologies were provided by Wesche and Rechar (1980), Bain et al. (1982), Orth and Maughan (1982), Loar (1985), Morhardt (1986), and Gore and Nestler (1988).

In conclusion, experience and the critical literature teach that there is simply no one best way. The choice of method or methodology depends on the circumstances. Literally dozens of approaches, models, and tools have been used, each developed to satisfy a specific need. To establish the necessary flow, the analyst must know the history and purpose of these techniques and must use this knowledge to make an informed choice of the best process to follow.

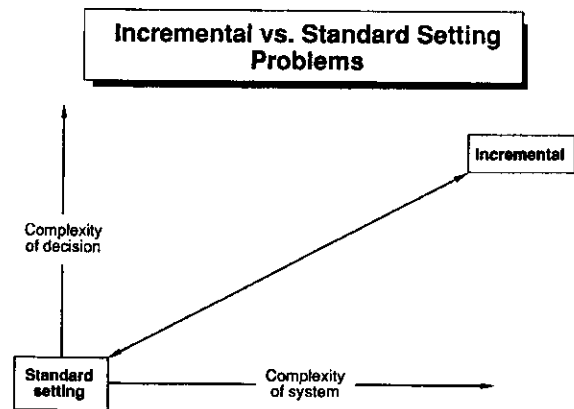


Fig. 2.6. Spectrum of problem-solving methodologies.

Chapter 3. Ecological Underpinnings of IFIM

IFIM is based on the analysis of habitat for stream-dwelling organisms under alternative management treatments. One could logically question why habitat was chosen as the decision variable in IFIM when there are so many other factors (such as stream productivity or fishing mortality) that can potentially influence fish populations. The simplest reason for basing the analysis on habitat is that IFIM was designed to quantify environmental impacts, and impacts to habitat are the most direct and quantifiable.

The more germane reason for basing IFIM on an analysis of habitat, however, is the progression of ecological studies that have implicated or directly shown that habitat is an important determinant of the distribution and abundance of fishes and aquatic invertebrates in streams. Though recent studies have concentrated on the microhabitat requirements of individual species and life stages, stream habitat studies have their origins in community ecology. Detailed information about life history requirements has led to the identification of key physical features of their habitat (e.g., depth, velocity, substrate material), quantification of their importance, and methods to estimate how they change as a function of stream flow.

Longitudinal Succession

Some of the earliest works relating the distribution and abundance of stream fishes to their habitat were conducted by Forbes (1907) and Shelford (1911). Shelford (1911) introduced the idea of 'longitudinal succession,' which he compared to a contemporary geologic theory developed by Davis (1909). Davis conceived the idea that the landscape develops systematically through erosional stages of youth, maturity, and old age. Headwater streams were considered 'young' and characterized by high energy and erratic behavior. A youthful stream was steep, had a relatively straight channel with large bed material, and typically exhibited a highly variable flow regime. In

contrast, a mature stream had a lower gradient, a meandering pattern in smaller bed material, and a less variable hydrograph. Longitudinal succession was based on the observation that species distribution and abundance also graded up and downstream, corresponding to Davis' stream-age classifications. Refer to Fig. 3.1.

Later authors tried to determine possible mechanisms or associations relating the faunal differences along the longitudinal profile with specific characteristics of individual locations. Trautman (1942) and Huet (1959) found that gradient was a good predictor of faunal regions, whereas Burton and Odum (1945) emphasized the effect of temperature along the headwater-to-lowland continuum. Going downstream in small watersheds, species were added to the assemblages rather than replacing other species. In contrast, species replacements occurred where distances were sufficiently large to create temperature barriers or where specific types of habitats were not present. However, studies of longitudinal succession were distinctly one-dimensional in that they did not attempt to distinguish the effects of temperature from the associated effects of habitat structure and complexity.

Habitat Segregation

The study of stream habitats on a two-dimensional scale developed as investigators observed that species tended to segregate by habitat type within the same longitudinal zone. Thompson and Hunt (1930) were among the earliest researchers to document the use of different habitat types by different species in short lengths of stream. Their study documented that fish communities tended to segregate by habitat type based on velocity, depth, substrate material, and cover type.

Hubbs (1941) postulated that the morphological and behavioral characteristics of stream-dwelling fishes were reflections of the habitat type in which the species most typically occurred. He

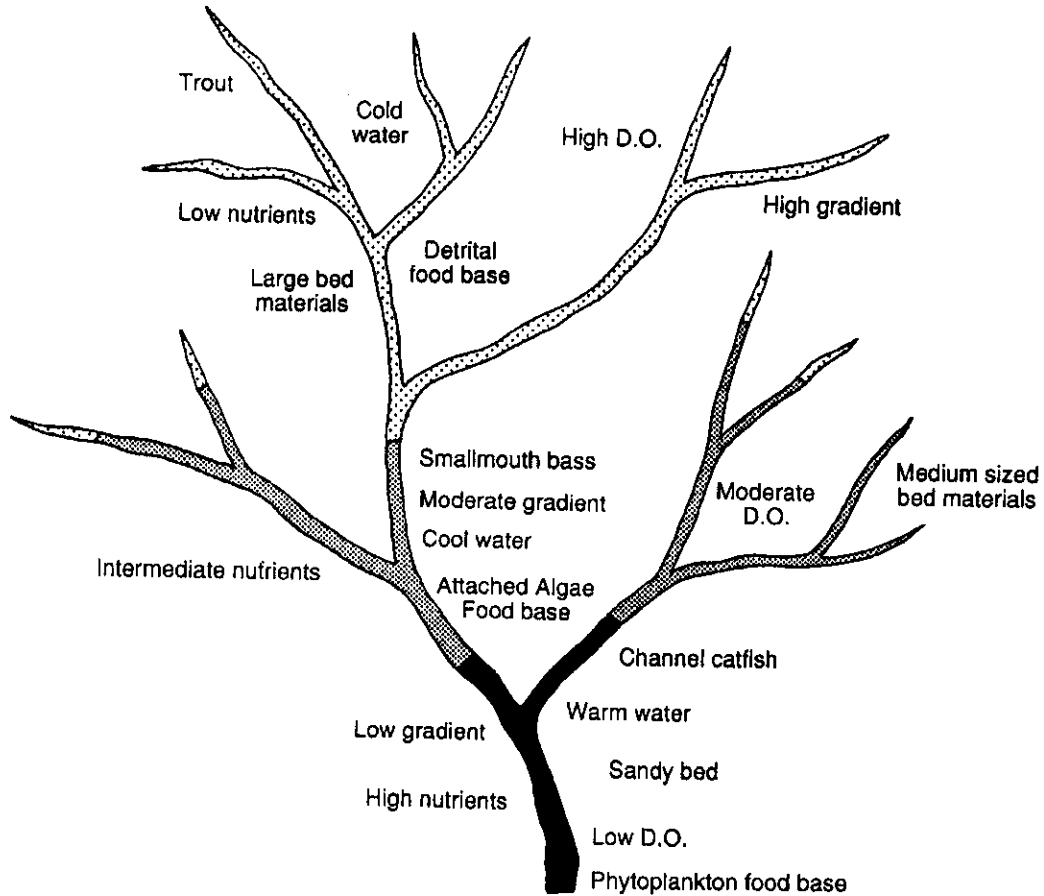


Fig. 3.1. Longitudinal succession schematic. *Shading* denotes approximate gradient from headwaters to intermediate stream to mature river.

made particular note of a fish's adaptations for inhabiting areas of high velocity, such as stream-lined body shape, expansive fins, and specialized mouth. Similar observations of the distributions of aquatic invertebrate species were documented by Sprules (1947). These investigators concluded that bottom type (substrate material) and velocity were the most significant determinants of invertebrate production and diversity in streams.

During the 1960's and 1970's, researchers learned that the distributions of fish and invertebrates were not random, even within the same habitat types, and began to investigate determinants of microhabitat selection (see Fig. 3.2). The three most commonly cited mechanisms involved reproductive success, energetic advantage, and biotic interactions (competition and predation).

Reproductive Success

Salmonid redds are typically located in areas with clean gravel, with enough velocity to prevent

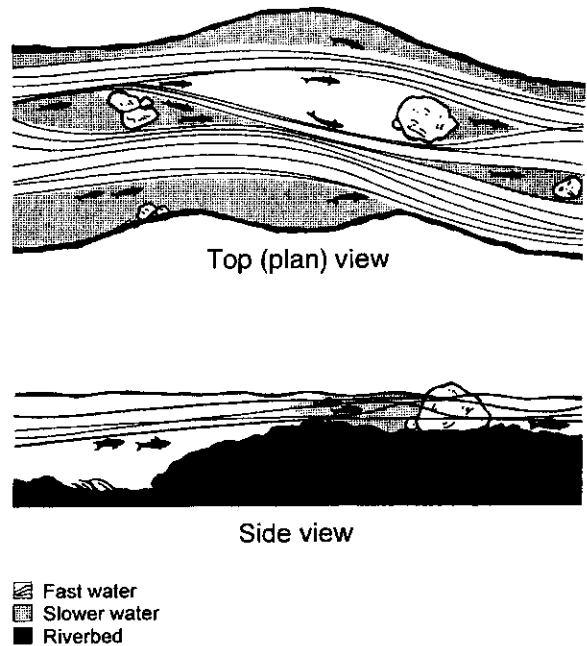


Fig. 3.2. An example of microhabitat specificity.

sediment deposition on the redd, and with the right combination of depth and bed form to ensure movement of water through the redd (Hooper 1973). Locations for redd construction are apparently selected because they provide the best conditions for incubation and hatching success. Rates of intra-gravel flow, water exchange between stream and gravel, and dissolved oxygen concentrations are important determinants of hatching success in salmonids. The exchange of water (measured as apparent or interstitial velocity) is directly and indirectly related to hydraulic conditions that enhance percolation through the redds (Coble 1961; Silver et al. 1963). Embryonic survival of steelhead was found to be significantly correlated with apparent velocity and intragravel dissolved oxygen concentrations (Coble 1961). Gangmark and Bakkala (1958) and Wickett (1954) likewise related salmon egg survival to dissolved oxygen content and intragravel velocity. Coble (1961) learned that the velocity of subsurface flow was mostly a function of hydraulic head and permeability. Hydraulic head is a function of the current's depth and bed form; the head creates a differential water pressure across and through the spawning bed. Permeability is related primarily to bed particle size and the amount of fine sediment occupying the interstitial spaces among the larger materials. Velocity and depth are important determinants of both bed particle size and the embeddedness of fine materials, thus influencing permeability.

Although the relations between microhabitat and spawning success are well documented in salmonids, many species of minnows spawn in microhabitats similar to those used by salmonids. These include chubs (Leonard et al. 1986; Lobb and Orth 1988), fallfish (Hubbs and Cooper 1936; Carbine 1939), and squawfish (Tyus 1990). Other species, such as stonerollers, daces, darters, and shiners, are known to spawn on the nests constructed by hornyhead and bigmouth chubs (Lachner 1952; Lobb and Orth 1988). This phenomenon led Lachner (1952) to suggest that the use of chub nests by other cyprinids for breeding purposes may be important in the maintenance of a large forage base for piscivorous species.

Spawning locations selected by centrarchids bear little resemblance to those chosen by salmonids but are also selected to maximize reproductive success. Whereas many species choose spawning locations with appreciable water movement through or over the substrate material, centrarchids characteristically select areas near some

form of instream cover where the velocity is zero or near zero (Newcomb 1992; Lukas 1993). Water movement over the nest greater than about 0.15 foot per second is often a significant cause of reproductive failure in smallmouth bass in lakes (Goff 1986) and in streams (Winemiller and Taylor 1982; Reynolds and O'Bara 1991). Lukas (1993) concluded that the primary cause of reproductive failure for smallmouth bass in the North Anna River (Virginia) was high flow. Some nests were destroyed by siltation during flood events, but more typically, when the velocities over the nest site increased, the guardian male abandoned the nest, or the eggs and larvae were washed away. Similar spawning behavior has been observed in other sunfishes. Rock bass and redbreast sunfish use spawning habitats that are similar to those used by smallmouth bass (Monahan 1991; Lukas 1993). Reproductive failure in redbreast sunfish was also linked to high water velocities over nests (Lukas 1993) by mechanisms similar to those found for smallmouth bass.

Energetics

Riverine environments are distinguished from other types of aquatic habitat by the presence of a current. Velocity is arguably the most significant abiotic factor affecting the energetics of stream communities, whether at the level of algal communities, aquatic invertebrates, or fish (Sprules 1947; Whitford and Schumacher 1964; Bovee 1975). If an organism is not morphologically adapted for living in currents (such as through streamlining, buoyancy control, attachment mechanisms, or other adaptation), it will adopt a behavior of seeking low velocity areas to reduce individual energy demands (Hubbs 1941). Many species of fish avoid velocity by occupying pools and locations in the water column near the streambed. Others make heavy use of instream cover or burrow into the substrate material to avoid energetic expenditure. McCrimmon (1954) observed that habitat requirements of fish change as they grow, with a general movement into deeper, faster water.

For drift-feeding fish, a resting location of low velocity in proximity to an area of higher velocity is advantageous because proportionately more food will be delivered to the resting location (Fausch and White 1981). Kalleberg (1958) found that territories were smaller in riffles and rubble than in pools, leading to speculation that fish require less space in high velocity water because the amount of food passing a given point in the

stream is proportional to velocity. Chapman (1966) suggested that the defense of territories exhibited by salmonids was a surrogate for competition for food: "Social status confers definite benefits on individuals . . . despotic fish in hierarchies or successful territorial fish grow more rapidly than subordinates or refugees." Chapman also postulated that a similar principle operated at the invertebrate level, thereby forming a link between habitat and the fish food supply. These are important concepts relating to the argument over food limitations or space limitations in stream populations. Chapman's (1966) study indicates that in territorial animals, food limitations may be shown to be actually space limitations in the form of competition over larger and higher quality microhabitats.

The energetically advantageous behavior of feeding from a 'low energy' location with forays into 'high energy' locations is not confined to salmonids. Lobb and Orth (1988) reported a nearly identical feeding strategy in the bigmouth chub. They suggested that the microhabitats selected by the chub not only presented the greatest energetic advantage, but also minimized the risk of predation by birds and fish. Stream-dwelling fish that ambush their prey, including many centrarchids and esocids, tend to select low energy areas associated with complex structural cover (Haines and Butler 1969; McClendon and Rabeni 1987; Monahan 1991). These species tend to select cover types that provide a shelter from the current and accentuate a contrast in lighting; ambushes succeed better if initiated from a dark area into a well-lit area (Helfman 1981). Probst et al. (1984) noted that smaller smallmouth bass often were observed occupying positions adjacent to moderate velocity, as if feeding on drifting invertebrates.

Some species (such as darters, daces, sculpins, and madtoms) tend to occupy microhabitats where their food supply is greatest (Hynes 1970). Morphological and behavioral adaptations are also common in stream-dwelling macroinvertebrates. Some species of mayflies exhibit extreme dorso-ventral flattening, which allows them to creep around in the laminar sublayer on top of and between rocks in torrential currents. Some species have suction devices to hold them in place on the substrate material. Still others, notably the stoneflies, must live in a current because their gills are immovable and cannot exchange oxygen in standing water (Usinger 1956). Needham and Usinger (1956) found that aquatic insects were

distributed along gradients of depth and velocity in a riffle composed of uniform substrate material. Minshall and Minshall (1977) suggested secondary feedback mechanisms between velocity and substrate material in providing greater surface area for habitation on the streambed and in determining the distribution of food materials for macroinvertebrates.

Although many species select and compete for microhabitats that optimize foraging energetics, prey species often select microhabitats that reduce their risk of predation. Whereas territorial expansion often occurs when a dominant competitor is removed from the system, a similar phenomenon has been observed in prey species when a predator is removed. Gilliam and Fraser (1987) proposed that animals do not select microhabitats by maximizing energetics or reducing predation hazard independently. Rather, locations are selected that minimize the ratio between mortality rate and foraging rate. In essence, the most favorable microhabitat for an organism would be a place where it could increase its energy input with the least risk of predation. Lewis (1969) concluded that stream trout populations were determined largely by the quality of the habitat; velocity was important as an energetic mechanism, but cover was related to a photonegative response and to predation avoidance. Power (1984) observed that armored catfish avoided shallow areas during the daytime, although their food is abundant there, and suggested that these areas were avoided because of susceptibility to avian predators.

Habitat Bottlenecks

Wiens (1977) coined the term *ecological bottleneck* to describe mechanisms by which communities of organisms are regulated by temporally variable, environmentally induced phenomena. An ecological bottleneck has the effect of depressing potentially competitive populations well below the *carrying capacity*. Once the restriction is relieved, competition is reduced or eliminated because adequate resources are available for the standing crop that remains. A *habitat bottleneck* is similar to Wiens' (1977) definition, but refers solely to habitat limitations that affect populations of individual species (refer to Fig. 2.4), rather than the community as a whole. In contrast to longitudinal succession and habitat segregation, which focus on spatial distributions, the primary dimension embodied by the habitat bottleneck concept is the element of time.

Habitat bottlenecks are important, but sometimes poorly understood. The basic premise of the habitat bottleneck is that populations of aquatic organisms are related to the availability of habitat *through time*. This definition has been commonly misinterpreted to mean that adult fish populations must be instantaneously correlated with habitat. Such an interpretation logically requires a belief in instantaneous mortality and spontaneous generation, or the ability of fish to move quickly among habitats, in order for fish populations to increase and decrease at the same rate that habitat can change in a stream. In reality, habitat limitations affecting a population usually occur prior to the time when the population size is measured. Adult populations are frequently determined by recruitment, which is highly correlated with the amount of habitat available for early life stages of the species. Such 'habitat events' usually affect recruitment via habitat types directly related to the production and survival of eggs, larvae, and fry (such as spawning habitat and young-of-year rearing habitat), or indirectly related to survival by the growth rates of age-0 fish (such as temperature regime, young-of-year rearing habitat, or microhabitat for invertebrate food supplies). These habitat bottlenecks typically occur 1 to 3 years prior to maturation, when their effects are detectable in the adult population (Nehring and Anderson 1993; Bovee et al. 1994). In addition, Bovee et al. (1994) found that

1. there may be several consecutive and independent habitat events that can affect adult populations (such as spawning habitat, fry rearing habitat, temperature regime, and adult feeding habitat);
2. limiting events frequently occur over variable time scales (such as acute events that limit fry survival versus chronic events, such as long-term crowding of adults during the summer);
3. habitat may be limited by both high and low flow events and by the rate of change of flow events;
4. the smallest amount of habitat available during the year may not necessarily be the limiting event (such as during the winter when fish are inactive); and
5. habitat types not directly utilized by the species (such as macroinvertebrate habitat as it affects food supply for fish) may be more important than the habitat directly used by the species.

Conclusion

A common misinterpretation of IFIM is that it is only a 'trout model.' This misunderstanding is undoubtedly related to the origins of the technique for quantifying salmonid microhabitat (Collings et al. 1972), which formed the conceptual basis for the Physical Habitat Simulation System (PHABSIM). Although the modeling techniques underlying PHABSIM originated in salmonid streams, Bovee (1975) concluded that there were sufficient parallels in microhabitat use across stream communities that the same basic approach could be used in most riverine environments for essentially any riverine species.

As discussed in this chapter, many concepts and components of IFIM are rooted in community ecology and were developed from many stream settings. Students of IFIM should have little trouble recognizing the influence of the longitudinal succession concept as a defining property of macrohabitat. Longitudinal succession has been confirmed in many studies, in coldwater and warmwater streams, since Shelford's (1911) original hypothesis.¹ In IFIM, macrohabitat components such as channel structure and discharge are used to define sampling strata for the quantification of microhabitat. Temperature and water quality are incorporated in IFIM to define the longitudinal limits where a species can or cannot survive.

The treatment of microhabitat in IFIM using PHABSIM is consistent with the two-dimensional partitioning of microhabitats documented for stream-dwelling organisms ranging from algae to fish. Although the reasons for habitat partitioning may vary, such behavior is commonplace in stream ecosystems worldwide. One possible reason for the universality of this phenomenon is that streams provide unique but repetitive types of microhabitat niches no matter where they are, and there will always be one or more species adapted to filling those niches.

PHABSIM has been criticized because it contains only a few variables, namely depth, velocity, and channel index (usually a combination of substrate material and cover). However, in nearly all of the studies conducted on habitat partitioning among stream-dwelling animals, these variables were consistently found to be important determinants of species distributions and abundance. The

¹ The concept of longitudinal succession has matured into what today is the river continuum concept (Vannote et al. 1980).

emphasis placed on the careful development and testing of habitat suitability criteria used in PHABSIM is a recognition that the microhabitat requirements by some (not all) species are flexible and can be modified by species interactions such as competition and predation.

The habitat time series is based on the fact that decisions related to habitat and water management *must* address the temporal variability of riverine environments. Habitat bottlenecks are difficult to identify without an abundance of hydrologic-, habitat-, and population-related data. Nevertheless, the existence of habitat bottlenecks has been demonstrated in cold- and cool-water stream environments. Studies in community ecol-

ogy provide evidence that they also exist in warm-water streams. Therefore, the idea of using a habitat time series to relieve potential habitat bottlenecks, avoid exacerbating them, or (rarely) amplify them is a reasonable approach to the problem of temporal variability. A more fundamental argument for employing the habitat time series is that temporal evaluations are routine in the water management disciplines. The habitat time series allows the presentation of biological information in a format that is familiar to water managers and engineers. IFIM is unique among habitat assessment tools in that it fosters the simultaneous examination of habitat variability over time and space.

Chapter 4. Philosophical Underpinnings of IFIM

Certain philosophical principles have guided the development of IFIM and help explain its organization and intended use. These include *principled bargaining*, *incrementalism*, *interdisciplinary problem-solving*, and *craftsmanship*. In addition, the *problem-solving approach*, based on ecological theory, guides us in dealing with complex and contentious issues and helps us continue learning about ecological systems.

Axioms

Principled bargaining recognizes and attempts to accommodate the values of every legitimate stakeholder in an instream flow case. This idea also stipulates that the best solution to a problem is derived through mutual agreement of negotiated issues. A hard realization of this philosophy is that the methodology is neutral; it can be used equally well to represent a developer's viewpoint or that of a conservation group. However, proper use of the methodology requires that *all* legitimate concerns be addressed. IFIM can be used to evaluate a problem from only one perspective, but such an approach carries substantial risk. Failure to incorporate all legitimate concerns in the formulation of alternatives may result in a solution that creates more problems than it solves. Such alternatives are likely to be vigorously contested by stakeholders who perceive that they have been left out.

Incrementalism is based on the observation that individuals and groups solve problems as they have solved problems in the past. Without a truly traumatic experience, we will not radically alter our value systems, our missions, or the way we assimilate and use information. Changes in these human factors occur in increments. The way we solve the next problem will look pretty much like the way we solved the last similar problem, with perhaps a little movement or flexibility in a particular direction. Incrementalism applies to IFIM through the process of iterative problem-solving.

It is almost inconceivable that the perfect solution, optimizing for all legitimate concerns, will be discovered on the first try. Rather, solutions are derived by starting with a plausible alternative and then tinkering with it until everyone is as satisfied with the outcome as possible. People unfamiliar with instream flow problems or IFIM are often concerned about the acceptance of IFIM by the courts, but IFIM does not stress litigation. Though IFIM has recently been accepted as a legitimate methodology by the U.S. Supreme Court, the vast majority of instream flow problems (we estimate around 99%) are resolved through negotiation rather than arbitration.

IFIM is an interdisciplinary tool requiring different skills and expertise throughout its implementation. Competence in political science, negotiation, and law is crucial when designing studies and preparing for negotiations. Experience in water management and hydrology is crucial in preparing alternatives that are physically feasible to implement. The ability to relate habitat phenomena to biological populations is essential to determine whether an alternative will result in a beneficial, detrimental, or neutral outcome. Simply collecting the data and running the models associated with IFIM may require skills in hydraulic engineering, biology, temperature modeling, chemistry, and geomorphology. The obvious value of interdisciplinary teams is that one person does not need to know how to do everything. Less obvious, however, is that different disciplines often use different strategies and logic in problem-solving. By incorporating multiple disciplines in a team, the opportunity exists to formulate innovative solutions that might not have been considered by a homogeneous group.

Craftsmanship refers to the fact that IFIM is a scientific approach to problem solving, but IFIM is not science. Its purpose is to help disparate groups resolve complex, multiple-issue problems in a systematic yet flexible manner. IFIM is based on the scientific method, but also relies on assumption,

subjectivity, and judgement. It is something that can only truly be learned by doing. Trust and credibility are essential to the implementation of IFIM, and they must appear in every application. Our knowledge about rivers, biology, and human nature will never be perfect, nor will our implementation of IFIM. We can, however, control the quality of our own work. We can be craftsmen.

Approach

IFIM is an adaptive system composed of a library of models that are linked to describe the spatial and temporal habitat features of a given river regulation. In addressing a river system problem, one must keep in mind the matter of scale. Table 4.1 describes a river system at five levels of resolution, from the river basin scale down to microhabitats (similar to that offered by Frissell et al. 1986). When addressing a river regulation problem, it is necessary to bound the area of influence and to stratify your approach so that observations can be expanded from the micro-scale up to at least the river segment scale, if not the stream network or full sub-basin scale. Most experience and application of IFIM techniques have been at the micro- and *meso-habitat* levels, focusing on one or a few river segments. Consequently, the greatest improvement in field techniques and the most tested concepts relate to (1) river hydraulics and microhabitat utilization by aquatic species and (2) longitudinal analysis of water chemistry and temperature through long river segments composed of many mesohabitat types.

Recent emphasis on reservoir operations and stream network analysis has linked habitat models with engineering models for water routing and reservoir storage and release (Waddle 1992). The combined effects of severe ramping rates associated with peaking hydropower operations and the re-evaluation of large storage reservoir operations have elevated the instream flow management issue in the United States to the stream network and even the river basin scale (Lubinski 1992; Hesse and Sheets 1993).

A thorough understanding of the hydroperiod, the water supply, and the management capabilities is essential to IFIM studies in regulated rivers. The most common instream flow problems being addressed today throughout the United States require the aggregation of habitat data at the stream network or sub-basin level and focus fishery managers' attention to the population level. The inherent need to describe the within-basin movement and life history periodicity (Fig. 4.1) establishes the utility of computer-based modeling for tracking and summarizing information throughout a stream network (Bartholow et al. 1993). It is no longer sufficient to argue for flows to maximize the habitat value for one life stage (adult) at a few isolated spots in a river. Computer simulations provide the mechanism for 'gaming' with various river regulation schemes. Allocated water budgets for fish production and decisions on storage and release from reservoirs are now becoming the responsibility of the fishery manager (Waddle 1991; Bartholow and Waddle 1994).

Table 4.1. Major factors influencing habitat of river ecosystems based on spatial scale of the processes.

Scale	Major factors influencing habitat
River basin	Climatic change; climax vegetation; geologic disturbances (earthquakes, volcanos); catastrophic floods and droughts.
Stream network	Valley gradient; local geology (natural or man-made barriers to fish migration); watershed vegetation and land use activities; runoff patterns; groundwater flow; soils and sediment yield; location of dams and diversions.
River segment (macro-scale)	Longitudinal gradients of temperature and water quality; habitat types and proportions (more similar within segments than among segments); canyons, floodplain segments, bedrock controlled reaches, alluvial reaches, etc. Periodic floods can reshape floodplain contours and reroute channels.
Mesohabitats (meso-scale)	Unique channel width/depth ratios: Pools, runs, chutes, oxbows, cutoff backwaters, riffles, pocketwater, plunge pools, side channels, navigation pools, channelized reaches.
Cross sections (micro-scale)	Channel geometry; stage/discharge relations; substrate material distribution; % fine materials; cover objects (instream, undercut banks, overhead vegetation, ledge rock, woody debris, root wads); depth and velocity distributions.

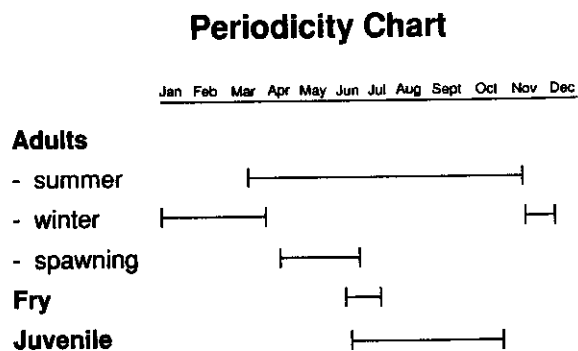


Fig. 4.1. Species periodicity chart.

In developing the Index of Biological Integrity (IBI), Gorman and Karr (1978) suggested that human-induced impacts to river systems fall into five major categories. Table 4.2 (as modified from Karr 1991) identifies food source, water quality, habitat structure, flow regime, and biotic interactions as equally important, but very different, mechanisms by which human activities can alter the biotic integrity of running-water ecosystems. The IFIM modeling approach has been influenced by this view of river system impacts, and models have been developed that fit within Karr's paradigm, as discussed below.

Flow Regime

During the 1950's and 1960's, construction of large storage reservoirs and massive withdrawal systems for irrigation in the western United States focused IFIM developers on techniques for evaluating changes in flow regime. Today, the most sophisticated modeling in the area of flow regime combines ideas from hydraulic engineering, river flood routing, and habitat-use behavior of fish with empirically measured calibration flows. Hydraulic simulation models allow for accurate prediction of water surface elevations, water depth, and water velocity at points in the water column and at various points across a river channel. Models allow simulations of these variables for many unmeasured discharges (Milhous et al. 1989). Such simulations allow the analyst to evaluate the duration and timing of inundation of the aquatic-terrestrial transition zone (ATTZ; Junk et al. 1989). The flow regime is also recognized as critical for channel maintenance, both in terms of maintaining habitat structure (e.g., stream width, riparian vegetation) and in flushing fine sediment out of gravel/cobble channels. (U.S. Forest Service 1984)

Habitat Structure

The influence of human-induced activity on habitat structure (channel-floodplain geometry) has been one of the most neglected areas of stream ecology (Hill et al. 1991). At present, riverine geomorphology is at the forefront of descriptive ecology, and much work is in progress. A prime example is the effort of the U.S. Army Corps of Engineers to restore floodplain channel connections along river corridors that have been severely impacted through river entrainment for navigation and reservoir operations. The classification of mesohabitat types, and the association of important species and life history events to those specific habitats, underscores the importance of adequately describing and manipulating channel morphology as a component of river management. Many riverine species throughout the United States are rapidly declining, and many species are proposed for listing as threatened or endangered. The loss of side channel, backwater, and edge habitats has been a primary reason for this decline (Hesse and Sheets 1993). There are no predictive habitat structure or channel models acceptable for evaluating flow regime in terms of the active channel response. Crude calculations of the extent of aggradation or degradation (Fig. 4.2) at selected cross sections below a large reservoir are possible but cannot be used to forecast channel widening, edge habitat building, or floodplain cutting. There has been much empirical research on the protection of existing channels (Stalnaker et al. 1989) and restoration of floodplain habitats (Hesse and Sheets 1993). Recently, researchers have focused interest on *flushing flows* as part of river management regime for flushing silts and sands from within the interstitial spaces among gravel and cobbles in trout and salmon streams (Reiser et al. 1989). This research is now progressing into the laboratory and, along with field studies, should provide algorithms suitable for computing the amount and timing of flow pulses for flushing fines from river reaches below large reservoirs.

Water Quality

There are sophisticated and well-developed water quality models (Bartholow 1989; Thornton et al. 1990). Water chemistry, dissolved oxygen (DO), and temperature can be very accurately predicted throughout a stream network system as a function of reservoir operations and water routing. However, modeling emphasis has been largely to

Table 4.2. Primary ways that human-induced alterations impact river ecosystem biological integrity (modified from Karr [1991]).

Flow regime	Habitat structure	Water quality	Food source	Biotic interaction
Important Variables				
Discharge	Channel geometry	Temperature	Particulate organic material	Competition for food and space
Water depth	Floodplain connection	Dissolved oxygen	Terrestrial insects	Predation
Water velocity	Substrate material	Turbidity	Seasonal pattern of energy input from floodplain and watershed	Disease
Floods	Percentage of fines	Nutrients		Parasitism
Droughts	Meso-type diversity (pools, runs, chutes, backwaters, riffles, woody materials)	Dissolved chemicals		
Dynamic inundation of aquatic-terrestrial transition zone (ATYZ) during peaking	Bank stability	Heavy metals and toxics		
Sediment transport	Cover objects	pH		
	Riparian vegetation			
Disruptions				
Depletion—reduced minimum flows and velocities	Decreased stability of banks	Increased or decreased turbidity	Isolation of floodplain and removal of riparian vegetation leads to decreases in organic materials (coarse and fine particles)	Shift in species composition and abundance—fishes and invertebrates
Storage-reduced inundation of AZZT, reduced energy input	Increased siltation over substrated material	Altered temperature regimes		Introduction of exotic species
Reduced reproductive success of floodplain rearing fish species	Removal of trees from riparian zone	Altered diurnal dissolved oxygen cycle		Disruption of seasonal rhythms
Peaking hydro—increased extremes (magnitude and frequency of high and low flows)	Reduced cover-loss of undercut banks and woody debris	Altered salinity		Alterations in primary and secondary production—trophic structure
Reduced diversity of depth/velocity combinations	Isolation of floodplain from channel	Increased nutrients, toxics or suspended solids	Increased algal production due to input of nitrogen and phosphorus	Shifts in habitat guilds—(increased omnivores and decreased piscivores)
Reduced feeding stations	Channelization—reduced sinuosity more uniform water depths		Altered decomposition rates	Increased hybridization among fishes
	Increased erosion from watershed (timbering, grazing, urban sprawl)			Decrease in obligate riverine fish species
				Increasing numbers of candidate species for listing as threatened or endangered

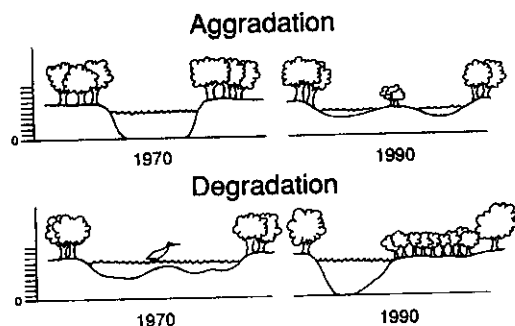


Fig. 4.2. Channel aggradation compared with degradation.

meet chemical criteria and public health criteria; little has been done to advance the state-of-the-art in managing healthy and viable biotic communities within regulated rivers. Nonetheless, temperature and DO can be modeled, and these approaches are useful in designing flow release patterns timed to provide optimal conditions for spawning and growth (Armour 1991, 1993a, 1993b). More must be accomplished in this arena.

Food Energy Source

Thus far, flow-related models for evaluating the food base in stream systems have been predominantly restricted to habitat use by benthic macroinvertebrates in streams inhabited by trout and salmon. Such models are based on velocity relations in the substrate material used by aquatic insects (Gore and Judy 1981; Minshall 1984; Gore 1987), and were recently shown by Jowett (1993) to account for a significant amount of the variation in brown trout production among 89 trout streams in New Zealand.

Biotic Interactions

Of the five areas, this one offers most promise for a research breakthrough in the development of management tools for application. Species competition as a consequence of flow management has thus far taken the form of examining the amount of usable habitat overlap among trout species (Nehring and Miller 1987; Loar and West 1992). Careful examination of simulated historical temperature and flow patterns for a stream reach can provide evidence for mechanisms supporting the observed dominance of one trout species over another in the reach. Unfavorable temperature during spawning and incubation, unfavorably high velocities during fry emergence, or large overlap in

preferred space during critical periods may tip the balance in favor of one species over another. Further research is needed for developing habitat models based on community structure. Habitat use guilds for fishes have been discussed by Leonard and Orth (1988) and Bain and Boltz (1989). There is ongoing research addressing guilds in southeastern United States coastal and piedmont warmwater stream systems (Bain and Boltz 1989; Freeman and Crance 1993).

Stream Habitat as an Integrator of Man's Influence on Stream Systems

The initial focus of instream flow studies using IFIM models was on understanding habitat dynamics as simulated for recent historical flow conditions in the stream system under study. Analytical procedures developed by scientists at the Midcontinent Ecological Research Center (formerly the National Ecology Research Center) aid the river analyst in examining the spatial and temporal aspects of stream habitat integrity. These procedures provide information compatible with three current concepts of stream ecosystems (Table 4.3): (1) longitudinal succession, starting with the principles introduced in Chapter III and expanded into the river continuum concept by Vannote et al. (1980); (2) habitat segregation and the importance of habitat patchiness and habitat boundaries in resource partitioning; and (3) biotic responses to stochastic processes such as weather (Wiens 1977; Grossman et al. 1982; Schlosser 1982, 1987). In dynamic stream environments the interaction of all three ideas into an integrated analysis of the spatial and temporal aspects of the environment is necessary to sort out the relative importance of deterministic and stochastic processes to the community being studied (Schlosser 1982; Gelwick 1990; Strange et al. 1992).

It is possible to model the linear distribution of temperature, dissolved oxygen, and important chemical constituents and to compute the linear extent of usable macrohabitat, the extent of optimal microhabitat, or the position of threshold bounds for limiting variables. Aquatic species distribution along a river segment continuum can be determined for many well-known aquatic organisms. Such analyses require adequate sampling of the water column along the linear distribution of mesohabitat types in the river segments of concern. Within mesohabitat types, measurements of the distribution of cover, substrate material, and water depths and velocities, when linked with hydraulic

Table 4.3. IFIM models developed for integrating the spatial and temporal scales of habitat analyses.

River perspective	Type of model
Longitudinal succession (river continuum)	One-dimensional macrohabitat models—temperature, dissolved oxygen, dissolved chemicals. Indicators: degree-day accumulations of temperature, thresholds of tolerance, extent of optimum or acceptable conditions.
Habitat segregation and patchiness	Two-dimensional microhabitat models—depth/velocity distributions in association with substrate material and cover in small cells.
Variable meteorological processes	Time series of the total amount of usable habitat present in the aggregate over the stream network or a specified portion. Indicators: seasonal occurrence and duration of ecological bottlenecks associated with flood, droughts, or human-induced hydro-peaking or flow depletions.

simulation, can model the qualities and patchiness of the usable microhabitats. Microhabitat analyses can identify velocity boundaries important to drift feeders and velocity barriers to rearing immobile or velocity-intolerant life forms.

Computer programs (Time Series Library; Milhous et al. 1990) allow the analyst to integrate the macro or longitudinal (one-dimensional) habitat data with the one-dimensional hydrologic data throughout a stream system to produce a time series analysis of the *total* amount of usable habitat available for specified species and life stages for particular periods. The spatial analyses are aggregated at the stream network or sub-basin level. Evaluations of atypical events (i.e., climatic disturbances such as droughts and floods) are made by examining the habitat time series for habitat bottlenecks; their magnitude, frequency,

duration, and timing of occurrence; and the life stages they appear to influence. With such historical analyses (back calculations), the analyst is better able to compare proposed operating alternatives and document the probable impacts of those changes.

These integrated analyses are termed effective habitat analyses (Bovee 1982). Effective habitat analysis and the identification of habitat bottlenecks have become the focus of instream flow studies involving trout and salmon in the western United States (Bovee 1988). In these analyses, the investigator transforms the habitat time series into a quasi-population model (Waddle 1992). Effective habitat analyses aid the biologists by allowing them to use population dynamics theory and experience to interpret the likely outcome of stream water management options.

Chapter 5. The Application of IFIM

The IFIM is meant to be implemented in five sequential phases: problem identification, study planning, study implementation, alternatives analysis, and problem resolution. Collectively, these phases encompass the individual steps shown in the previous flowchart (Fig. 1.1). This chapter summarizes each phase, telling who the major players are for each phase and what is to be accomplished in that phase. Two things should become apparent as you read about the five phases of applying IFIM. First, each phase must precede the remaining phases, though cycling through them will be a necessity as projects increase in complexity. Skipping or minimizing any step is likely to result in an unsatisfactory assessment. Second, full and open communication is an essential ingredient of each phase. Such communication will help ensure that all parties accept the IFIM process and have a positive view of what should be mutually beneficial results. In some ways, communication is an ingredient as well as a product of each phase because a successful application of IFIM should result in mutually acceptable decisions.

Problem Identification

After a proposed change in the water management system becomes known, the first phase of an IFIM assessment begins. This phase has two parts, a legal-institutional analysis and a physical analysis. The interagency group should perform the legal and institutional analysis. This analysis identifies all affected or interested parties, their concerns, information needs, and relative influence or power, as well as the likely decision process (i.e., Is it more likely to be a brokered or arbitrated decision?). Thus, phase one will result in a better understanding of the proposed project, the likely impacts, and the objectives of all interested parties. This understanding sets the stage for multi-objective planning that will encourage analyses other than just the proposed project operation. Also, negotiating the details at an early stage

provides the foundation for continued successful negotiation throughout the assessment.

In the second part of phase one, the physical analysis determines (1) the physical location and geographic extent of probable physical and chemical changes to the system, and (2) the aquatic (and perhaps recreational) resources of greatest concern, along with their respective management objectives. Problem identification is often accomplished with a scoping meeting involving the management and regulatory agencies likely to be involved with the decision. A preferred alternative may be identified by the project proponent, and the consequences of this alternative are translated into a hydrologic time series that assumes the project is in place and operating as proposed. The group should also jointly develop a baseline hydrologic time series representing either the *status quo* or another baseline that is mutually acceptable. The two (or more) hydrologic time series, in a preliminary sense, establish the basis for the next phase—study planning.

Study Planning

Carefully planning the course of an IFIM assessment is critical. The focus of this phase is to identify what information is needed to address the concerns of each group, what information already exists, and what new information must be obtained. Study planning details should dominate the discussions and result in a concise, written plan documenting who is going to do what, when, where, how, and for how much money. The study plan must be feasible, given the decision schedule, and the human and financial resources available.

The interdisciplinary planning team must build on the objectives and information needs of each party. The team should not try to predict the outcome of a study but focus on data collection and the methods to be used. Proper planning will lead to the collective identification of (1) the pertinent temporal and spatial scale of evaluations, (2) the most important variables for which information is needed, and (3) how information will be obtained

(e.g., measurement methods, simulation, expert opinion) if it does not exist. The planning group must also agree on methods of quantifying the effects of each alternative to be analyzed.

The hydrologic information chosen to represent the baseline or reference condition should be reexamined in detail at this point in the study. All parties must understand and agree on one or more hydrologic time series that will be used for comparison. The baseline hydrologic time series serves as a reference point for judging potential impacts. Often the reference baseline condition is not the actual historical hydrology used in problem identification, but a synthetic time series representing present water uses, operational procedures, and waste loads superimposed on the variability found in the historical hydrologic records. (Occasionally, the baseline hydrology includes future operational procedures that are not yet in place but have been formally approved and are imminent.) Two or more reference hydrologic time series are commonly used for baseline conditions.

The resource agency responsible for fisheries must describe the biological reference or benchmark conditions. Identifying the geographic distribution and important times of the year (for spawning, migration, etc.) is critical in evaluating different life history phases of the fish populations. A population benchmark may be constructed using historical habitat conditions (from best estimates of actual historical hydrology) and 'backcasting' to identify critical events that populations may have experienced due to physical or chemical limitations reflected as habitat bottlenecks (Burns 1971).

A written study plan should (1) determine when data collection must be completed in the field; (2) synchronize the collection of data needed for model input, calibration, and testing; and (3) estimate the labor, equipment, travel, and other costs required to produce the needed information by the agreed study deadline. An interdisciplinary planning effort representing all the major interest groups can result in considerable savings of time and effort during the conflict resolution phase. A common mistake in planning is to go about describing a 'set' of data and 'standard collection procedures' appropriate for commonly used models. This shortcut simplifies initiation of the data collection phase but often does not build a common understanding of data needed or agreement on the analytical approach. Lack of group planning may lead to polarization of the parties, which may stifle the negotiation process.

Study Implementation

From the field biologists' and the resource agencies' perspective, the implementation phase is often the most interesting and scientifically challenging. This phase consists of several sequential activities: data collection, model calibration, predictive simulation, and synthesis of results. Proper implementation of the study is critical and can bring biological credibility to the decision process but will not, by itself, result in good decisions.

During implementation, sampling locations are selected for collecting empirical data used in predictive models. Data collected can include temperature, pH, dissolved oxygen, biological parameters, and measures of flow such as velocity, depth, and cover. These variables are used in describing the relation between stream flow and stream habitat utility. IFIM relies heavily on models because they can be used to evaluate new projects or new operations of existing projects. Model calibration and quality assurance (Fig. 5.1) are keys during this phase and, when performed carefully, lead to reliable estimates of the total habitat within the study area during simulation of the alternative flow regimes. Total habitat is synthesized by integrating large-scale macrohabitat variables with small-scale microhabitat variables (Fig. 5.2). An important intermediate product from this phase is the baseline habitat time series. This analysis determines how much habitat in total would be available for each life stage of each species over time. The baseline habitat time series provides the base from which rational judgements can be made about proposed alternative management schemes.

Inappropriate selection and use of models and failure to verify model assumptions can lead to major errors in application (Shirvell 1986; Scott and Shirvell 1987). Because all habitat-based instream flow models rely on empirical measurements of the stream channel as inputs, adequate understanding of sediment transport and channel dynamics must be incorporated into any habitat time series analysis. If a channel is not in dynamic equilibrium, the modelers may have to hedge on simulation of alternative futures and call for periodic adjustments, with empirical measurements at regular intervals.

Some site-specific empirical evidence should be collected to ensure validity when applying instream flow models to the decision-making process. Site-specific data help reduce the large amount of uncertainty in understanding how biological systems

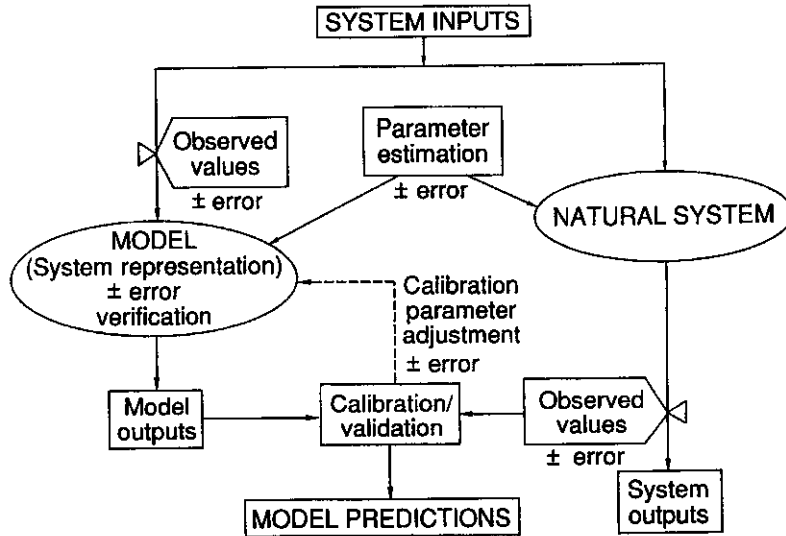


Fig. 5.1. Calibration process.

work and reduce the imprecision of small samples that are used to represent a dynamic stream system. Site-specific data also foster communication among the diverse disciplines of engineering, law, ecology, and economics. Just as grab sample measurements of temperature, water quality, depths, and velocities are routinely used to calibrate physical and chemical models, samples of the aquatic organisms and their habitat use must be used to 'calibrate' the habitat simulations used in IFIM alternatives analyses.

Properly completed, phase three results in reliable estimates of the relation between flow and total habitat, as well as good measures of the amount of habitat available under the chosen baseline conditions and the various with-project alternatives. This habitat quantification leads naturally

into the next phase, which will compare and evaluate the alternatives. Before discussing the next phase, however, it would be best to make specific mention of PHABSIM.

PHABSIM

Many people confuse IFIM with the Physical HABITat SIMulation System (PHABSIM). Whereas IFIM is a general problem-solving approach employing systems analysis techniques, PHABSIM is a specific model designed to calculate an index to the amount of microhabitat available for different life stages at different flow levels. PHABSIM has two major analytical components: stream hydraulics and life stage-specific habitat requirements (Figs. 5.3a and 5.3b).

The stream hydraulic component predicts depths and water velocities at specific locations on a cross section of a stream. Field measurements of depth, velocity, substrate material, and cover at specific sampling points on a cross section are taken at different flows. The sampling points are called verticals and describe conditions for some distance around them (cells) judged to be relatively homogeneous. Hydraulic measurements, such as water surface elevations, are also collected during the field inventory. These data are used to calibrate the hydraulic models. The models are then used to predict depths and velocities at flows different from those measured. It is usually assumed that the substrate material and cover do not change at different flow levels, but this assumption is not required.

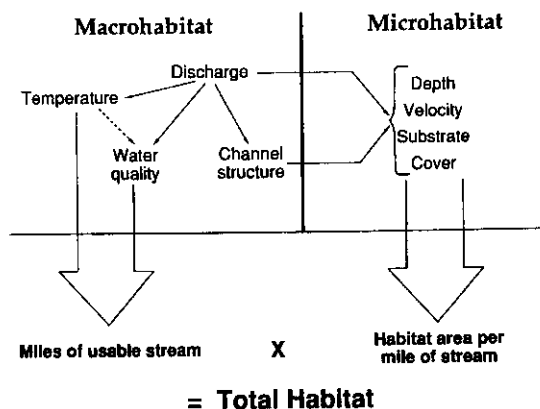


Fig. 5.2. Total habitat combines elements of macrohabitat and microhabitat.

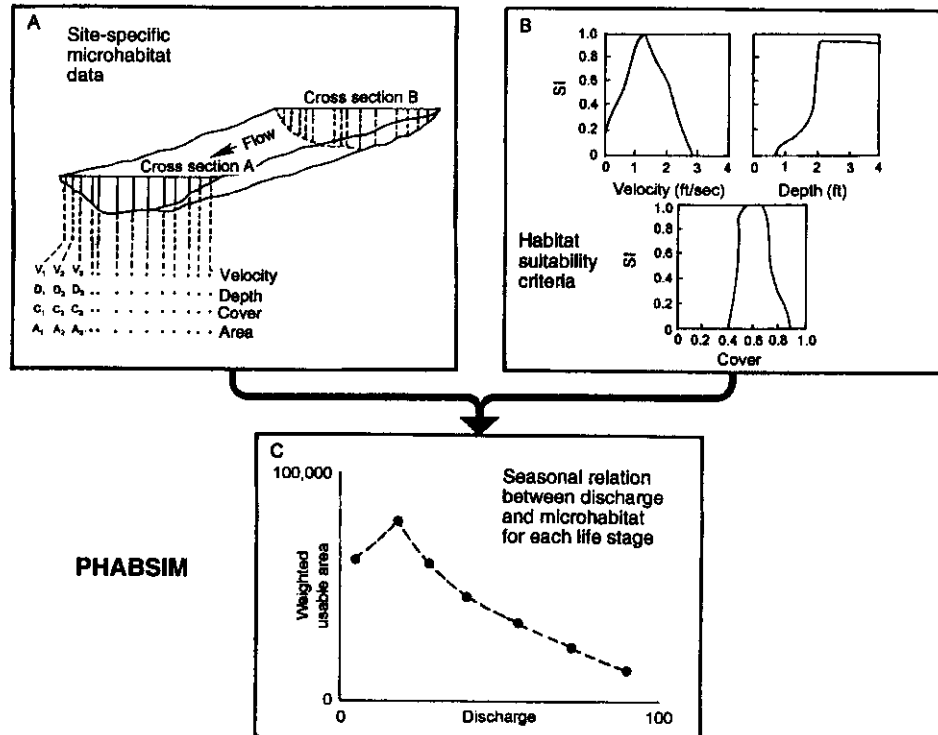


Fig. 5.3 Conceptualization of how PHABSIM calculates habitat values as a function of discharge. (A) First, depth (D_i), velocity (V_i), cover conditions (C_i), and area (A_i) are measured or simulated for a given discharge. (B) Suitability index (SI) criteria are used to weight the area of each cell for the discharge. The habitat values for all cells in the study reach are summed to obtain a single habitat value for the discharge. The procedure is repeated for a range of discharges to obtain the graph (C). (Adapted from Nestler et al. 1989.)

The hydraulic models have two major steps. The first is to calculate the water surface elevation for a specified flow, thus predicting the depth. The second is to simulate the velocities across the cross section. Each of these two steps can use techniques based on theory or empirical regression techniques, depending on the circumstances. The empirical techniques require much supporting data; the theoretical techniques much less. Most applications involve a mix of hydraulic sub-models to characterize a variety of hydraulic conditions at various simulated flows.

The habitat component weights each stream cell using indices that assign a relative value between 0 and 1 for each habitat attribute (depth, velocity, substrate material, cover), indicating how suitable that attribute is for the life stage under consideration. These attribute indices are usually termed *habitat suitability indices* and are developed using direct observations of the attributes used most often by a life stage, by expert opinion about what the life requisites are, or by a combination. Various approaches are taken to factor assorted biases out

of suitability data, but they remain indices that are used as weights of suitability. In the last step of the habitat component, the hydraulic estimates of depth and velocity at different flow levels are combined with the suitability values for those attributes to weight the area of each cell at the simulated flows. The weighted values for all cells are summed—thus the term weighted usable area (WUA).

There are many variations on the basic approach outlined above, with specific analyses tailored for different water management phenomena (such as hydropeaking and unique spawning habitat needs) or for special habitat needs (such as bottom velocity instead of mean column velocity) (Milhous et al. 1989). However, the fundamentals of hydraulic and habitat modeling remain the same, resulting in a WUA versus discharge function (Fig. 5.3c). This function should be combined with water availability to develop an idea of what life stages are impacted by a loss or gain of available habitat at what time of the year. Time series analysis plays this role and also factors in any

physical and institutional constraints on water management so that alternatives can be evaluated (Milhous et al. 1990).

Several things must be remembered about PHABSIM. First, it provides an index to the microhabitat availability; it is not a measure of the habitat actually used by aquatic organisms. It can only be used if the species under consideration exhibit documented preferences for depth, velocity, substrate material/cover, or other predictable microhabitat attributes in a specific environment of competition and predation. The typical application of PHABSIM assumes relatively steady flow conditions, such that depths and velocities are comparably stable for the chosen time step. PHABSIM does not predict the effects of flow on channel change. Finally, the field data and computer analysis requirements can be relatively large.

Alternatives Analysis

The water project proponent will usually have a preferred alternative, but other alternatives must be identified for comparison. Other parties to the decision process should propose their own alternatives. The alternatives analysis phase compares all alternatives with the baseline condition to facilitate an understanding of potential impacts and to begin negotiating and creating new alternatives more compatible with the multiple objectives of the many parties. When properly completed, simulation modeling using IFIM tools allows for straightforward comparison of many alternatives, each of which is examined for

1. Effectiveness—Are the objectives of all parties from phase one sustainable? Is no net loss of habitat possible on a sustainable basis? What are the habitat costs and benefits of each alternative?
2. Physical feasibility—Do reservoirs dry up? Are priority water rights not met? Will flooding occur? Is enough water available?
3. Risk—How often does an alternative lead to failure or collapse of the biological system? Is a failure reversible? Can contingency plans be developed?
4. Economics—What are the costs and benefits of each alternative?

Probably the biggest mistake the interagency group could make at this point is to choose one alternative from a group of poor alternatives. It is far better to create new alternatives, learning as

you go. When complete, this phase results in a comprehensive array of alternatives, each quantitatively described.

Problem Resolution

Given several alternatives that have been thoroughly evaluated, the choice should be obvious, right? Usually, this is not the case; the IFIM does not guarantee a single, best solution. The optimum solution can rarely be identified because (1) biological and economic values are never truly commensurate, (2) data and models are never complete or perfect, (3) rational people can reach different conclusions, and (4) uncertainty about the future is ever-present. IFIM was designed to aid in formulating and evaluating alternatives; however, it still relies heavily on professional judgement by interdisciplinary teams. The teams must integrate their knowledge and understanding of a problem with their professional judgements about the biological resources and social needs to reach a negotiated solution implying some kind of balance among conflicting social values.

The methodology is not fixed. It is open-ended and imaginative. Flexible, mutually beneficial, negotiated solutions are encouraged (after Fisher and Ury 1983). Negotiation is the key: (1) carefully examine your interests and objectives before entering a negotiation, and invite criticism during negotiation; (2) check your assumptions about the other sides' interests; (3) focus on the problems and each group's underlying concerns, not on the individual negotiators or their 'positions'; (4) strive to identify opportunities for water withdrawal or use that maximize mutual gain; (5) insist on using fair standards and procedures; and (6) understand the consequences of all agreements.

We do offer one guideline for fisheries managers. When the present fishery is considered good to excellent, the best alternative is often the one that deviates the least from the baseline habitat condition. This alternative is often called the 'no net loss of habitat' philosophy, which is followed by many resource agencies. For example, no net loss of habitat is the official policy of the Canadian Department of Fisheries and Oceans.

Though an IFIM assessment concludes with the Problem Resolution phase, many projects offer the opportunity for continued learning by all parties. Because our models and judgements are by their nature incomplete and imperfect, our predictions are likewise incomplete and imperfect. Post-project

monitoring and evaluation, with the intent of developing into adaptive management, should be considered when appropriate. The more we understand, the better we can assess and manage the next project. Ultimately, our goal is ensuring the preservation or enhancement of our fish and wildlife resources.

For More Information

We are often asked for more information about successful applications and tests of IFIM. There have been hundreds of small IFIM applications resulting in the incorporation of flows for sustained aquatic systems in project operations. However, they are not regularly published, nor do they always meet everyone's definition of success. Perhaps the earliest and most completely documented application of IFIM involved a large hydroelectric project on the Terror River in Alaska. This application has been carefully chronicled in an information paper by Olive and Lamb (1984) and discussed further by Lamb (1984). Another high profile successful application involved a Section 404 permit on the James River, Missouri (Cavendish and Duncan 1986). There have been many 'scientific tests' of the methodology through the years, with varying degrees of support or refutation. The recent paper by Nehring and Anderson (1993) is certainly a good confirmation of the habitat bottleneck hypothesis. Another recent paper (Thomas and Bovee 1993) details the generality of some forms of habitat suitability criteria. However, the widespread use of IFIM by state and federal agencies (Reiser et al. 1989; Armour and Taylor 1991) probably is the best indicator of acceptance. Widespread use does not imply perfection, just a lack of something better. Additional references on IFIM and related issues may be obtained by contacting our office (see page iii) and asking for our publications list.

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Glossary²

- Abiotic** The nonliving, material components of the environment, such as water, sediment, temperature, etc.
- Acre-foot** That volume of water required to cover 1 acre of land to a depth of 1 foot, equal to 43,560 cubic feet or 1,233.49 cubic meters.
- Age-class** A cohort of organisms, all the same age, born within the same year. In fisheries, an age group is often called Age 0, 1, 2, 3, etc. See Year-class.
- Aggradation** The geomorphic process in which inorganic materials carried downstream are deposited in streambeds, floodplains, and other water bodies, resulting in a rise in bed elevation.
- Anadromous** Fish that mature in seawater but migrate to fresh water to spawn.
- Annual flow** The total volume of water passing a given point in 1 year. May be expressed as a volume (such as acre-feet) but may also be expressed as an equivalent constant discharge over the year, such as cfs.
- Appropriation Doctrine** A rule of law applied most commonly by states west of the 100th meridian providing that the best water right accrues to those who first put water from a given stream to beneficial use; characterized by the adage "first-in-time-is-first-in-right."
- Arbitrated decision** A decision made by an objective third party. An example would be a decision in which the parties make their best case and a third party makes the final decision based on the evidence. A typical arbitrated decision would be one made by a court.
- Area, drainage** The surface area tributary to a lake or stream. Sometimes called catchment area, watershed area, or river basin area; we prefer drainage area, which is less geographic and has specific units (square miles).
- Area, usable** The area under the wetted surface of a stream that can be used by aquatic organisms. Units: square feet or square meters, usually per specified length of stream.
- Area, weighted usable (WUA)** The wetted area of a stream weighted by its suitability for use by aquatic organisms or recreational activity. Units: square feet or square meters, usually per specified length of stream.
- ATTZ** The aquatic-terrestrial transition zone, often periodically inundated and dewatered during hydropeaking cycles.
- Autecology** That branch of ecology dealing with interrelations between individual organisms or individual species, not communities.
- Backwater** Generally an off-shoot from the main channel with little flow and where the water surface elevation is maintained by conditions in the main channel acting on the downstream end of the backwater.
- Baseline** The conditions occurring during the reference timeframe, usually referring to water supply, habitat values, or population status. Baseline is often some actual recent historical period but may also represent: (1) the same climatological-meteorological conditions but with present water development activities on line; (2) the same climatological-meteorological conditions but with both current and proposed future development on line; or (3) virgin or pre-development conditions. The definition of baseline will *always* depend on the objectives of the study. Quite often, two or more baseline conditions may be necessary to evaluate a specific project.
- Bed material** Mixture of substances composing the stream's bed.
- Biological (or fish) year** Various defined. Often used beginning with egg deposition but may be defined as the logical start of any given life stage or phenological relation.
- Biomass** The total weight of the living organisms in some biological system at a given time.
- Biotic** Of or pertaining to the living components of an ecosystem.
- Bottleneck** See Ecological bottleneck or Habitat bottleneck.
- Brokered decision** A negotiated decision facilitated by one of the parties to a dispute. For example, a Section 404 permit would be brokered if the Army Corps of Engineers managed the decision process and helped the parties reach agreement on conditions to be included in the permit.
- Bypass** (1) A channel or conduit in or near a dam that provides a route for fish to move through or around the dam without going into the turbines. (2) That stream reach below a dam that is essentially skirted by the flow used to generate electricity.
- Carrying Capacity** The maximum number (or biomass) of organisms of a given species that can be sustained during that period of least available

²The glossary items were liberally adapted from Armantrout (nd), U.S. Fish and Wildlife Service (nd), Deason (1975), Norem and McCurry (1975), Schwarz et al. (1976), Milhous et al. (1989, 1990), as well as from standard dictionaries.

- habitat under a dynamic flow regime. Carrying capacity should be considered a mean value for a specified, short interval (such as 1 day, 1 week, 1 month) around which populations may fluctuate.
- Centrarchid** A member of the sunfish family.
- Channelization** The mechanical alteration of a natural stream by dredging, realignment, lining, or other means to accelerate the flow of water.
- CFS** Cubic foot per second.
- CMS** Cubic meter per second.
- Coldwater** Generally, a stream populated with salmonids.
- Competition** Active demand by two or more organisms or species for some environmental resource in excess of the supply available.
- Competitive exclusion** Competition resulting in ultimate elimination of the less effectual organism from the particular niche.
- Conspecific** Of the same species.
- Cover** Areas of shelter in a stream channel that provide aquatic organisms protection from predators or a place in which to rest and conserve energy due to a reduction in the force of the current or visual isolation, such as pools, undercut banks, rock crevices, deep water, surface turbulence, vegetation, etc.
- Cross section** A section across a stream channel that is perpendicular to the direction of the flow. Sometimes called a transect.
- Curves, preference** See Suitability curves.
- Curves, Suitability-of-use SI** See Suitability curves.
- Curves, usability** See Suitability curves.
- Cyprinid** A member of the family that includes carps and minnows.
- Degradation** The geomorphic process by which streambeds and floodplains are lowered in elevation by the removal of material. The opposite of aggradation.
- Depth** The vertical distance from a point on the bed to the water surface.
- Deterministic** A system with fixed, specified states or regular patterns.
- Detritus** Non-dissolved organic debris such as leaves, twigs, etc.
- Dewatered** A length of stream without water (for our purposes, due to human intervention).
- Discharge** The rate of flow, or volume of water flowing in a given stream at a given place and within a given time, usually expressed as cfs or cms.
- Discharge, bankfull** Discharge corresponding to the stage at which the overflow plain begins to be flooded.
- Diversion** A withdrawal from a body of water by means of a ditch, dam, pump, or other man-made contrivance.
- Diversity** That attribute of a biotic (or abiotic) system specifying the richness of plant or animal species (or complexity of habitat).
- Dorsal** Situated near or on the back of an animal.
- Drift-feeding** Feeding on food items drifting in the current.
- Drought** A prolonged period of less-than-average water availability.
- Dry season** That period of a year that is characteristically dry (and has the lowest streamflow), implying an annual seasonal cycle.
- Dry year (or dry month)** A time period with a given probability of representing dry conditions; for example, a given year or month may be as dry or drier than 80% of all other similar periods.
- Duration** (1) The percentage of time a class of events occurs. (2) An event's time span.
- Duration analysis** Examination of a certain period of record to categorize the frequency of classes of events within that period, often resulting in a duration 'curve.'
- Ecological bottleneck** An environmental constraint resulting in mortality sufficient to substantially reduce the population size in a given locality. Ecological bottlenecks may include habitat bottlenecks, catastrophic floods, disease, etc.
- Effective habitat** (1) That portion of available physical habitat occupied by a life stage due to mortality (or other constraint) of previous life stages. Effective habitat analysis implies following cohorts of habitat use through time, as a population-limiting habitat event may not manifest itself until some later date. (2) Habitat effectively available due to hydropeaking or other flow fluctuations reducing the habitat for a single life stage.
- Effluent** A discharge or emission of a liquid or gas.
- Entrainment** Construction of engineering works to prevent the movement of a river, as through dikes and other structures.
- Epilimnion** The upper, warmer portion of a lake, separated from lower, colder portion (hypolimnion) by a thermocline.
- Esocid** A member of the pike family.

- Estuary** The zone between the fresh water of a coastal stream and the seawater of an ocean influenced by the tide.
- Exceedence** That probability of an event exceeding others in a similar class. Note that the probability may be 'equal or exceed' or 'exceed' only. Probabilities may also be expressed as nonexceedence, that is, the probability of being 'less than or equal' or just 'less than.'
- Exotic** Introduced species not native to a given area.
- Firm yield** That value of flow, power, or habitat that could be maintained year-after-year despite the circumstances; for example, a reservoir's firm yield might be that amount of water that could be delivered to meet the demand 95% of the time for a specified planning horizon (such as 5 years).
- Flood** Any flow that exceeds the bankfull capacity of a stream or channel and flows out on the floodplain.
- Floodplain** That area along waterways subject to periodic inundation by high water.
- Flow** (1) The movement of a stream of water or other mobile substances from place to place; (2) Discharge; (3) Total quantity carried by a stream.
- Flow, base** (1) The sustained low flow of a stream, usually considered groundwater inflow to the stream channel. (2) The flow that is released during the storage phase of a peaking cycle.
- Flow duration** See Duration analysis.
- Flow, enhancement** A flow regime that is better (in quantity or quality) than the baseline regime for fish, wildlife, water quality, or recreation.
- Flow, flushing** (1) Flow of sufficient magnitude and duration to remove fines from the interstitial spaces among the stream bottom gravel and to maintain intragravel permeability. (2) A discharge sufficient to form and maintain channel shape and size.
- Flow, mean annual** The average annual volume passing a specific site. May be expressed as a mean discharge (e.g., cfs) averaged for an entire annual period.
- Flow, natural** The flow regime of a stream as it would occur under completely unregulated conditions, that is, not subjected to regulation by reservoirs, diversions, or other human works.
- Flow regulated** Natural flow modified by reservoirs, diversions, or other works of humans to achieve a specified purpose or objective.
- Flow, steady and unsteady** Flow in an open channel is said to be steady if the depth of flow at a single cross section does not change or can be assumed constant over a specified interval; the flow is unsteady if the depth changes with time.
- Fry** A fish between the egg stage and the fingerling stage. Depending on the species, a fry can measure between a few millimeters and a few centimeters.
- Gage, stream** A device for measuring the magnitude of discharge in a stream at a specific location.
- Gradient** The rate of change of any characteristic, expressed per unit of length. See Slope. May also apply to longitudinal succession of biological communities.
- Habitat** The place where an organism, or population, lives and its surroundings, both living and nonliving; includes life requirements such as food and shelter (see Physical Habitat).
- Habitat bottleneck** The cumulative constraint on an individual species population size caused solely by repeated reductions in habitat capacity through time due to micro- or macro-habitat limitations. A habitat bottleneck is a special case of an ecological bottleneck.
- Habitat capacity** A limit to the maximum number or biomass of a given species' life stage that can exist for a specified period in a stream reach.
- Head, hydraulic** The difference in elevation of a fluid between two points.
- Headwater** The source for a stream in the upper tributaries of a drainage basin.
- Hydrograph** A graph showing the variation in stage (depth) or discharge over a specified time.
- Hydropeaking** The practice of abruptly alternating between a low base and a high peak flow, typically for on-peak electrical power generation; compare with hydropulsing, in which flows may also range from low to high but are gradually varied over a longer period.
- Hydroperiod** The timing of significant flow events, natural or human induced.
- Hypolimnion** The lower, colder portion of a lake, separated from the upper, warmer portion (epilimnion) by a thermocline.
- IFIM** Instream Flow Incremental Methodology.

- Incremental method** The process of developing an instream flow policy that incorporates multiple or variable rules to establish, through negotiation, flow-window requirements or guidelines to meet the needs of an aquatic ecosystem, given water supply or other constraints. Usually implies the determination of a habitat-discharge relation for comparing stream flow alternatives through time (see Standard-setting).
- Instantaneous (peak) flow** The single largest flow measured instantaneously and not averaged over a longer time, such as a day or month.
- Invertebrate** All animals without a vertebral column. For example, aquatic insects.
- Juvenile** Young of a species.
- Laminar** Non-turbulent, streamlined fluid flow near a solid boundary.
- Larva** An immature form that must pass through one or more metamorphic changes before becoming an adult.
- Lentic** Standing waters, such as lakes, reservoirs, ponds, and marshes.
- Life stage** An arbitrary age classification of an organism into categories related to body morphology and reproductive potential, such as spawning, egg incubation, larva or fry, juvenile, and adult (see Cohort).
- Limnology** The scientific study of physical, chemical, and biological features of inland freshwater lakes and rivers.
- Longitudinal succession** Gradation in the composition of communities along a gradient.
- Macrohabitat** Abiotic habitat conditions in a segment of river controlling longitudinal distribution of aquatic organisms, usually describing channel morphology, flow, or chemical properties or other characteristics (e.g., temperature) with respect to suitability for use by organisms.
- Mainstem** The main channel of a river, as opposed to tributary streams and smaller rivers that feed into it.
- Mean daily flow** (1) The discharge volume passing a given point averaged over 1 day. (2) The average flow for 1 day computed from several years' worth of data for that day. Usually expressed as cfs or cms.
- Mean monthly flow** (1) The discharge volume passing a given point averaged over 1 calendar month. (2) The average flow for 1 month computed from several years' worth of data for that month. Usually expressed as cfs or cms.
- Median daily flow** That discharge at a given point for which there are equal numbers of greater and lesser flow occurrences during 1 day.
- Median monthly flow** That discharge at a given point for which there are equal numbers of greater and lesser flow occurrences during 1 month.
- Mesohabitat** Habitat types intermediate between micro- and macro-habitat (often characterized as pools, riffles, or runs) that tend to behave similarly in response to discharge fluctuations.
- Microhabitat** Small localized areas within a broader habitat type used by organisms for specific purposes or events, typically described by a combination of depth, velocity, substrate material, or cover.
- Minimum flow** The lowest stream flow required to protect some specified aquatic function; established by agreement or rule.
- Mitigation** Actions taken to compensate for actual or potential adverse effects.
- Morphology** The form and structure of organisms, apart from the function of those structures.
- Multivoltine** Having several broods in a season.
- Niche** The place occupied by or function of an organism in its broad environment. May also refer to a narrower set of habitat requirements; for example, the microhabitat niche of smaller fish is in slower, shallower water.
- Open channel hydraulics** The analysis of water flow and associated materials in an open channel with a free water surface, as opposed to a tunnel or pipeline.
- Operation rule** Criteria by which managers of water projects decide when and how much water to store, release, or divert.
- Palustrine** Living in a marsh or swamp environment.
- Periodicity** That pattern or timing during a biological year when a given organism or life stage is active or present in the system under study.
- Persistence** A nonrandom process within a time series of hydrological or meteorological events that tend to have high events following other highs and low events following other lows.
- PHABSIM (pronounced P-HAB-SIM)** The Physical HABitat SIMulation system; a set of software and methods that allows the computation of a relation between stream flow and

physical habitat for various life stages of an aquatic organism or a recreational activity.

Phenology The periodic natural patterns of maturation, timing, or distribution in the life history of an organism.

Phenotype Visible characteristics of an organism.

Physical habitat Those abiotic factors (such as depth, velocity, substrate material, cover, temperature, water quality) that make up some of an organism's living space (see Habitat).

Phytoplankton Plants drifting with the surrounding water.

Piscivorous Feeding on fishes.

Pool Part of a stream with reduced velocity, often with water deeper than the surrounding areas, which is usable by fish for resting and cover.

Preference curves See Suitability curves.

Q7-10 The lowest continuous 7-day flow with a 10-year recurrence interval. Sometimes called 7Q10.

Ramping The rate of change in discharge at a controlled release for hydropower purposes.

Reach A comparatively short length of a stream, channel, or shore. One or more reaches compose a segment. The actual length is defined by the purpose of the study but is usually no greater than 5-7 times the channel width.

Reach length The length of a section or piece of a river.

Recurrence interval The inverse of the probability that a certain event will occur, normally expressed in years. For example, a flow with a recurrence interval of 10 years would be expected to occur, on average, once every 10 years.

Redd A fish nest typically dug in a river or lake.

Regime The general pattern (magnitude and frequency) of flow or temperature events through time at a particular location, (such as, snowmelt regime, rainfall regime).

Riffle Shallow rapids in an open stream where a turbulent water surface is induced by obstructions wholly or partly submerged.

Riparian On or by a water supply, such as near the water's edge.

Rule curve See Operation rule.

Salmonid A member of the family that includes salmon, trouts, chars, and whitefishes.

Sediment Solid material, both mineral and organic, that is in suspension in the current or deposited on the stream bed.

Segment Relatively homogeneous section of a stream composed of one or more reaches (homogeneity usually refers to at least the channel morphology and discharge within that segment). Boundaries are placed wherever the stream undergoes a significant change in discharge, channel structure, water quality, or temperature, usually at tributary confluences and at major diversions. Usually considerably longer than 10-14 times the channel width.

Segment length The length (in miles or kilometers) of a reach of stream for which relatively homogeneous conditions exist, allowing characterization of habitat versus flow by a single relation.

Slope The inclination or gradient from the horizontal of a line or surface. The degree of inclination can be expressed as a ratio, such as 1:25, indicating one unit rise in 25 units of horizontal distance or as 0.04 length per length. Sometimes also expressed as feet per mile.

Spawn To lay eggs, especially of fish.

Stage The elevation or vertical distance of the water surface above a datum or reference (a plane of known or arbitrary elevation).

Standard-setting (1) A stream flow policy or technique that uses a single, fixed rule to establish (minimum) flow requirements despite dynamic aquatic ecosystem needs. (2) The process of determining minimum flow requirements for a water project or water right. The minimum flow may, to varying degrees, consider generic ecosystem needs (see Incremental Method).

Standing crop Quantity of living organisms present in the environment at a given time. Often refers to the harvestable portion of a population.

Steady flow See Flow, steady and unsteady.

Stochastic Allowing for randomness or variability in processes. Literally, making a best guess.

Stream width See Width, stream.

Streambed The bottom of the stream channel; may be wet or dry.

Substrate The material on the bottom of the stream channel, such as rocks or vegetation.

Suitability curves or indices Collectively refers to category one to four suitability index (SI) curves (see next four entries).

Suitability curves—Category one or literature-based The first category of curves, based on available speculative information, including literature sources and expert opinions; usually

- concerns a species response to a macrohabitat variable.
- Suitability curves—Category two or utilization** A curve based on frequency analysis of fish observations in the stream environment.
- Suitability curves—Category three or preference** A utilization curve that has been corrected for environmental bias; for example, if 50% of fish are found in pools over 1.0 m deep, but only 10% of the stream has these pools, the fish are actively selecting that habitat type.
- Suitability curves—Category four or conditional** A preference curve that is conditioned (stratified) by cover, season, or another subdivision.
- Synthetic hydrograph** A flow time series artificially constructed for a given location through various analytical techniques.
- Time series** A record of events (flow, habitat, or other) through time; usually describes those events for a regular averaging interval, such as hours, days, weeks, months, or years.
- Time series analysis** Analysis of the pattern (frequency, duration, magnitude, and time) of time-varying events. These events may be discharge, habitat areas, stream temperature, population factors, economic indicators, power generation, and so forth.
- Total habitat** Total available wetted area conditioned by microhabitat and macrohabitat suitability and summed for all relevant river segments.
- Transect** See Cross section.
- TSLIB** A set of computer programs and analytic methods useful for performing time series analysis.
- Turbidity** A measure of the extent to which light passing through water is reduced due to suspended materials.
- Uniform flow** See Flow, uniform and varied.
- Unsteady flow** See Flow, steady and unsteady.
- Usable area** See Area, usable.
- Utilization curves** See Suitability curves.
- Varied flow** See Flow, uniform and varied.
- Velocity** The time rate of motion; the distance traveled divided by the time required to travel that distance.
- Velocity, adjacent** A velocity in a cell near the cell being considered.
- Velocity, mean column** The velocity averaged from the top to the bottom of a stream.
- Velocity, nose** The velocity at the point where a fish is located. This is point velocity expressed in terms of an organism.
- Warmwater fishery** Generally, an aquatic environment too warm for salmonids.
- Water budget** (1) The balance of all water moving into and out of a specified area in a specified period. (2) An administratively segregated volume of water reserved for a specific use.
- Water right** A legally protected right to divert or store water for beneficial use.
- Water surface elevation (WSL)** The elevation of the water's surface in relation to an arbitrary datum.
- Water year** 1 October through 30 September; usually considered representing the annual hydrologic cycle beginning with that period of consistently low flows.
- Weighted usable area (WUA)** See Area, weighted usable.
- Wet season** That period of a year that is characteristically wet (and having the greatest stream flows), implying an annual seasonal cycle.
- Wetted perimeter** The distance across the bottom and sides of a channel cross section, perpendicular to the flow, in contact with water. Roughly equal to the width plus twice the mean depth.
- Wetted width** See Width, wetted.
- Wet year** A water year characterized by above average discharge. Exact measure of deviation from some average or median value depends on the decision setting.
- Width** The distance across a channel at the water surface measured normal (90°) to flow.
- Width, stream** Either the same as the channel width or the width of the wetted stream.
- Width, wetted** The width of the stream with water in it.
- Year-class** A cohort of organisms born within a specified calendar year (such as the 1986 year-class; see Age-class).

Reader Comment Form for Primer (V2)

We would like to improve this document over time and would welcome your contribution to that effort. Please take a few moments to complete this questionnaire by circling the appropriate letter, as related, in order, to the first six questions.

	Strongly Agree				Strongly Disagree
1. This primer helped me understand what IFIM is all about.	SA	A	N	D	SD

2. This primer contains more than I wanted to know about IFIM.	SA	A	N	D	SD
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List where we have too much:

3. This primer omits material I feel is essential to a primer on IFIM.	SA	A	N	D	SD
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List omissions:

4. This primer is too technical in areas:	SA	A	N	D	SD
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5. This primer is well organized.	SA	A	N	D	SD
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6. This primer is clear.	SA	A	N	D	SD
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7. I recommend distribution of this primer to:

Your Name: _____

Title: _____

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8. Other comments:

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