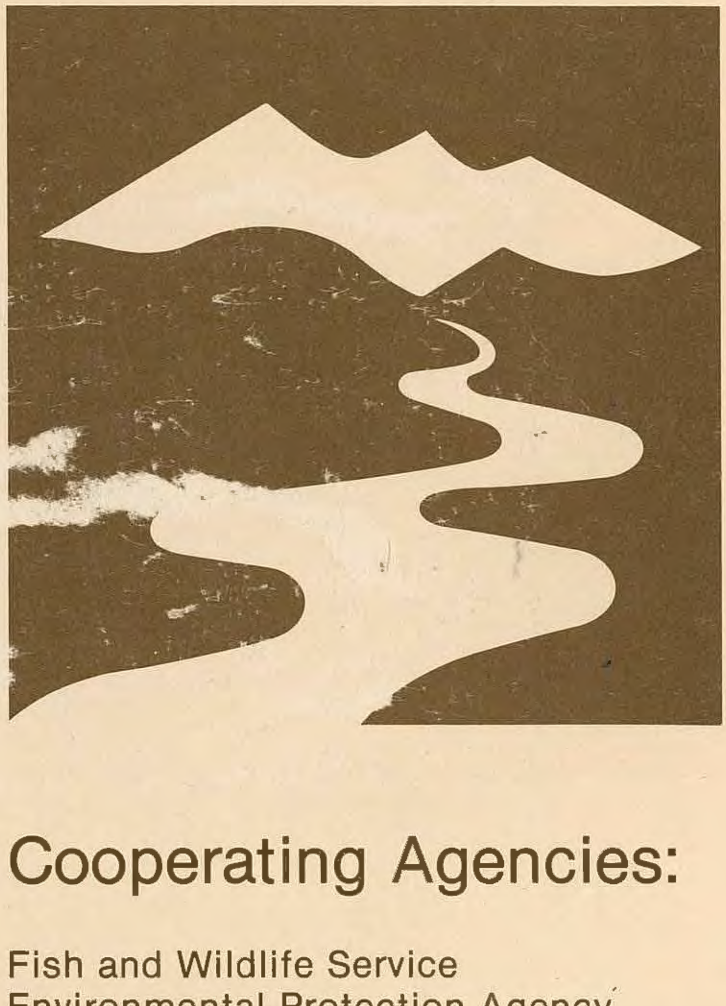
A GUIDE TO STREAM HABITAT ANALYSIS USING THE INSTREAM FLOW INCREMENTAL METHODOLOGY



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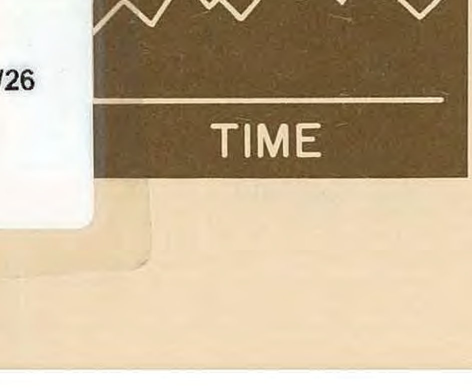

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A GUIDE TO STREAM HABITAT ANALYSIS USING THE INSTREAM FLOW INCREMENTAL METHODOLOGY

Instream Flow Information Paper No. 12

by

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PREFACE

The Instream Flow Incremental Methodology (IFIM) draws on a wealth of approaches that have been developed to assess instream flow problems. Beyond this history of existing approaches, however, the methodology has undergone a period of significant expansion, refinement, and evolution. The result is an approach to the assessment of riverine habitats that has a very wide range of applications. Perhaps the greatest strength of the IFIM is its flexibility; the methodology can be applied to virtually any kind of disturbance to a riverine ecosystem. This flexibility may also be the biggest disadvantage of the methodology. Although we have provided a fairly comprehensive procedure for analyzing a variety of problems, a "cookbook" approach is impossible. Each time a user applies this methodology, he or she essentially builds a model specific to the problem at hand. It would be very difficult, if not impossible, for the Instream Flow Group to direct and specify the analysis of every problem to which this method might be applied. It, therefore, becomes the responsibility of the user to thoroughly understand the methodological approach and all of the available options to any analysis.

In this context, this user's guide is designed as a reference for anyone conducting an instream flow or riverine impact study, regardless of how many previous studies the user has conducted. This manuscript should be as appropriate for the one-hundredth application of this method as it is for the first. The emphasis of this information paper is on what to do and in what sequence to do it, rather than on how to do it. The "how to do it" can be found in the references cited as suggested additional readings at the end of each chapter.

This manual has been constructed in two parts. Part I consists of Chapters 1-5 and contains information regarding the preparation, analysis, and interpretation needed to solve particular types of problems. Chapter 1 explains the overall approach of the IFIM. Chapters 2 and 3 relate to activities that preceed data collection: determining the scope of the study and selecting study areas. Chapter 4 shows the sequence of data collection and analysis that should be followed to address a particular problem. It is at this stage that the user essentially builds his or her own model to solve a specific problem. Chapter 5 details the various options for preparing, displaying, and interpreting the output from the IFIM.

Part II contains ancillary information regarding specific parts of the IFIM. Chapter 6 presents some of the concepts of hydrology and channel dynamics that must be understood in order to apply the method effectively. The goal of Chapter 6 is not to make hydrologists or hydraulic engineers out of everyone using the methodology. Rather, it is intended to provide a background about how water supplies can be estimated, how reservoirs are operated, and how channels change in response to watershed or streamflow alterations. Much of this information is derived from outside sources during most applications of the methodology, and it is incumbent on the user to understand the methods used to supply the information, as well as the assumptions and limitations inherent to the estimation technique.

The subject of Chapter 7 is the Physical Habitat Simulation System (PHABSIM). More specifically, Chapter 7 addresses those aspects of PHABSIM that are not well documented elsewhere: the development of species' microhabitat preference criteria; the options for using substrate and cover information in the model; and the evaluation of passage flows. Chapter 8 is a brief description of how PHABSIM can be used to evaluate channel modifications to increase habitat potential.

Conspicuously absent from this information paper is any detailed discussion about predicting water quality. This should not be interpreted to mean that water quality is not a part of the IFIM. Indeed, water quality analysis is an integral part of the method. It has been omitted from this manual because the subject has been covered in another information paper in this series, Instream Flow Information Paper 17. The use of water quality information in the methodology is explained in Chapter 5.

We would suggest that Part I be read at least once in its entirety. This will give the reader an appreciation of how the entire methodology fits together. Individual chapters in Parts I and II should be reviewed, as needed, during an actual application.

A word regarding units of measurement is appropriate. The IFIM involves the disciplines of hydrology, engineering, sedimentation, water chemistry, biology, and ecology. We have used the units of measurement traditionally utilized by each discipline. Most hydrologic and engineering data and equations are in English units. Water chemistry and biology use metric units. When these disciplines interface, the potential exists for mixing units. We have attempted to minimize such mixtures, but the reader should not be too surprized to see standing crop expressed in grams per square foot. We apologize for any inconveniences this may cause the reader, but due to the diversity of subject material, we could not see a satisfactory alternative.

Questions or comments regarding this manual would be welcomed by the Instream Flow Group. They should be addressed to:

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SUMMARY

Instream flow determination and implementation involves a wide range of agencies, professions, and interests. Decisions made regarding streamflow allocations require the evaluation of numerous factors over a range of events. Certain factors are used to judge the benefits and liabilities resulting from a particular management practice. These factors are called decision variables, and may range from tons of corn to kilowatt hours of electricity to square feet of fish habitat. The role of technical information in the decision process is to quantify changes in the decision variable in response to various management alternatives. The Instream Flow Incremental Methodology (IFIM) is designed for iterative problem solving in this context of decisionmaking.

The decision variable generated by the IFIM is total habitat area for fish or food organisms. Habitat, as computed by the IFIM, incorporates longitudinal changes in channel characteristics, streamflow, water quality, and temperature. These factors are called macrohabitat features, and determine the longitudinal distribution of various species. Habitat also includes the distribution of hydraulic and structural features comprising the actual living space of the organism, called microhabitat. The total habitat available to a species at any streamflow is the area of overlap between available microhabitat and suitable macrohabitat characteristics.

All applications of the IFIM begin with a five-step scoping process. The first step is to define the problem to be addressed and to rigorously define the objectives of the study. The objectives must anticipate the kinds of information the study is to provide, and must sometimes be negotiated to fit the availability of time, money, and personnel. The second and third steps in the scoping process are designed to place bounds on the problem. The geographical extent of the study area is determined, including the length of mainstem river to be considered and whether or not tributaries are to be included in the analysis. Project impact studies differ from instream flow studies, in this respect, because tributaries are not evaluated in the former unless they are directly affected by the project. The third step in the scoping process is a determination of the environmental variables that must be analyzed and those that can be safely ignored. This process actually involves two determinations: an evaluation of present macrohabitat conditions and an estimation of these conditions with the project in place. Several screening techniques are presented to help the investigator judge the necessity for quantitative analysis of a specific environmental variable. The fourth step in the scoping process is the selection of appropriate evaluation species. These may include game, sport, or commercial species, endangered species, indicator species, food organisms, and major competitors of the management objective species. This step is important because all interpretations regarding the significance of an environmental change are based on consequences to the evaluation species. The final scoping activity is to describe temporal variations in habitat usage by each evaluation species. This step determines the life stages and types of microhabitat that must be evaluated during each month.

Habitat characteristics are measured at study sites within the geographical study area. Some study sites are established to measure or monitor

macrohabitat characteristics such as water quality or temperature. Microhabitat characteristics are measured at other study sites. The basic habitat accounting unit is the river segment, a relatively long reach of stream exhibiting homogeneity in channel characteristics and flow regime. Guidelines for establishing segment boundaries include places where the average base flow changes by 10 to 15%, or where changes in slope, channel dimensions, or channel pattern are apparent.

A river segment may contain one or more study sites for macrohabitat and/or microhabitat measurements. A single study site is used to describe one or the other type of habitat, but generally not both. Macrohabitat study sites include control sites, point sources, and a network of stations to define concentration or temperature profiles along the stream. Control sites are used to determine the background concentrations or temperatures above the influence of chemical or thermal inputs. Point sources include outfalls of pollutants, runoff points for aggregated nonpoint sources, and confluences of tributaries. Many biologically important water quality constituents change concentration through chemical and biochemical reactions as they move downstream. A network of monitoring stations, often evenly spaced along the stream, is used to define such concentration or temperature profiles.

Several types of study sites are utilized for the measurement of microhabitat characteristics. Representative reaches are selected through a random or uniform sampling process, and are used to describe the typical microhabitat in a segment. Several representative reaches may be needed in segments exhibiting gradual longitudinal changes in slope, channel dimensions, or channel pattern. Critical reaches are generally atypical of the microhabitat in a segment. The two criteria used to define a critical reach are:

1. The microhabitat characteristics of the critical reach are controlling or limiting to the evaluation species (such as limiting migration or spawning); and

2. These microhabitat characteristics are unavailable or in short supply in the representative reaches.

A special type of critical reach is termed a unique reach. Unique reaches apply only to endangered species, and are typified by large concentrations of these species in streams where such concentrations are unusual. The reasons for the concentration of an endangered species are usually unknown, but a unique reach can be designated by virtue of the status of the evaluation species.

The analytical sequence followed in an application of the IFIM consists of six steps:

1. Describing the river or system in its present state;

2. Determining the mathematical expressions and functional relationships describing the temporal macro- and microhabitat availability of the present system and integrating to determine total habitat availability;

3. Incrementally changing one or more driving variables to reflect a particular management alternative and determining total habitat availability under the "new" system;

4. Determining alternative courses of action or remedial procedures to correct adverse impacts found in Step 3;

5. Repetition of Steps 3 and 4 to derive an array of effective management or mitigation alternatives to minimize adverse impacts; and

6. Evaluation of the alternatives to ensure that they meet management objectives and that internal conflicts and trade-offs have been resolved.

The sequence of analytical procedures varies considerably depending on the initial condition of the system and the nature of the problem to be solved. Therefore, completion of the six-step analysis can follow numerous pathways, and because of this, a single approach cannot be used to address all problems. The approach described in this report takes the format of a dichotomous key which allows the flexibility to route the user through the appropriate processes in the correct order.

A typical application of the IFIM will result in a large volume of output. In order to be useful in the decision process, it is necessary to reduce the volume while retaining the essence of the information. Several methods can be used to prepare, display, and interpret the output. The goal of these activities should be to make a solution more obvious without requiring assumptions that cannot be defended by the user.

The first step in this data reduction process is the computation of the total habitat in each segment as a function of discharge. Total habitat for a life stage is defined as the area of microhabitat per unit length of stream times the length of stream having suitable water quality and temperature. There are several ways of integrating total habitat, depending on the number of microhabitat study sites and whether or not water quality or temperature are suitable throughout the segment. Total habitat must be computed for the entire range of discharges to be evaluated. The result is a single functional relationship between total habitat and discharge for each life stage.

Habitat display and interpretation techniques include optimization, habitat time series and duration curves, and stochastic or probabilistic effective habitat time series. Optimization techniques are generally used for instream flow recommendations and involve finding a flow for each month that minimizes habitat reductions for all life stages and species occupying the stream during the month. Habitat amounts can be weighted to reflect different spatial requirements among life stages or different management priorities among species.

A habitat time series is constructed by integrating the habitat-discharge function with a time series of discharge. Habitat conditions without a project are displayed using the existing habitat-discharge function and the historical flow time series. Conditions with the project are simulated by developing a habitat-discharge relationship reflecting the environmental changes caused by the project and by imposing project operations on the historical flows to develop a new flow time series. One way to define the impact of the project is to integrate the areas beneath the habitat time series with and without the project and find the difference. A habitat duration curve summarizes the habitat time series in terms of the percent of time a certain amount of habitat is equalled or exceeded, with and without the project. Biologically significant impacts can be defined by the area under the habitat duration curve, between the 50% and 90% probabilities of exceedance. The habitat duration curve can also be used to express an impact in terms of frequency rather than amount.

The effective habitat time series uses estimates of the relative spatial requirements between life stages or trophic levels (called habitat ratios) to compute the habitat requirements for each life stage at a particular time. A life table is compiled, comparing the required habitat for any time step in the time series with the amount available. If the amount available exceeds the amount required, then the required amount is carried forward to compute the habitat required for the next life stage during the next time step. The available amount of habitat is carried forward when it is less than the required amount. The effective habitat time series estimates the amount of adult habitat that can be utilized over time and incorporates lags in habitat utilization resulting from extreme events or water supply patterns that affect several life stages at once. A version of the effective habitat time series, based on a steady state population and probabilistic hydrology, can be used to construct an instream flow regime that ties the flow requirement for any month with those for all other months.

Habitat ratios are extremely useful in the interpretation of habitat-related data and can be derived by professional judgement, historical evidence, comparisons among streams, and by mathematical derivation. Habitat ratios among life stages are functions of the age-biomass distribution of the population, and the densities and survival rates of each life stage. Generally, subadult life stages require relatively less space than the adult phase. Habitat ratios among trophic levels are affected by the relative production rates at each level, the energy transfer efficiency between levels, the cropping efficiency, and the relative proportion of a food item in the diet. Because of the difficulty in determining each of these factors, the best estimate of trophic level habitat ratios may be derived by establishing a relationship between the habitat ratios for several streams and the condition factor for the fish in each stream. A method of estimating total community food requirements and supply is proposed in Appendix B.

In a typical application of the IFIM, the investigator must compute or obtain an estimate of the water supply on which the instream flow recommendation or mitigation plan is based. Chapter 6 outlines several techniques for synthesizing hydrographs in gaged and ungaged streams, and discusses considerations of reservoir operations. The concept of water budgets or water balances is also introduced. The water budget plays three important roles in the IFIM. First, because the instream flow recommendation is based on the computed available water supply, the water budget helps establish credibility with water managers. Second, the instream flow recommendations for several streams can be integrated into a cohesive, internally consistent network. Third, the water balance of recommended flows serves as a first level check of the accuracy of the results.

The investigator must also be concerned with the relationships between discharge, sediment yield, and channel structure. Channel dimensions are largely determined by the bankfull or dominant discharge. Changes in channel dimensions due to changes in the dominant discharge can be estimated through the use of hydraulic geometry equations. The shape and pattern of the channel are primarily determined by the amount and size of the sediment transported by the stream. Changes in shape and pattern are predictable when the sediment/discharge ratio is altered, but actual quantification of a new channel structure requires the use of sediment transport models and considerable expertise.

Discharge and channel structure combine to define the range of physical microhabitat conditions available to a species. Chapter 7 discusses the Physical Habitat Simulation System, with particular reference to microhabitat criteria, cover and substrate quantification, and the estimation of passage flows over natural barriers and through culverts. Several types of microhabitat criteria can be used in the Physical Habitat Simulation System (PHABSIM): binary criteria, preference curves, multivariate suitability functions, and combinations of preference curves and suitability functions. All criteria are used to estimate a joint preference of a fish for a combination of hydraulic and structural features at a specific location in a stream. The joint preference factor is found by multiplication of weighting factors for each variable when binary criteria or preference curves are used. The joint preference factor is computed directly when the multivariate suitability function is used. The advantages of the preference curve are that it can be constructed and modified by professional judgement and can represent very complex or discontinuous mathematical functions. The advantage of the multivariate approach is the inclusion of interactions among variables in the joint preference factor.

Cover and substrate are often represented by very complex, discontinuous functions. Therefore, preference curves are usually used to depict cover and substrate characteristics. The use of cover and substrate information in PHABSIM involves the development of a numerical code to depict various types and combinations of these characteristics, and a curve to describe the preferences of an organism for each combination. Cover can also be treated as a discrete variable, with separate depth and velocity criteria associated with each cover type.

Passage flows over natural barriers are evaluated by computing the width of stream meeting the clearance requirements of a species at each flow. Culverts present unique passage barriers and are evaluated by computing the time required for a fish to negotiate a culvert at different streamflows.

Channel modification to enhance the physical structure of the stream is one way to increase or maintain the availability of habitat. This alternative is most feasible when channels have already been modified to increase water conveyance or when water supplies are so short that negotiation over instream flows will not succeed. Structural modifications to improve habitat include artificial cover devices, deflectors, weirs, and headgates. Nonstructural modifications include deepening pools, raising the elevation of riffles, importing special substrate materials, or otherwise increasing bed profile diversity without the use of structures. Whenever channel modifications are contemplated the investigator must evaluate them in terms of their effectiveness in improving habitat, the frequency with which they must be replaced, installation and maintenance cost, and the chances of increased flood potential.

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1. OVERVIEW OF THE INSTREAM FLOW INCREMENTAL METHODOLOGY

1.1 BACKGROUND PHILOSOPHY

Incrementalism is an approach to problem solving that refers to an institutional policy of slightly modifying procedures or positions from those previously established. This is a common means of decisionmaking. An incremental approach allows a problem to be addressed, at least at first, from a familiar perspective. If a solution cannot be found, it is then possible to either slightly redefine the problem or the perspective until a solution can be found. Incrementalism is a particularly valuable approach when applied to a problem with multiple aspects or solutions (Lindblom 1959; Lamb 1976; Doerksen and Lamb 1979).

The issue of managing water for instream uses may be viewed from several directions, and individual problems often have many potential solutions. A limited perspective requires only a simple solution, but will be prone to failure when new circumstances or a different alternative is encountered. A good example of a limited perspective is the concept of a "minimum" streamflow. From the perspective of a hydrologist, the minimum streamflow is often defined as the 7-day, 10-year low flow. This is the lowest average flow for 7 consecutive days which statistically occurs once every 10 years. This definition is based solely on water supply, and the statistic is often used in the determination of storage requirements or in the design of sewage treatment facilities. From the perspective of the fishery biologist, the 7-day, 10-year low flow would be a ridiculously low level at which to instigate flow protection. The biologist might make a recommendation for a minimum flow based solely on what is perceived to be best for the ecosystem, or even an individual species, without considering other uses of the water supply. Such recommendations are usually considered infeasible by water managers.

Instream flow determination and implementation usually involves a number of agencies and professions, therefore, a variety of perspectives. Each profession or agency has a particular approach to problem solving and often is blessed or encumbered (depending on your perspective) with a list of "stock" definitions and solutions (Lamb 1976). Given the multiagency and interdisciplinary nature of instream flow issues, it is important for each professional to understand at least the perspectives and constraints of other professions and agencies. This philosophy falls several steps short of the "Universal Man Theory." It is not intended that one individual should learn everything about all aspects of instream flow, but each professional should understand enough about these aspects to ask the right questions and to know whether the answers are reasonable.

Understanding the perspectives and constraints of other agencies or professions does not mean that your own perspectives or solution techniques should be ignored. Rather, this understanding should increase your ability to solve problems. One way to accomplish understanding is to develop a system by which a present condition, or the status quo, can be described. The driving variables can be modified slightly to describe a new condition, which can then be evaluated from numerous perspectives. This approach does not require anyone to abandon a particular perspective or problem solving approach. It does require that two or more parties agree on what the status quo is. The methodology described here is designed to define a starting condition, and then provide data on incremental changes so that professionals can evaluate new conditions. It is quite possible that a solution arrived at through incrementalism would have been considered radical had it been proposed at the outset.

The Instream Flow Incremental Methodology (IFIM) adheres to the principle of incrementalism. In one sense, the IFIM can be thought of as a collection of computer models and analytical procedures designed to predict changes in fish habitat due to increments of flow change. Indeed, this methodology does enable such predictions. It can also be used to evaluate such diverse impacts as changes in channel structure or alterations in waste loading from a pollution source. In fact, it can be used to translate changes in land use to changes in the stream environment, if the user follows it that far. However, the IFIM is much more than a collection of computer models. It is, in fact, a thought process that begins with the structuring of the study design and carries through to the final negotiation of a problem solution. Several of the underlying principles of the methodology are presented and discussed below.

The first, and probably most important principle, is that implementation of an instream flow regime is inseparable from water management. Therefore, the IFIM should be thought of as a water management tool. It is not intended to be an ecosystem model. However, it is designed to have environmental and ecological applications. The IFIM will not ensure against ecological blunders, as is true with other decision systems, including ecosystem models. Ecological blunders can be prevented only insofar as we are able to foresee the consequences of our actions and adapt our management accordingly. The IFIM does allow a systematic evaluation of different management options, providing quantitative estimates of fish habitat available under each option.

The second principle is that the method is not intended to generate a single solution, but to predict the impacts of different alternatives. Users seeking a mechanistic solution to a problem may find this methodology difficult to understand. The methodology has been specifically designed to provide multiple solutions. Therefore, the user must embrace the philosophy of incrementalism and iterative problem solving before the methodology can be used to its full advantage. Following this philosophy, the methodology best lends itself to a systems approach. Such an approach opens a wider variety of options and water management alternatives to an application of the methodology.

The third principle is that the objectives of any application must be rigorously defined. It is quite possible for two identical applications of the methodology to result in vastly different solutions, due solely to the objectives of the analysts. For example, two groups may have as their objective, "the design of a flow regime to maintain a fishery at a minimally acceptable level." To one group this really means, "To maximize fish habitat within the constraints of the available water supply." To the other group, the same objective means, "To maximize out-of-channel water use without eliminating the fishery."

1.2 METHODOLOGY DESIGN

An initial hurdle in the development of this methodology was how to describe habitat and the various factors influencing it. This problem was rooted in the diverse approaches to describing riverine ecosystems. One perspective is to examine a river from its headwaters to its mouth. Numerous authors have reported the addition or replacement of species as a function of stream order, stream size, gradient, or other descriptions of longitudinal gradations of environmental conditions (Shelford 1911; Burton and Odum 1945; Huet 1959; Sheldon 1968). This type of study considers the "longitudinal succession" of species as a function of variables such as mean depth, mean velocity, temperature, water quality, or other characteristics exhibiting gradational change. This perspective might logically be defined as a macrohabitat approach to riverine ecology.

A second approach is to hold the macrohabitat as a constant and examine resource partitioning by different species at a microhabitat level. Dettman (1977), and Alley and Li (1978) found that competition between rainbow trout and Sacramento squawfish was reduced by habitat isolation and different feeding habits. Everest and Chapman (1972) showed that young of the year and juvenile steelhead and chinook salmon utilize virtually identical microhabitats and food items. However, because the spawning cycle for the two species is approximately 6 months out of phase, there is little competition between like age groups of the two species. Thus, ecological segregation can occur on either a large and small scale and both spatially and temporally.

The IFIM has been designed to incorporate both macro- and microhabitat concepts. Certain macrohabitat characteristics, such as temperature and water quality, define limits of suitability for different species. The net result of changes in these characteristics is a change in the longitudinal distribution of species. These macrohabitat conditions determine the length of stream that could potentially be inhabited by a species. Other macrohabitat characteristics, such as geology, elevation, slope, and water supply, create longitudinal changes in the shape, pattern, and dimensions of the river channel. These, in turn, are major determinants of the types of microhabitats which occur at any location on the stream. Thus, the types and spatial distribution of microhabitats also grade longitudinally in response to geomorphic characteristics and processes. Fish and invertebrates do not respond directly to physical macrohabitat characteristics; instead, they respond to the microhabitat conditions associated with the macrohabitat. Because it is not feasible to measure all the microhabitat for the entire length of the river, it is necessary to measure the microhabitat in locations that reflect the longitudinal change in physical macrohabitat. A sampling strategy has been developed to aid the investigator in the selection of these microhabitat measurement sites. This strategy is discussed in Chapter 3.

Two different functions are developed in the course of this analysis: a macrohabitat suitability function; and a microhabitat availability function. The relationship between temperature or water quality and discharge is generally a simple linear function; the more water in the channel, the better the water quality and the more kilometers of suitable macrohabitat. The relationship between microhabitat and discharge is usually (but not always) nonlinear. The total available habitat occurs within the area of overlap between available microhabitat and suitable macrohabitat conditions. This area is computed in the IFIM by conducting two separate analyses, superimposing the macrohabitat analysis on the microhabitat analysis, and computing the area that has suitable conditions in both categories.

Before the evaluation of macro- and microhabitat conditions, it is necessary to evaluate the watershed conditions and relate these conditions to the macrohabitat characteristics of the stream. This step is needed for two reasons. First, all measurements are made at a point in time and assumed to be representative of the stream as the analysis is extended into the future. If a land use change or natural disturbance has recently changed the characteristics of the watershed, these changes are reflected in the stream macrohabitat at the time of measurement. Therefore, the measurements may not accurately reflect future conditions. Second, problems in the amount of total habitat available may be related to a land management factor, rather than water management. The most effective corrective action, and the benefits derived from such action, cannot be fully determined without identifying the source of the problem.

Figure 1 shows the overall analytical strategy of the IFIM. Individual components in Figure 1 are discussed and expanded in the following section. Each application of the IFIM begins at the watershed level and proceeds through both a macrohabitat and microhabitat analysis. A proposed action may act on the watershed, indirectly affecting macrohabitat characteristics, or directly on one or more macrohabitat characteristics. These effects will be reflected in the total amount of habitat available. Based on this computation, the impact of the proposed action can be quantified, and a judgment made on the acceptability of the proposed action. If an action is determined to be unacceptable, corrective measures may be suggested, model variables changed, and the analysis process repeated.

1.3 MAJOR HABITAT COMPONENTS AND ANALYSIS SEQUENCES

1.3.1 Step 1: Determine Watershed Influences on Macrohabitat Characteristics

The first step in the habitat analysis sequence of the IFIM is the determination of the present status of the watershed. Watershed and land use patterns largely control the yield of water, sediment, and chemicals to the river. Disturbances on the watershed may alter one or more of these delivery processes. An evaluation of watershed processes is necessary to distinguish those factors which can be modified by water management from those which can (or must) be modified by land management. The prevailing land use may limit the effectiveness of water management in controlling a particular problem.

The investigator should evaluate the current status of the watershed to determine two conditions: the relative permanancy of existing water, sediment, and chemical yields as currently measurable in the stream; and the effectiveness of instream flows as a mitigation strategy. This step can be considered an early screening process to determine whether an instream flow study should be conducted immediately, deferred for a period of time, or not done at all.

Undisturbed watersheds, or watersheds in which the disturbance is considered permanent (such as agricultural lands), are usually amenable to

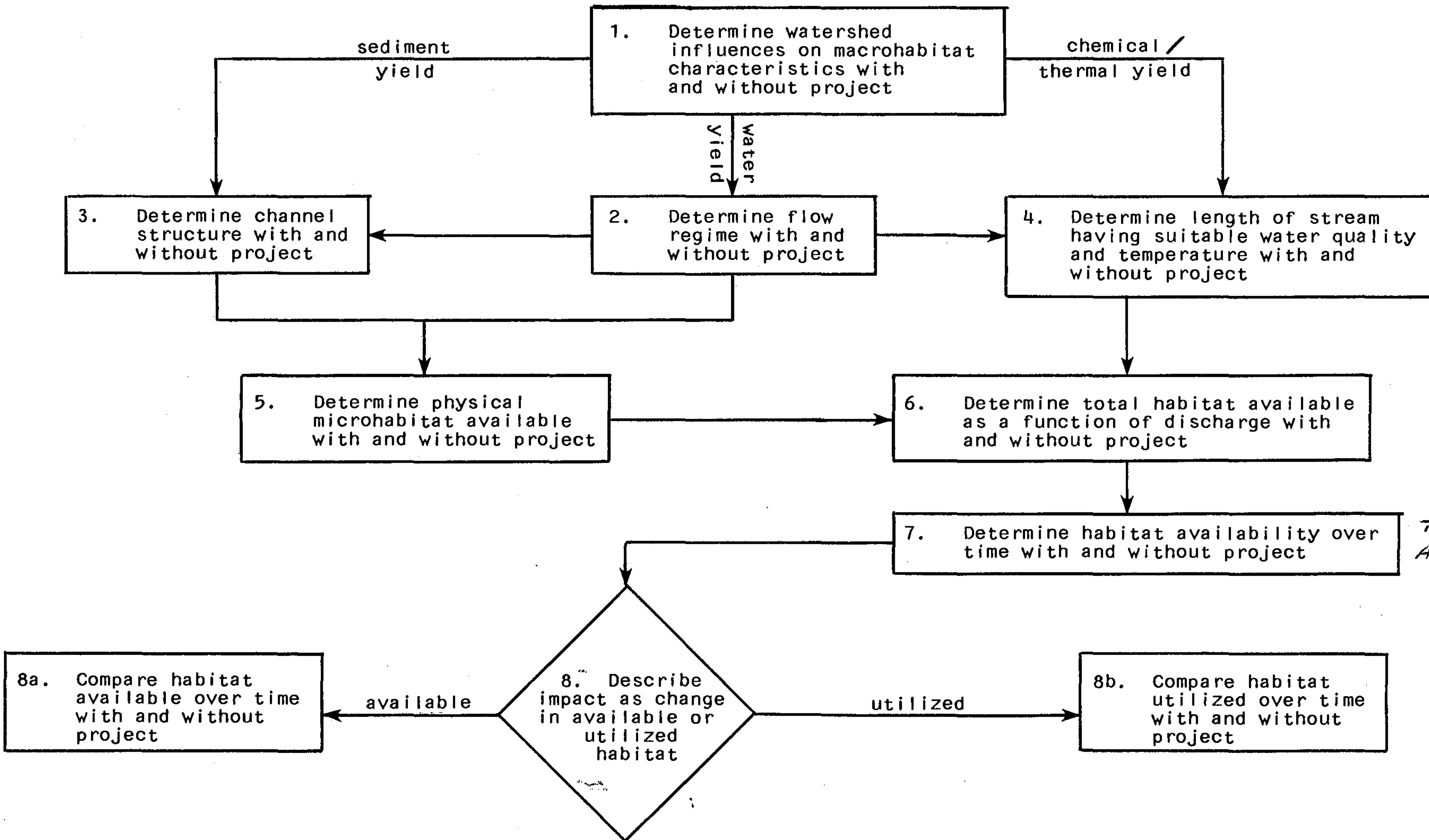


Figure 1. Overview of the analytical sequence performed in an application of the IFIM.

instream flow studies at any time. It may be advisable to defer an instream flow study in disturbed watersheds in the process of recovery until recovery is essentially complete. The decision on whether or not to delay a study must consider the estimated recovery time and the time frame in which water management decisions must be made. Short term water management decisions may require a prediction of future water supply, water quality, and channel characteristics in order to complete an instream flow study. Instream flow considerations may enter the decision process too late to have any influence when a study is deferred until watershed recovery is complete. Finally, a watershed disturbance may be so pervasive that instream flow management would not be effective, either in terms of ecosystem management or water management.

Figure 2 illustrates the watershed evaluation process as it applies to the IFIM. Figure 2 expands Step 1 in Figure 1 (i.e., determine watershed influences on macrohabitat characteristics). An instream flow study may be initiated immediately if the watershed is in equilibrium and the project will not affect the watershed. The investigator has four choices if the watershed is not in equilibrium: (1) to defer the study until equilibrium is reestablished; (2) to predict the flow regime, channel structure, and water quality in the stream after a certain recovery period; (3) to recommend watershed treatment practices that will accelerate the recovery process; or (4) abandon the study and monitor the recovery. These options are discussed in detail in Chapter 2.

a. Water yield. Water yield is important to an instream flow investigation for two reasons. The most obvious reason is that the amount and timing of streamflow (the flow regime) is directly linked to runoff from the watershed. Less obvious is the fact that the channel dimensions and the proportions of pools, riffles, and meanders are determined by the flow regime.

Only a small portion of the annual precipitation falling on a watershed contributes to streamflow. Even less water reaches the stream as surface runoff. Runoff in an undisturbed watershed is impeded by vegetation, surface irregularities that create small storage basins, and soil structures that encourage infiltration. These factors retard overland flow, allowing the water to soak into the ground. Eventually, percolating surface water enters the ground water reservoir, which becomes the source of streamflow during periods of little or no precipitation. The discharge during such periods is called base flow.

Large scale disturbances on watersheds may alter the water yield by reducing resistance to overland flow, reducing or obliterating surface irregularities, and compacting the soil. This change in water yield is usually indicated by an increase in surface runoff during periods of precipitation and a reduction in the base flow during dry periods. The result is a flashy flow regime where the stream may run at nearly bankfull during a moderate rainstorm and practically dry up when the rain stops. The same type of flow regime is typical of agricultural lands which have been tile-drained or urban areas drained by storm sewers where infiltrating water is intercepted by a pipe and routed directly to the river.

These types of alterations to the flow regime create two problems for the water or habitat resource manager. First, there is a problem with the timing

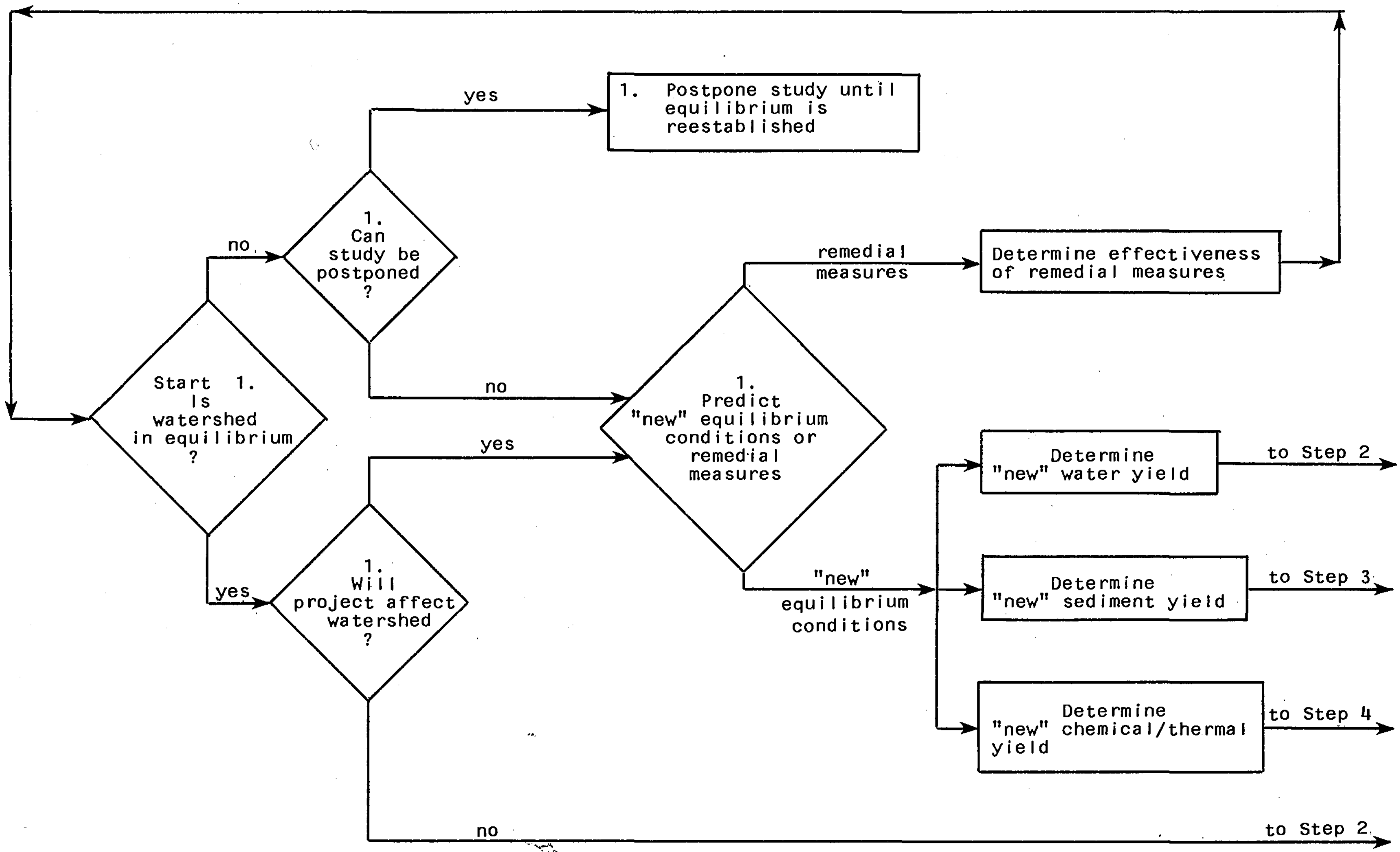


Figure 2. Step 1 (Figure 1): Determine watershed influences on macrohabitat characteristics with and without project.

of the water supply. The mean annual flow might indicate a plentiful water supply but, due to the "feast and famine" delivery pattern, the aquatic community cannot take full advantage of the available supply. The second problem is that increased peak flows tend to enlarge the channel, magnifying the problem of diminished base flows.

b. Sediment yield. Although the flow regime essentially determines the size of a channel, the amount of sediment reaching the stream and the ability of the stream to transport sediment jointly determine its shape. If the sediment load supplied to the stream is balanced by the ability of the stream to transport that load, no net change in channel structure occurs over time, and the stream and watershed are said to be in equilibrium. However, if the watershed contributes more sediment than can be transported by the stream, the channel structure changes to a more efficient shape for transporting sediment. This shape is usually wider and shallower than the original channel and, in extreme cases, the stream reverts from a meandering or riffle-pool sequence to a braided channel. This process is called channel aggradation. The channel response is just the opposite if the watershed contributes less sediment than can be transported or if the sediment is intercepted (as in a reservoir). This is termed channel degradation.

These changes affect the microhabitats of fish, invertebrates, and even aquatic vegetation. The most obvious effect in many streams is a change in the particle size of the bed material. The bed material frequently becomes smaller in aggrading channels. In degrading channels, the bed material gets larger because the finer material is swept away. Redistribution of hydraulic characteristics of the discharge (depth and velocity) usually accompanies a change in channel shape and particle size.

c. Chemical yield. Water chemists classify the sources of chemicals entering the waterway as point loads and nonpoint loads. The watershed and the associated land use determine the nonpoint sources. Unlike sediment, chemicals may enter an open channel either through surface runoff or ground water inflow, with certain chemicals often predominantly associated with one mode of entry or the other. The distinction between point and nonpoint sources, and surface or ground water entry, may be very important to an instream flow study because the concentrations of some water quality constituents may be established before the water reaches the stream. Changing the concentrations of these constituents may not be possible by manipulating the streamflow, particularly if the entire water supply for the stream originates within one homogeneous watershed. Such water chemistry problems are related, but independent of streamflow, and cannot be resolved solely by an instream flow study.

The water chemistry of a stream in an undisturbed watershed generally reflects a homeostasis between streamflow and nonpoint chemical yield. The primary water quality concerns will probably be with point sources, many of which can be at least partially mitigated by water supply manipulations. However, changes in land use on the watershed can result in accelerated chemical loadings, only some of which can be resolved by increasing the streamflow. Runoff from feedlots or agricultural lands can increase the loading rates of nutrients and oxygen consuming compounds. Although these are nonpoint sources, they can be treated as dispersed point sources because their effects can be reduced by water management.

Watershed disturbances that result in removal of vegetation or exposure of easily weathered geologic formations may cause accelerated solution of a variety of anions and cations. Bormann and Likens (1967) found that removal of vegetation can upset the nitrogen cycle in forest ecosystems. The primary result of such an imbalance is a preponderance of highly soluble nitrate salts at the expense of ammonium salts. Following denudation of the watershed, the net output of dissolved inorganic substances increased to nearly 15 times the predisturbance yield, and the pH was reduced from 5.1 to 4.3 (Bormann and Likens 1967). Manipulation of the water supply during base flow periods has little effect on the water quality in streams draining such watersheds. The only way that instream flow management could be effective in reducing this type of impact would be to introduce water from an unaffected watershed. This alternative is often feasible only at major confluences, where the affected stream is essentially treated as a point source.

1.3.2 Step 2: Determine Flow Regime With and Without Project

It is almost a foregone conclusion that an application of the IFIM will involve a change in flow regime. The principal exceptions are channelization and stream rehabilitation projects. This step is illustrated in the top half of Figure 3. The determination of the flow regime with and without the project is frequently more complicated than it appears in Figure 3. Many of the streams which will be analyzed will not be gaged, so hydrographs must be synthesized. A project that alters the runoff pattern in the watershed will change the flow regime in the stream. Hydrographs for these stream must be synthesized from a runoff model. The most straightforward impact analyses would probably be flow modifications caused by reservoirs and diversions. However, project sponsors often do not know exactly what the operating schedules will be, especially early in the development process. These problems, and some of their solutions, are discussed in detail in Chapter 6.

The output from Step 2 is an anticipated flow regime with and without a project. The project might simply be a recommended flow regime in the case of an instream flow study, but the recommended flow will quite likely be different from the existing flow regime. Note that the output from Step 2 is used in each of of the next three steps: (1) to ensure that a change in flow regime does not result in a change in channel structure; (2) to determine the effect that altered flows might have on water quality; and (3) to determine the range of flows over which microhabitat availability will be calculated.

1.3.3 Step 3: Determine Channel Structure With and Without Project

Channel structure is considered first at a macrohabitat level to determine the longevity of the existing structure. This factor is separated from watershed considerations because not all channel disequilibria are caused by watershed disturbances. Streams in unaltered watersheds may be in disequilibrium due to manipulations of the stream itself. Three types of alterations are notorious for creating channel changes: (1) construction of dams; (2) channelization; and (3) diversion of peak flows.

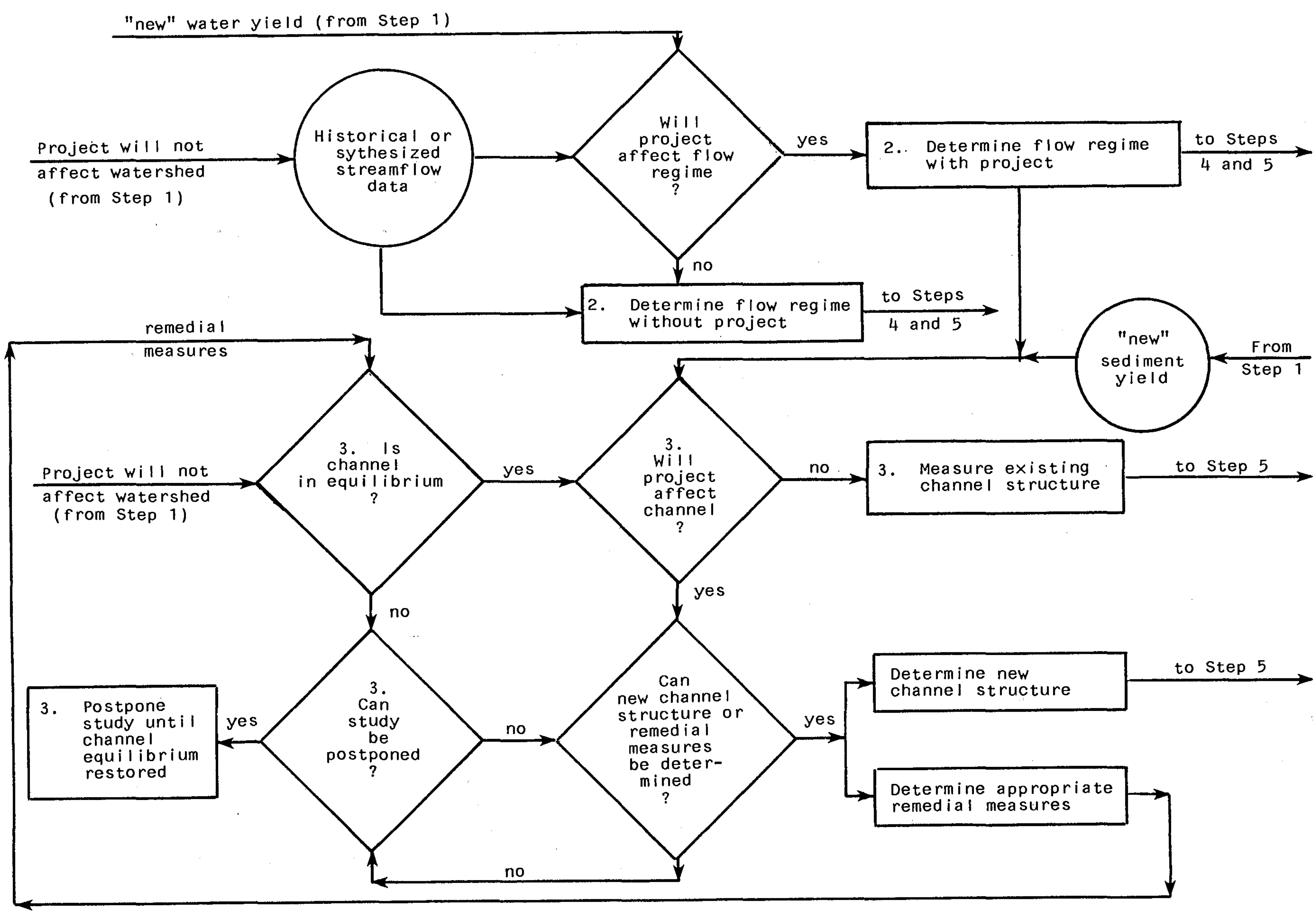


Figure 3. Step 2 (top): Determine flow regime with and without project; and Step 3 (bottom): Determine channel structure with and without project.

Generally speaking, the most frequent channel response after the construction of a dam is degradation of the reach downstream of the dam. Sometimes the change in bed elevation exceeds 6 m, and the effect may extend downstream for 150 to 300 km (Lane 1955). Clearly, one necessary action in evaluating changes in microhabitat due to dam construction is to predict what the channel will look like in its new equilibrium state.

Channelization (or channel realignment) increases the slope of the stream in the channelized reach. This gives the available discharge more energy with which to carry sediment. The result is frequently degradation of the channelized reach and of unchannelized upstream reaches as well. As the water proceeds downstream from the channelized reach, it often carries more sediment than can be transported by the discharge in the unchannelized downstream reaches. This results in aggradation downstream of the realignment. This series of events is one of the reasons that channelization tends to be a self-perpetuating activity. Microhabitat studies which concentrate on the reach of stream physically altered by the bulldozer fall short of documenting the full impact of the channelization.

Removal of seasonally accumulated sediments in streams generally occurs during high discharge periods associated with snowmelt or storm runoff. Diversion of large amounts of this high discharge can cause aggradation of the channel by not providing enough flow to remove previously deposited sediments. The high discharge period is also highly correlated with the peak watershed sediment yield, and more sediment may enter the channel than the discharge can transport, causing deposition. Diversion during high discharge might be expected to remove a proportionate amount of sediment along with the water. However, diversion works are commonly designed in such a way that most of the coarse sediment remains in the stream.

Step 3, the determination of the channel structure with and without the project, is summarized in the bottom half of Figure 3. The outputs from this step are a measure of the channel structure as it currently exists and an estimate of the future structure. The existing and future channel structures are assumed to be the same only if:

1. The watershed and channel are currently in equilibrium;

2. The project will not directly or indirectly affect the channel; and

3. The flow/sediment load relationship (particularly during high flows) remains the same.

1.3.4 Step 4: Determine Length of Stream Having Suitable Water Quality and Temperature

Water quality is related to streamflow in an intriguing number of ways. Water quality considerations can be classified into three general types: conservative and nonconservative constituents and temperature. Conservative water quality constituents do not decompose or significantly react with other chemicals in the water. Many inorganic salts fall into this category. The concentration of these materials is related to discharge only through dilution.

Given a constant supply of conservative chemicals, the concentration decreases with increased discharge and vice versa.

Nonconservative constituents are those materials which, because of biochemical reactions, change in concentration over time. Typical examples of nonconservative constituents are oxidizable organic material, ammonia, and dissolved oxygen. Nonconservative chemical concentrations are related to streamflow by numerous mechanisms. For example, consider the factors that affect dissolved oxygen concentration. The saturation concentration of dissolved oxygen and the decomposition rate of organic materials are both governed by temperature, and temperature is related to streamflow in several ways. First, there is a greater volume of water to be heated by the sun with more discharge. Second, velocity determines the travel time for a body of water, and the longer it takes for the water to travel through a system, the longer it is exposed to thermal gain (or loss). Third, the larger the ratio between the width and depth of flow, the greater the proportion of the water volume exposed to sunlight. This ratio is often increased with reduced discharge. Reduced discharge generally results in higher water temperatures during the summer, at least until a thermal equilibrium is reached with ambient atmospheric conditions. As temperature increases, the saturation concentration for dissolved oxygen decreases and the rate of oxidation of organic material increases.

The dissolved oxygen concentration is also a function of the concentration of oxygen-demanding organic material. Therefore, dilution of organic matter by the total discharge is an important determinant of the dissolved oxygen concentration. In addition, water velocity plays a major role in the dispersion of oxygen-demanding material, both locally and longitudinally. Insufficient velocity allows settling of larger organic particles, which can lead to the formation of sludge deposits. Higher water velocity disperses the organic material over a larger longitudinal distance. This means that a larger area of stream is involved in the oxidation process at higher flows, reducing the demand on reaches closest to the source of the oxidizing material. Finally, the rate of mechanical reaeration is a function of depth and velocity.

Temperature alone may have significant effects on a community, in addition to its role as a driving variable in the dissolved oxygen equation. The most obvious effects of temperature are on survival and growth of aquatic organisms. Less obvious is the effect of temperature on the timing of the life history stages of a species or species phenology.

The metabolic rate of all coldblooded animals is directly related to temperature. A disruption in the thermal regime of a river may make certain stream reaches uninhabitable for some species, but not for others. In some cases, the temperature may be so high that a reach will be totally uninhabitable or so low that growth is impaired. Alternately, a source of very warm or very cold water may block the migration of a species into upstream areas where the habitat is satisfactory. The longitudinal distribution of a species implies at least some avoidance of areas where temperature may affect survival. However, suboptimal temperatures, even though nonlethal, may significantly reduce fish production.

The determination of the length of stream having suitable water quality and temperature is illustrated in the top half of Figure 4. Several pathways

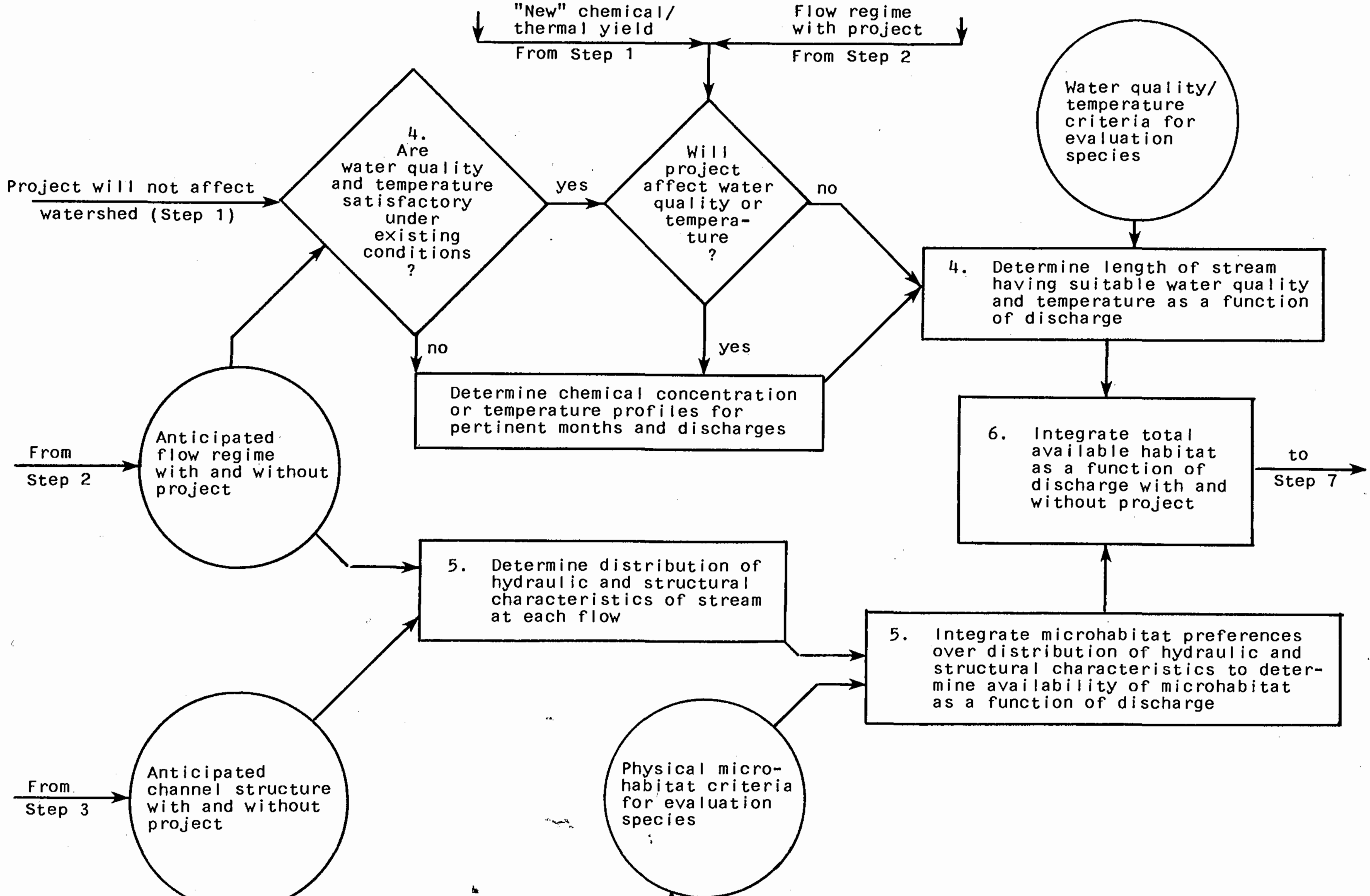


Figure 4. Determination of length of stream having suitable water quality and temperature (Step 4), determination of physical microhabitat availability (Step 5), and integration to determine total habitat available as a function of discharge with and without project (Step 6).

can be followed to make this determination, depending on initial conditions and the effects of the project. The length of stream having suitable water quality and temperature will equal the total length of stream under study if it is determined that both water quality and temperature are always satisfactory under existing conditions and the project will not change this situation. The suitable stream length may be less than the total length of stream under study if a current water quality problem exists or if the project will change the flow regime or the chemical or thermal loading rates. The suitable stream length in this case is found by developing a profile of temperature or the concentration of a chemical along the length of stream. These profiles may be empirically derived if a current water quality problem exists, but must be modeled if a change in streamflow or loading rate is anticipated. The tolerances or preferences of the evaluation species for each water quality parameter are then superimposed on the appropriate profile and the suitable stream length determined from the point of intersection of the two lines. This process is repeated for the range of discharges that are likely to occur during the period of interest. If it appears that water quality is a severe constraint on the availability of habitat, the investigator has the option of inputting a remedy (such as increased waste treatment) to increase the suitable length of stream.

The analysis is complete after this step if the water quality is always the limiting factor for the entire stream and nothing can be done to remedy the problem. It is pointless to analyze microhabitat if the water quality is so poor that the important management species cannot live in the stream. An exception might be the determination of physical habitat potential to evaluate the benefits obtained by eliminating the water quality problem. Water quality often improves with distance downstream from a waste load source, and only the length of stream with unsuitable water quality is excluded from the microhabitat accounting, at least for the months that water quality is limiting.

1.3.5 Step 5: Determine Physical Microhabitat Available With and Without Project

The lower half of Figure 4 illustrates the process used to determine the availability of physical microhabitat as a function of discharge. An understanding of the components that describe microhabitat is necessary to evaluate microhabitat conditions as a function of streamflow. Microhabitat, as defined under this methodology, consists of two basic components: rigid structural characteristics and variable hydraulic conditions.

Structural habitat characteristics reflect the physical structure of the channel. Examples include bed configuration, channel width, riffle-pool ratio, meander wavelength, dominant particle size and percent fines comprising the substrate, and overhead or object cover. These channel characteristics are assumed to be constant for a specified time period and range of flows; in essence, they are not directly influenced by discharge under the definition given above. An undercut bank, for example, is created by erosion of a bank with some cohesive element (usually root masses) that prevents slumping. Once created, an undercut bank is assumed to be representative of a portion of the stream, and that condition is fixed in time. Therefore, the physical presence or absence of a particular structural element does not change as a function of discharge. What does vary is the utility of that element. For example, when the discharge decreases to the point that the water withdraws from the banks, the undercut features are still present, but cannot be used as microhabitat.

Structural elements do change over time; e.g., pools will fill or scour, undercut banks will collapse, and log jams will float away. However, if a stream is in equilibrium, it may be assumed that the structure measured at one time is representative of the overall stream structure at all other times. Furthermore, many structural changes occur in a cyclic and predictable manner. Pools and bars are usually built during high runoff. During the rest of the year the bars erode and the pools fill up. Therefore, the channel structure immediately preceeding runoff may be quite different from that following runoff. The investigator must determine whether or not these cyclic changes occur and assign time limits to each structural configuration.

The hydraulic variables which affect microhabitat utility are width, depth, and velocity. All three variables change differentially as functions of discharge. In addition, organisms utilizing an area of microhabitat do not respond to the average value of depth or velocity in the whole channel. They respond to the depth and velocity that occur in conjunction with the structural habitat in their own space, a microcosm, as it were. In other words, physical microhabitat is a complex array of combinations of depths, velocities, and structural characteristics. This array is redefined with a different set of depth, velocity, and structure combinations each time the discharge changes.

Riverine organisms utilize a variety of microhabitats at different times. The microhabitat used by a species during a particular life history phase is a reflection of its evolutionary history. Size, shape, swimming performance, feeding strategy, predation, and competition all combine in various degrees to define the optimal conditions of a microhabitat, as well as the limits of toleration. Small fish are often found in shallower, slower water than are larger fish. Such areas provide protection from aquatic predators and do not tax the swimming ability of small fish. Larger fish and many aquatic invertebrates select microhabitats that optimize their abilities to feed without expending large amounts of energy. Many of these species are morphologically adapted to live in a particular type of microhabitat. Rivers tend to contain more specialized species, in this sense, than do bodies of standing water.

Analysis of microhabitat-discharge relationships requires knowledge of the life histories of the species of concern and the ecology of the stream under study. Such analyses also require the determination of those combinations of structural and hydraulic conditions that comprise the various microhabitats utilized by a species during the course of its life cycle. The quantification of these characteristics in the IFIM is referred to as criteria development. Appropriate criteria are crucial to the use of the method. Chapter 7 in this document, and several information papers published by the Instream Flow Group, have been devoted to this subject.

1.3.6 Step 6: Determine Total Habitat Available as a Function of Discharge

The combination of microhabitat and macrohabitat to compute total available habitat is shown near the right margin of Figure 4. Inputs to this step are derived from Steps 4 and 5. The anticipated channel structure and flow regime with and without the project are used to define the respective relationships between microhabitat area per unit length of stream and discharge. The anticipated chemical/thermal loading and flow regime with and without the project, along with water quality criteria for the species, are used to determine the suitable length of stream. The total habitat available in the stream at one discharge is defined as the intersection of these two components.

1.3.7 Step 7: Determine Habitat Availability Over Time With and Without Project

The total amount of habitat available at any time is a function of the amount of habitat available at a particular discharge and the discharge in the channel. The total habitat versus discharge function (with and without project) is combined with a time series of discharge (with and without project) and species periodicity information to form a time series of available habitat for each life stage with and without the project. This step is illustrated near the top of Figure 5.

1.3.8 Step 8: Describe Impact as Change in Available or Utilized Habitat

Step 8, shown in the lower portion of Figure 5, allows the option of defining the impact of a project in terms of changes in available or utilized habitat. Step 7 produces a time series of available habitat for both the existing (without project) conditions and anticipated conditions with the project. One way of quantifying the impact of the project is simply to compute the difference in area beneath both time series curves. Summary statistics of available habitat, such as the habitat duration curve (Chapter 5), can be used to quantify habitat changes occuring only under the more biologically significant portions of the habitat time series.

Another technique, shown as Step 8b, utilizes population statistics to compute the amount of subadult habitat needed to support a given amount of adult habitat. These subadult requirements can be used to estimate habitat ratios from one life stage to the next. The habitat ratios are used to determine the amount of adult habitat that can be utilized at a particular time, given the amount of subadult habitat available or utilized in previous years or months. The result is a time series of effectively utilized adult habitat, with or without the project. The project impact can then be quantified as the difference in area beneath the effective habitat time series, with and without the project.

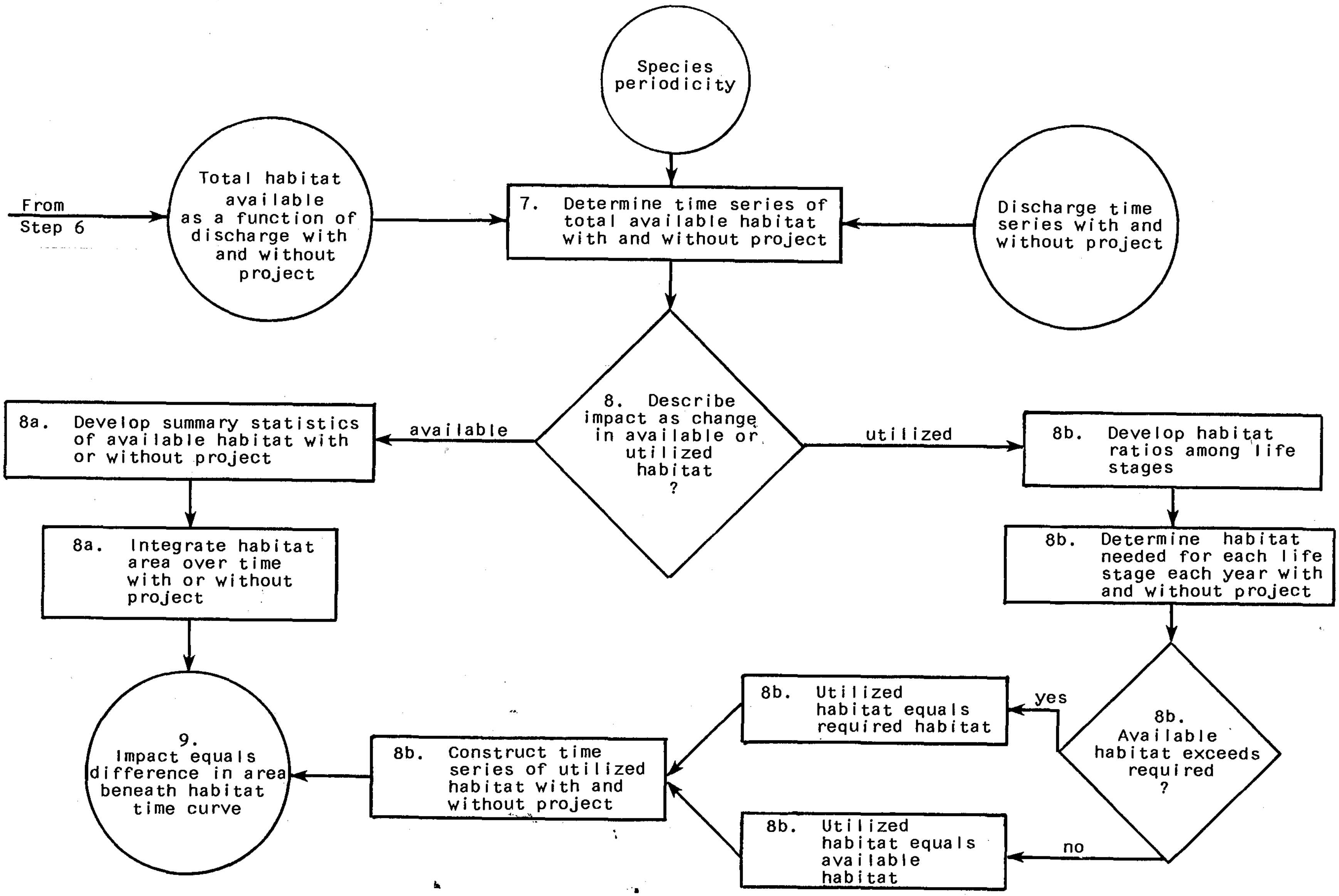


Figure 5. Determination of habitat availability over time (Step 7) and description of impact as change in available or utilized habitat.

2. DETERMINATION OF PROJECT SCOPE

Proper planning and determination of the scope of a study are necessary preparatory measures to the application of the IFIM. Project scoping includes an analysis of the present system and identification of potential problem areas. The process of determining the scope of an application of the Incremental Methodology is analagous to the "five W's" taught first year journalism students. In this case, the logical order might be: why, where, who, what, and when.

1. Why - Why am I doing this study? What are the study objectives? Have opposing viewpoints been identified and evaluated? What are the objectives of other involved parties? Is the study to be used in planning, management, impact assessment, or mitigation? Who makes the final decision? How are study results to be incorporated in the final project design - by recommendation, negotiation, arbitration, or litigation? What information does the decisionmaker need?

2. Where - Where does the study area start and where does it end? Does the study include only a portion of one stream, a drainage, or several drainages? What is the longitudinal distribution of each species in the stream during the course of the year? Will that distribution be changed if some feature of the macrohabitat is changed? What kind of microhabitat does each species utilize during each of its life history stages?

3. Who - Which species are to be investigated in this study? Are study objectives concerned only with the major sport and game fishes which occur in the river? Should macroinvertebrates and forage fishes be included in the analysis?

4. What - Which environmental attributes are currently affecting the habitat potential of the stream? Are they related to streamflow? Would they be affected, for better or worse, if the streamflow were changed? What is the anticipated nature of change? Do habitat limitations related to streamflow originate in the stream or outside the channel boundaries?

5. When - When do the species of interest inhabit a particular reach of stream? When do different life stages of a species occupy the reach? Are certain food sources inaccessible or absent during certain times of the year? Are certain environmental limitations effective only for a portion of the year? When will projected changes produce a measurable alteration of flow regimes within the hydrologic cycle?

It is important to realize that the "five W's" tend to be conditional on one another. For example, the species selected for analysis are often determined by the objectives of the study (what will be studied conditioned by why the study is being done). In many streams, the "where" for a species will be conditioned by answers to the what and when questions.

The objectives of the scoping process are ultimately to determine where to locate study sites, what parameters to measure, what criteria to apply, what range of flows to investigate, and when to do the study. These items ultimately determine the resources, manpower, and lead time needed to follow a study to completion. The study manager can plan the logistics of the study only after the study has been thoroughly scoped. Logistics planning may include manpower allocations, travel costs, equipment requirements, the hiring of consultants, coordination with cooperating agencies, allocation of computer time, and so forth.

2.1 STATEMENT OF STUDY OBJECTIVES (WHY)

The study objectives should be stated explicitly, such as, "The objective of this study is to determine the impact of the proposed Miller Creek dam on the habitat potential for game fishes downstream of the damsite." The statement of objectives reflects the kind of study being conducted, determines the study approach, and describes the way the results will be analyzed. A project impact study will be designed differently from a study that results in recommended instream flow reservation to a regulatory agency. Other objectives may be implicit, but hidden agendas tend to obscure the real goals of the study and cause misunderstanding and confusion when the results are compiled. All objectives should be stated as precisely as possible.

The audience receiving the study influence the presentation of the methods, results, and recommendations. It is necessary for the investigator to thoroughly document what was done, how it was done, when it was done, and the chain of custody of data if the study is likely to be evidence in a court of law. Arguments need to be well founded, concise, and easily understood by laymen. The great volume of technical material generated in instream flow studies should be well organized for quick referral, but should be generalized in such a way that laymen can easily focus on the concepts. Conversely, highly technical audiences may require detailed technical information. For technical audiences, detailed information can be organized and presented in such a manner that the audience can draw their own conclusions. More importantly, it is necessary to present technical material in such a way that it is clear how <u>your</u> conclusions were reached. The major consideration is to design the study to meet the requirements of the decisionmaker. The format of the results may vary depending on the audience.

Data requirements for interpretation of the results must be determined early in the scoping process. Chapter 5 details a variety of display and interpretation techniques; there is a vast difference in the kinds and amounts of data needed to implement each one. The stated objectives of the study must anticipate the kinds of questions the study is supposed to answer. Quantification of changes in habitat can be done with relatively little biological information. Quantification of changes at the population or community level requires a large amount of biological data. A study designed to quantify only habitat changes will not be able to address changes at a population or higher level. Many mitigation studies require only that the impact to the habitat be quantified, and gathering additional biological data might not be justifiable in terms of time and money. This decision should be made before the budget for the project is determined. Insufficient funding to answer all the questions means that all parties to the study be informed about which answers can be provided. The objectives of the study may need to be scaled down in this instance, either by answering simpler questions or by covering a smaller area.

2.2 GEOGRAPHICAL EXTENT OF STUDY AREA (WHERE)

The general study area is identified in the statement of study objectives. Now it is necessary to determine the number of streams and the length of each stream to incorporate in the study. The geographical extent of studies can vary by several orders of magnitude. River basin studies may encompass entire drainages, and it is unlikely that all of the streams in the entire drainage can be studied. Therefore, a selection process is used to determine which streams will be studied. At the other end of the scale is the determination of instream flow recommendations for protection under State and Federal reservation, licensing, or permitting procedures. Instream flow allocation studies require that individual reaches, to which instream flow recommendations apply, must be specified to the nearest river mile. [See, for example, Colorado Revised Statutes, Section 148-21-7 (1973)]. Determination of the geographical extent of an instream flow investigation can be rather simplistically classified as one of three types: river basin studies; site specific instream flow allocation studies; or project impact studies.

2.2.1 River Basin Studies

The objectives of river basin studies are generally broad, frequently dealing with issues of water supply in association with large scale, but not site specific, developments. An example is the incorporation of instream flows as a constraint on the water supply for the oil shale industry in the Upper Colorado River Region. Water resources planning studies are designated as Level A, Level B, or Level C (Water Resources Council 1970). Level A studies are the most general and usually cover a large territory. Level B studies are usually specific to a particular subregion or group of rivers and focus on alternative solutions to complex problems. Level C studies are site specific. Bayha (1980) discusses in detail the determination of study scope for appropriate methods for Level A and B studies. Therefore, these will not be discussed in this paper. Level C studies include both instream flow protection studies and project impact studies.

2.2.2 Site Specific Instream Flow Studies

As mentioned previously, it is important that river distances be specified when applying instream flow recommendations. The investigator must decide whether to examine the whole river or a portion of it and which, if any, tributaries. These considerations depend in part on the environmental factors affected by (and affecting) streamflow and, in part, on the usage of the river by various species. In river systems where water quality is affected by tributary inflow, it may be necessary to study tributaries regardless of whether or not fish use them. If the macrohabitat conditions are sufficient for all species inhabiting the river, the inclusion of tributaries in the study scope is determined primarily by the usage of the tributaries by the fish.

Another consideration in the decision to include or exclude tributaries from an instream flow determination is their role in the water budget for the study area. There are two ways to approach this decision. The first is to make an instream flow recommendation on the mainstem river and apportion instream flows to each of the tributaries on the basis of drainage area. This approach has the advantage of economy because study areas are not established in any of the tributaries. The second approach is to make independent instream flow analyses on the mainstem and the tributaries. If the instream flow requirement for the mainstem is greater than the summed instream flow requirements for all the tributaries, the feasibility and consequences of increasing the flow in the tributaries (through storage or other means) can be examined. An instream flow requirement in the mainstem that is less than the summed instream flow requirements for all the tributaries above a point on the mainstem may identify a potential diversion point. The advantage of this method (called water balancing) is that it allows the examination of trade-offs. For example, suppose that two tributaries supply identical amounts of water to a river, but one is an important nursery stream and the other has a very impoverished fauna. Rather than apportion 50% of the total contribution of water to each stream, it would make more sense to determine an optimal flow in the nursery stream and divert water from the poorer stream. An attempt to rehabilitate the impoverished stream might be made if that option is more desirable. The point is that neither option is open unless a systems-oriented approach to water management is used.

2.2.3 Project Impact Studies

Project impact studies are similar in scope to other instream flow studies, with one major difference: an impact study is confined to that portion of the river system actually affected by a particular activity. For example, the impact assessment associated with construction of a dam would be primarily downstream of the dam, although loss of upstream habitat to migrating species must be accounted for if upstream migration is blocked. It therefore becomes essential for the investigator to determine the geographical extent of a particular impact; i.e., the distance from the perturbation to where its effect is no longer discernible. This may require an effort of nearly the same magnitude as many instream flow studies.

The question of including tributaries depends on whether or not the tributaries are affected by the perturbation. Both direct effects, such as head cutting or siltation, and indirect effects, such as blocked access to the tributaries, must be considered. Because the geographical extent of the study is essentially determined by the nature of the perturbation, a convenient introduction to the next step in the scoping process is provided.

2.3 DETERMINATION OF AFFECTED ENVIRONMENTAL VARIABLES (WHAT)

The degree to which different environmental variables respond to a disturbance in the system depends on the nature and scale of the disturbance and the robustness of the variable. It is important that affected variables be identified. A dichotomous key to the appropriate analytical sequences for instream flow and project impact studies is presented in Chapter 4. The first steps in the key are designed to aid the user in the scoping process. Considerable background research may be required to determine which environmental factors are likely to change. While it is sometimes inaccurate to generalize, Table 1 gives a brief synopsis of environmental changes associated with various actions.

Microhabitat changes will be analyzed and documented in virtually every application of the IFIM. The only scoping decisions to be made are the number of study sites to be used in the analysis and the physical habitat models to be employed. Study site selection is discussed in Chapter 3 and physical habitat modeling in Chapter 7.

Several major scoping decisions may be required regarding the macrohabitat components of channel structure and water quality, particularly if a change in one of these parameters is implied from Table 1. There are really two aspects of each component that should be addressed. The first is whether or not a problem currently exists and would be made worse by a proposed action. The second is that, under existing conditions, the macrohabitat may be in a natural state, or at least satisfactory from a management perspective. This condition may change as a result of a proposed action. The ultimate decision during the scoping process is whether or not the existing macrohabitat limitations or anticipated changes are significant enough to include their analysis in the study. This is a critical decision point, because the addition of water quality analysis may double or triple the cost of the study. Analysis of sediment transport and potential channel changes may quadruple the cost. These costs are essentially wasted if the analysis is done when unnecessary. However, the cost of not analyzing an affected environmental parameter, and ending up with invalid study results can be much higher. A preliminary screening analysis of channel change and water quality should be included in the scoping process to determine if further analysis is warranted. This screening process should address both aspects of macrohabitat conditions: (1) Is there a problem now?; and (2) Will there be a problem later?

2.3.1 Watershed and Channel Equilibrium

The first step in this portion of the scoping process should be an evaluation of the equilibrium condition of the channel. This evaluation is first because subsequent analyses of water quality and microhabitat assume persistence in channel structure and dimensions. This assumption is obviously invalid if the stream has not achieved a state of dynamic equilibrium.

Stream channels respond to significant alterations in sediment load and runoff by changing shape, dimension, alignment, bed particle size, and stream pattern. The extent of the channel response depends in part on the interaction of the sediment and water load of the stream and in part on the material through which the stream is flowing. Streams underlaid by bedrock are relatively immune to downcutting (degradation) but can fill with excess sediment, raising the streambed elevation (aggradation). A bedrock stream may change its width unless the banks are also nonerodible. In sharp contrast, alluvial channels may change shape and size rapidly in response to alterations in either flow or sediment supply. Other streams may be alluvial in character but controlled by localized bedrock outcrops. In these streams, degradation will be controlled by the bedrock where it occurs, but intermediate alluvial

Table 1. Generalized environmental changes associated with a variety of land and water uses.

Affected variable	Impoundment	Channelization	Grazing	Silviculture	Surface mining	Agricultural drainage	Ground water extraction	Surface water diversion	Flow augmentation	Urbanization	Irrigation	Hydropeaking
Sediment yield	X		X	X	X	X					X	0
Water yield	0		X	X	0	X	X	X	X	0	X	
Channel morphology	X	X	X	0	0	0		0	0	X	0	X
Substrate character	X	X	X	X	0	0		0	0	X	0	0
Cover	0	X	X	0	0	0	0	0	0	0	X	X
Timing of flow	X	*						0	0	0	X	X
Magnitude of peak flow	X	*	0	0	0	X	0	0	0	X	0	X
Magnitude of base flow	X		0	0	0	X	X	X	X	X	X	X
Thermal regime	X	0	0	0	0	0	X	0	0	0	X	X
Water quality	0		0	0	X	X	0	0	0	X	X	0
Drainage density			0	0	0	X	0			X	X	

X = Dominant influence
0 = Lesser influence
* Channelization can result in shorter detention of flood flows. Consequently, flood events may be of greater magnitude and frequency downstream of the channelized portion. The severity depends on the slope and length of the impacted section.

sections may degrade. Any stream can aggrade, regardless of the bed type, if the sediment supply exceeds the transport capacity.

There are several diagnostic channel features which may reveal a potential disequilibrium. Channel widening, which may indicate channel enlargement or aggradation, is often manifested by trees from opposite banks falling into the river. Trees falling in from only one bank may be indicative of nothing more than meander migration, so this diagnostic tool is useful only if both banks are being eroded simultaneously.

Channel narrowing is usually more difficult to detect than channel widening, unless evidence has been collected over a period of years. Normally, the narrowing process occurs much more slowly than does widening. In this respect, old aerial photos, when available, are very valuable. One instance where channel narrowing is fairly obvious occurs when a braided channel reverts to a meandering channel. This is normally caused by a large scale reduction in the amount of sediment delivered to a reach of stream. At some distance downstream from the point of sediment reduction (often a dam), a braided channel may persist. Moving upstream, the first indication of channel narrowing is the colonization of islands by vegetation. Further upstream, the vegetation on the islands is more mature and the islands begin to coalesce. Finally, the islands are totally joined and form new banks with a single meandering channel. If old aerial photographs are not available for comparison, the sequence described above can sometimes be detected from observations along the stream.

Another useful feature for diagnosing watershed or channel disequilibrium is a persistent change in bed elevation. This can be detected by comparing old channel surveys to recent ones. The best single source for this type of information is the Water Resources Division of the U.S. Geological Survey (USGS). The Water Resources Division is responsible for maintenance and operation of all USGS stream gaging stations. A rating curve or table, correlating gage height to discharge, is developed for each station. A new rating curve must be developed for the gage if the bed elevation changes. The old rating curves are usually kept on file by USGS for several years following the change in rating. Do not immediately assume a channel disequilibrium just because the rating for a gage has been changed. Many stations experience episodic scour and fill cycles, which are not the same as aggradation or degradation. There will be a persistent upward adjustment of the ratings if a streambed is aggrading. A persistent lowering of the rating suggests degradation. An upward adjustment one year and a downward adjustment the next probably only reflect a temporary fill and scour cycle. The senior hydrologist at the local Water Resources Division office can provide valuable insights into the channel dynamics at any gage in his district.

Another indication of a recent channel change can be found by examining fences crossing small streams. The fence posts will be buried more deeply in the deposit if recent aggradation has occurred. (Caution: a fence may also cause local deposition.) This technique is not as useful for estimating degradation. Fences are sometimes strung across the stream without driving the posts into the bed. Dangling fence posts do not necessarily indicate degradation. However, if the posts were driven into the bed, and they are now dangling, it is indicative of channel degradation.

The analysis can proceed if it is determined that the channel structure is in a state of dynamic equilibrium and that the proposed action will not affect this state. The analysis should not proceed when a disequilibrium condition is discovered, until the appropriate steps have been taken to analyze or resolve the problem. Three different approaches can be taken to reduce the chances that channel disequilibrium will invalidate the results of a study. The first approach is to simply defer the initiation of the study until an equilibrium is reestablished. Megahan et al. (1980) reported that a stream severely disturbed by logging returned to nearly predisturbance conditions within 10 years after the logging stopped. The obvious difficulty with deferring the study until equilibrium is reestablished is that decisions on water allocation may be made without input from instream flow concerns. Mitigation plans derived for a channel in disequilibrium may not be effective when channel equilibrium is reestablished. Futhermore, the project itself may exacerbate the disequilibrium condition. Although waiting until channel equilibrium has been attained may not be advisable in many situations, this is the best choice where out-of-channel demands are expected to be small during the recovery period.

An intermediate level solution is to evaluate the system periodically, revising the instream flow recommendations every 3 or 4 years during the recovery period. This option allows work to begin early enough in the water allocation process to include instream flow requirements in the total water allocation budget. The only disadvantage is that the final instream flow recommendation will not be known until the channel stabilizes. This may not be as big a problem as it seems. Channels undergoing a disturbance, especially aggradation, often do not have the structure needed to provide good physical microhabitat. Consequently, more water is required to provide that habitat. As the channel recovers to its predisturbance state, it is possible that the instream flow recommendation could be revised downward. All parties to the water allocation process must recognize, however, that there is no guarantee that a downward revision will be made. It is unlikely that an upward revision will be made, unless the management objectives for the stream were changed.

The third option is to predict what the channel will look like when a new equilibrium state is attained. This alternative requires the services of an expert in sediment transport. There are relatively few specialists in this discipline, but the expertise tends to be concentrated in several agencies: the U.S. Geological Survey; the U.S. Army Corps of Engineers; the U.S. Bureau of Reclamation; the Soil Conservation Service; and to a lesser extent, the U.S. Forest Service. Engineering colleges in many major universities and some private consulting firms also specialize in channel dynamics and modeling. This approach has the advantage of providing a final estimate in a fairly short time. The state-of-the-art of sediment and channel change modeling, although complex, is still not very precise and the services of an expert may be quite expensive. This may be the least desirable option for most instream flow studies. However, this option is strongly recommended for project impact and mitigation studies if a proposed action is likely to cause a channel change (see Table 1). This is particularly true when a change in the sediment supply is involved.

2.3.2. Water Quality and Temperature

The same type of screening process is applied to water quality and temperature: first determine whether existing conditions are satisfactory and then whether or not they will remain so if the flow or the load is changed. The investment in a water quality study is warranted if the response to either of these questions is "no."

The stream ecosystem is a natural integrator of the past history of water quality and a good indicator of the overall health of the stream. It may be tempting early in the screening process to search all available water quality records for a stream in an effort to detect the occurrance of unsatisfactory water quality episodes. These data may be necessary at some stage in the screening or analytical process, but the first step in the screening process should be a trip to the field. There are several diagnostic characteristics of stream communities that can be used to infer good or poor water quality. Most of these characteristics apply to the invertebrate portion of the community, especially macroinvertebrates. Bottom dwelling organisms are especially amenable to use in pollution surveys. Many species exhibit pronounced responses to pollution and they are relatively long-lived and immobile (Keup et al. 1966). Benthic macroinvertebrates can also be categorized according to general tolerance groups.

Immature stoneflies, mayflies, and caddisflies are quite sensitive to environmental conditions. Blackfly larvae, amphipods, molluscs, dragonfly and damselfly nymphs, and most midge larvae have intermediate tolerances. Oligochaetes, annelid worms, leeches, and some midge larvae can tolerate comparatively poor water quality (Keup et al. 1966). The key diagnostic condition in an initial water quality screening is not the presence of the tolerant species, but the absence of the sensitive species in places they would normally be found. The absence of sensitive species indicates that some type of water quality problem has occurred in the recent past, but does not indicate what caused the problem or whether it was a short duration or a chronic incident.

Lee and Jones (1981) state that chemicals affect aquatic life in two ways. Some chemicals are necessary to life and, if they are not present in sufficient concentration, changes in species composition, growth, or condition may result. Dissolved oxygen, nitrogen, and phosphorus fit this category. Temperature, although not a chemical, can have a similar effect. Other chemicals act as toxicants, impairing growth, condition, or survival.

It is often difficult to distinguish between the effects of limiting factors and toxicants simply by examining the benthic fauna. However, streams which are overloaded with organic wastes may exhibit a variety of symptoms. The most severe condition is the formation of sludge deposits, which undergo anaerobic decomposition. This process is accompanied by the release of methane and hydrogen sulfide bubbles which may dislodge parts of the deposit. These bubbles and the floating masses of dislodged solids are symptomatic of sludge deposition and indicative of a severe overload of the stream's assimilation capacity.

Less severe organic waste overloads may be indicated by an abundance of tolerant forms of invertebrates, such as oligochaetes, and the exclusion of less tolerant forms. However, this characteristic may also result from the presence of toxic compounds in relatively small concentrations. Organic wastes from sewage outfalls, feedlots, and slaughter houses usually contain relatively high concentrations of nutrients, which enhance the growth of algae, both periphyton (attached) and phytoplankton (floating). Certain species of algae can be used as indices when organic pollution is suspected. Many of the blue-green (Cyanophyta) and yellow-green (Chrysophyta) algae species are pollution-tolerant forms. Conversely, species such as Cladophora (Chlorophyta) and the diatom Nitzschia linearis are indicators that a stream is relatively unpolluted with organic waste. Prescott (1968) presents a good discussion of the use of algae as a pollution indicator.

A high oxygen demand can also result from high concentrations of sugars or reduced chemicals (e.g., hydrogen sulfide or ammonia) in the water. Paper mills, food processing industries, and sugar refineries often input large amounts of simple and complex sugars, resulting in the growth of bacterial mats of Sphearotilus (Hynes 1971).

Lee and Jones (1981) warn that investigations of microhabitat and fish populations should consider the possible influence of chemical contaminants on the numbers and types of fish present. The converse of this statement is that investigations into possible chemical influences should consider the recent history of the physical microhabitat. The most obvious example is the effect of a freshet. High flows may dislodge large numbers of invertebrates, having the greatest effect on those species that are more exposed. Very high flows will move the substrate, resulting in a virtually barren streambed. There may be no invertebrates, no attached algae, and not even any diatoms on the rocks. The same thing can happen during the breakup of surface ice during the spring. Therefore, the initial screening of water quality considerations should not be done immediately after a major flood event or ice breakup.

The initial stream survey may indicate that the recent history of water quality has not caused any problems. The investigator should then review the low flow characteristics of the stream over the previous month. The water quality in the stream can be assumed to be satisfactory under the prevailing meteorology and waste loading at least down to the lowest 4-day (96-hour) average flow occurring in the last month. If this flow is lower than any anticipated flow recommendation for that month, it can be safely implied that water quality will be satisfactory for all flows under consideration. However, further screening is necessary if there is a chance that the instream flow may be lower than the low 4-day average found in the previous step, or if the loading rate or temperature is likely to change. This requires the use of a screening equation to estimate temperatures or chemical concentrations under conditions not empirically observed.

Dilution equations are useful in estimating the concentration of conservative water quality constituents. Many of the chemicals entering rivers are really nonconservative. Biological and chemical reactions result in the storage of chemicals in tissue or as precipitates. Chemicals react with each other as well, creating new compounds. However, nearly all chemicals, with the exception of dissolved oxygen, can be treated as conservative constituents during the scoping processs. The dilution equation takes the form:

$$C_t = \frac{Q_r C_r + Q_i C_i}{Qr + Qi} \qquad (2\text{-}1)$$

where C_t = the concentration of the constituent following complete mixing of the material in the stream

Q_r = the discharge of the river above the input point of the chemical

C_r = the background concentration of the constituent in the river above the input point

Q_i = the discharge of the outfall

C_i = the concentration of the constituent in the outfall

The evaluation of potential dissolved oxygen concentrations is more difficult because temperature must be determined first and because the most adverse oxygen concentrations will occur at some distance from an outfall. There is no simple way of predicting temperature. However, Theurer (1982) has developed and adapted a temperature model for small programmable calculators. A more sophisticated version of the same model, suitable for stream network analysis, has been prepared for use on the large mainframe computers where the rest of the IFIM software resides. The calculator version is easy to access and use and should be very helpful in the scoping processs. It is accurate enough for actual simulation of stream temperatures under different meteorological conditions and flows in simple applications. The computerized version should be used for large, complex systems requiring iterative applications.

The temperature must be estimated before attempting to determine dissolved oxygen concentrations, even in a screening process. The rate of decomposition of organic material is determined primarily by the temperature, as is the solubility of oxygen in water. The rate of decomposition is related to temperature by:

$$K_{1(t)} = K_{1(20)} \times 1.047^{(t-20)} \qquad (2\text{-}2)$$

where $K_{1(t)}$ = the deoxygenation rate, empirically derived and adjusted to the temperature (t)

$K_{1(20)}$ = the deoxygenation rate at 20°C

The rate at which oxygen is added to the water is related to the turnover rate of the water column:

$$K_2 = \frac{5V}{D^{1.67}} \qquad (2\text{-}3)$$

where K_2 = the reaeration rate, based on the rate of oxygenation from 0.0 mg/L dissolved oxygen to saturation. The actual rate is somewhat smaller in partially oxygenated water

V = the mean velocity for a reach

D = the mean depth for a reach

The dissolved oxygen, at its minimum value, can be estimated by the critical sag method. This approach estimates the time period required to fully develop the dissolved oxygen sag under the prevailing rates of deoxygenation and reaeration. The critical time period is found by:

$$t_c = \frac{1}{K_2 - K_1} \log \left\{ \frac{K_2}{K_1} \left[1 - \frac{Da\left(K_2 - K_1\right)}{L \quad K_1} \right] \right\} \qquad (2\text{-}4)$$

and the critical deficit by:

$$D_c = \frac{K_1}{K_2} L \times 10^{-\left(K_1 t_c\right)} \qquad (2\text{-}5)$$

where t_c = the critical time period in days

K_1 = the temperature-adjusted deoxygenation rate from equation 2-2

K_2 = the reaeration rate from equation 2-3

D_a = the initial deficit computed as the saturation concentration (see Table 2) minus the dissolved oxygen concentration. (Measured as background above the source of organic waste)

L = the initial organic waste load, measured as ultimate biological oxygen demand, in the streamflow in mg/l, from equation 2-1

D_c = the critical dissolved oxygen deficit at the sag

The critical deficit can be converted to mg/l of dissolved oxygen by subtracting the deficit from the appropriate saturation concentration from Table 2.

Table 2. Solubility of oxygen in freshwater.[a] From Velz (1970).

Temperature (°C)	Dissolved oxygen (mg/l)	Temperature (°C)	Dissolved oxygen (mg/l)
1	14.23	21	8.99
2	13.84	22	8.83
3	13.48	23	8.68
4	13.13	24	8.53
5	12.80	25	8.38
6	12.48	26	8.22
7	12.17	27	8.07
8	11.87	28	7.92
9	11.59	29	7.77
10	11.33	30	7.63
11	11.08	31	7.5
12	10.83	32	7.4
13	10.60	33	7.3
14	10.37	34	7.2
15	10.15	35	7.1
16	9.95	36	7.0
17	9.74	37	6.9
18	9.54	38	6.8
19	9.35	39	6.7
20	9.17	40	6.6

[a]Further corrections may be needed for changes in elevation, barometric pressure, and salinity. Consult a handbook of physical and chemical properties for these correction factors.

Velz (1970) provides a complete description of the derivation of these equations. He states that the use of the critical sag equation is restricted to a single composite source of BOD without increments of tributary inflow.

The deoxygenation and reaeration rates must be assumed constant, so they should represent average conditions for the reach. Therefore, the practical value of these equations in the prediction of dissolved oxygen concentrations is limited. The equations can be used to estimate average dissolved oxygen concentrations at the point on the stream where the smallest value is likely to occur. The use of a more sophisticated model is warranted if these equations predict oxygen concentrations approaching a biological threshold. The critical sag equations contain no terms for photosynthesis and respiration. The dissolved oxygen concentration will fluctuate considerably about the mean value predicted by the screening equations if there is a large amount of algae present. If this condition exists, the investigator should measure the dissolved oxygen concentration just before dawn during the growing season, and compute a ratio between the mean oxygen concentration and the minimum. This ratio can be applied to the mean computed by the screening equation, and the result used to determine whether or not more sophisticated water quality models need to be used.

2.4 SELECTION OF EVALUATION ORGANISMS (WHO)

After determining the geographical extent of a study and the affected environmental parameters, the investigator should have a fairly good idea of the length of mainstem and the tributaries to be included in the study. Each river system will have an associated longitudinal distribution of species; the community structure may be perceptibly different from the headwaters to the mouth. Except in the simplest of communities, it is not likely (nor necessarily desirable) that every species within the community be selected for detailed study; rather, species selected for study should reflect the environmental constraints on the community as a whole.

There are numerous ways of selecting evaluation species, each having certain merits in any particular situation. Most of these approaches agree, however, that the major game, sport, or commercial species should be among the targeted species. Endangered species are included as evaluation species in many studies. Although little information may exist regarding their life histories, distribution, and habitat requirements, this is not a valid reason for their exclusion. Instead, the investigator may need to initiate basic research into their habitat requirements.

Bovee (1974) suggested that indicator species, sensitive to particular environmental parameters, be identified and selected as evaluation species in instream flow studies. Their abundance is highly dependent on environmental changes affecting specific parameters. The assumption is made that as long as conditions are satisfactorily maintained for the indicator species, conditions are also satisfactory for the rest of the community. Indicator species have long been used to examine potential water quality and sedimentation problems. However, there are two basic problems with using indicator species to evaluate microhabitat requirements and impacts. First, different indicator species are needed depending on the problem. Gore (1978) found that *Rhithrogena hagani*, a tiny mayfly nymph, abandons stream areas of reduced velocity. This makes the species valuable as an indicator of conditions where velocity has been reduced, such as reductions in discharge. However, *Rhithrogena* is not very sensitive to environmental changes that result in increased velocity, such as flow augmentation or channelization. The second problem is that many of the potentially good microhabitat indicator species are highly specialized and not very abundant. Therefore, it is difficult to determine where and how they fit into the daily operation of the community and to generate much interest in their welfare on the part of fisheries managers.

The most important species from a management standpoint are often predators, which may be limited by the habitat available for their prey. If a food limitation is thought to be important, then the following items should be determined:

1. What are the principal food items of these species?

2. Is the availability of food items related to water quality, temperature, channel boundary conditions (i.e., substrate), flow regime, or something else?

It may be a fairly involved process to figure out whether or not a population is food limited. The condition factor, discussed in Chapter 5, can be used as an index of the adequacy of the food supply. The fact that a food limitation exists and the underlying cause will be obvious in some streams. The most obvious situation is where the macroinvertebrate population is severely impoverished due to siltation of riffle areas. The basic cause of the problem is the loss of large substrate particles from the upper stratum of the streambed. In this instance, the recommended remedy might be the provision of a large flow in the recommended flow regime for the expressed purpose of removing the fine sediments. Alternatively, practices designed to reduce the sediment load of the stream could be recommended.

Determination of the principal food items at various stages in its life history is an important step in determining which types of food producing microhabitat are most important to a species. Food items need not be classified down to genus. In fact, such detail might be counterproductive. Most fishes are opportunistic and will eat whatever is available and most abundant. It is enough to know the proportions of aquatic and terrestrial organisms in the diet at various times of the year. The analysis need not extend to individual food organisms, but to the areas in and around the streams where these food organisms are produced. The differentiation between the utilization of autochthonous (produced within the stream) and allochthonous (produced outside the stream) food bases may be very important in some streams. Trout streams often produce a wide variety of aquatic invertebrates, many of which mature during the spring and begin to emerge in the summer. As summer progresses, the fish may rely more and more on terrestrial insects, many of which were not available during the spring. The dependence on terrestrial foods increases the importance of microhabitat areas nearest the stream margins. These areas also provide most of the overhead cover sought by fish, making them even more valuable. The availability of terrestrial foods may be limited if summer discharges are reduced to the point that the stream begins to withdraw from its banks. The Physical Habitat Simulation System (PHABSIM), discussed in Chapter 7, can be manipulated to describe this phenomenon, if necessary.

The selection of evaluation organisms can sometimes be simplified by grouping two or more species into a guild. A guild is defined as a group of species having similar habitat requirements and exhibiting similar responses to changes in streamflow. The grouping of species can vary considerably depending on the objectives of the study and the level of detail desired. The formation of guilds of aquatic invertebrates is often advisable, but forming guilds of fishes may not be the best approach. The biologists involved in the study should determine whether the guild concept is appropriate (Prewitt 1982).

The Habitat Evaluation Procedures (U.S. Fish and Wildlife Service 1980) recognize the importance of careful selection of evaluation species. The HEP procedures suggest a ranking system based on several criteria:

1. Importance of species from a management perspective;

2. Vulnerability; and

3. Availability of information on the species.

A score is assigned for each criterion based on the degree to which the criterion is met by a species. The scores for all the ranking criteria are summed for a species, and species with the highest scores are given the highest priority in an analysis. This concept is illustrated in Table 3.

Table 3. Ranking criteria for selection of evaluation species.

	Ranking value		
	Importance	Vulnerability	Information
High	5	5	5
Moderate	3	3	3
Low	1	1	1

Using this system, an important game species, which is highly susceptible to a proposed change in the environment, and for which a great deal of information exists, would receive a score of 15. An endangered species is probably important from a management perspective and also quite vulnerable, but would probably suffer from a lack of information and, therefore, receive a score of 11 or so. The concept of ranking criteria for the selection of target species is an excellent idea. For complete details regarding this process, the reader is referred to the HEP manuals (U.S. Fish and Wildlife Service 1980). Even when the stated criteria do not exactly fit a particular situation, the ranking criteria can be modified and the concept used.

It is important to bear in mind that interpretations about the significance of environmental change are based on what happens to the evaluation species. If the wrong species are evaluated, or if an insufficient variety of species is used, the analysis may be useless.

2.5 TEMPORAL VARIATIONS IN HABITAT USAGE (WHEN)

Temporal variations in habitat use occur at both the macro- and microhabitat levels. The simplest description of temporal variations at the macrohabitat level is expressed as changes in the longitudinal distribution of a species over the period of a year. Species may be more widely dispersed during winter than during summer due to temperature restrictions during the warmer months. A change that affects the macrohabitat characteristics of a stream poses two problems for the resource manager. The first consideration is that the total length of stream having suitable macrohabitat conditions for different species may change. The macrohabitat area for warmwater species may expand at the expense of cool- and coldwater species, and vice versa. This phenomenon is not necessarily good or bad, but it may be contrary to the management objectives for the stream. The second consideration is that areas of suitable macrohabitat and microhabitat may not overlap. For example, an area having suitable macrohabitat for smallmouth bass and a microhabitat conducive to rainbow trout will probably not support good populations of either species.

In addition to longitudinal variations in distribution, species use different kinds of microhabitat during the course of their life cycle. Utilization often is at least partially influenced by temperature. The investigator must determine which types of microhabitat are used by a species at different times of the year. This requires the description of the species' phenology and construction of a periodicity table describing the natural distribution of microhabitat use by a species over time. Such a table is shown in Figure 6 for smallmouth bass.

The periodicity table helps ensure that necessary microhabitat conditions in the stream are evaluated at the time they are needed. If a particular activity has the potential for changing the thermal regime of a river, it may also have the potential for changing the periodicity chart for a resident species. The timing of spawning, the duration of incubation, and transition from fry, juvenile, and adult stages are all affected by temperature. The consequences of offsetting this timing may be drastic.

Table 4 is a checklist of scoping activities that should be completed before an application of the IFIM. A copy of this table is provided in Appendix A for reproduction and use in an actual study. In an actual application, the checklist should be completed before proceeding to study site selection.

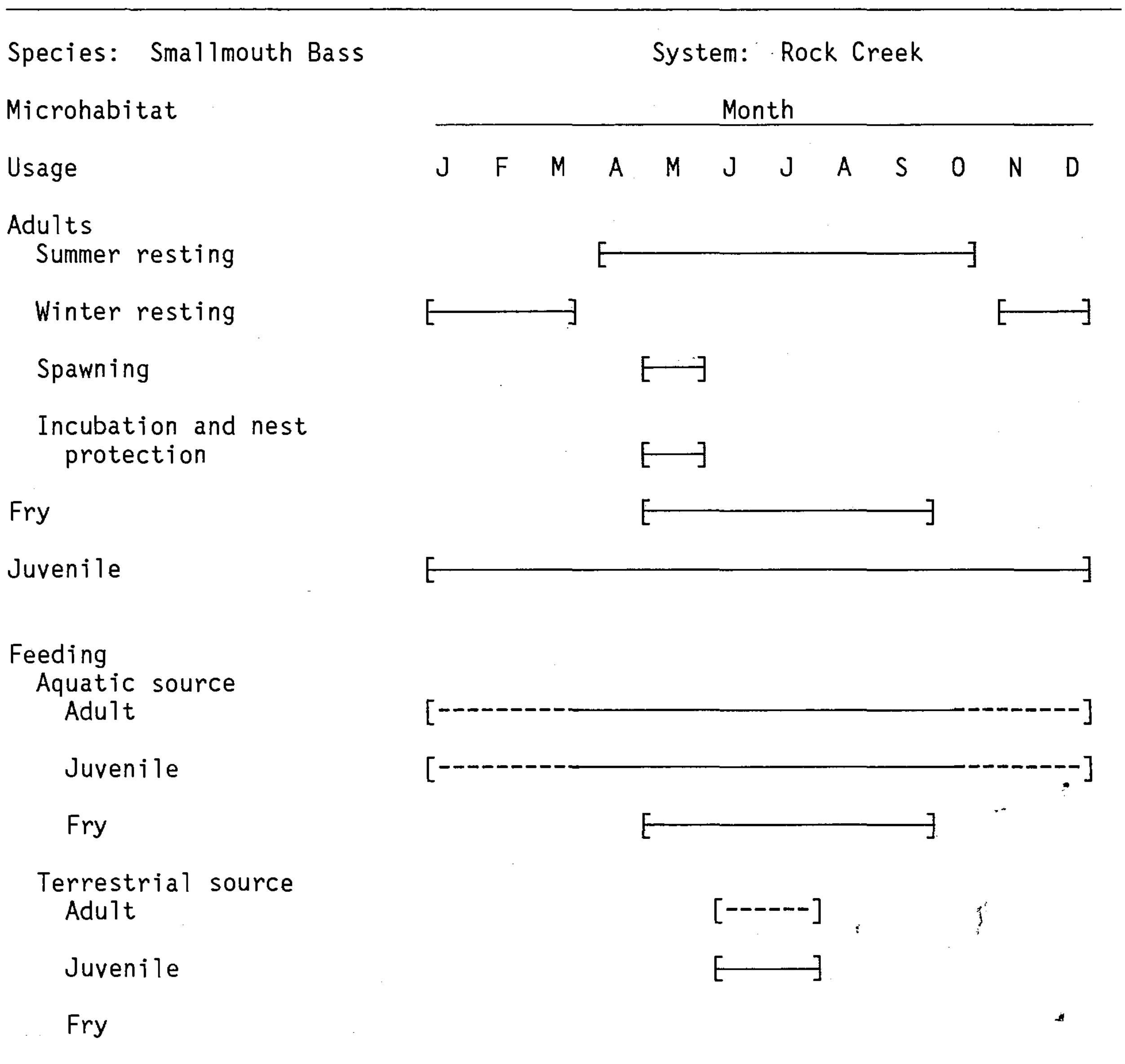


Figure 6. Sample species periodicity chart for smallmouth bass.

Table 4. Checklist of scoping activities in preparation for applying the incremental methodology.

- ______ Study objectives have been identified and stated.
- ______ Project area has been reconnoitered.
- ______ Length of mainstem to be included in study has been determined.
- ______ Environmental conditions affected by proposed action have been identified (check those which apply):
  - ______ Watershed
  - ______ Channel structure
  - ______ Water quality
  - ______ Temperature
  - ______ Flow regime
- ______ Initial contacts with professional personnel have been made.
- ______ Tributaries to be included in study have been identified, if applicable.
- ______ Topographic maps of area have been obtained.
- ______ Geologic maps of area have been obtained, if available.
- ______ Streamflow records for area have been obtained.
- ______ Arrangements have been made to develop synthetic hydrographs for ungaged streams.
- ______ Equilibrium conditions of watershed and channel have been evaluated.
- ______ Arrangements have been made to model future channel structure, if necessary.
- ______ Existing water quality characteristics have been evaluated and screening equations applied to determine future water quality status.
- ______ Arrangements have been made to model future water quality, if necessary.
- ______ Longitudinal distribution of species has been determined.

Table 4. Concluded.

______	Evaluation species have been selected.
______	Pertinent details of target species have been compiled (life history, food habits, water quality tolerances, and microhabitat usage).
______	Periodicity charts for target species have been prepared and referenced to stream segments (see Chapter 3).
______	Display and interpretation requirements have been determined and acquisition of biological data, if required, has been included in study design (see Chapter 5).

3. STUDY SITE SELECTION

A study site is a location on a stream where some characteristic of the habitat is measured. Some study sites are established to measure or monitor macrohabitat characteristics, such as temperature or water quality. Other study sites are established to measure microhabitat characteristics. These measurements provide the basis for determining a relationship between the total amount of habitat and the discharge in a reach of stream represented by the study site. This relationship is a function of the usable microhabitat per unit length of stream, multiplied by the length of stream having suitable macrohabitat, as characterized by water quality and temperature, over a range of discharges. The computational details of this superpositioning process are in Chapter 5.

A series of very similar reaches, having a common channel morphology and flow regime, but not necessarily the same water quality, temperature, or species composition, comprise a river segment. The characteristic feature of a river segment is homogeneity of channel structure and flow regime, but longitudinal changes in either are common in most streams. Therefore, more than one segment are usually required to describe the entire study area. Theoretically, each river segment could be defined by one microhabitat study site. However, depending on the method used to compute total habitat, some segments may have several microhabitat study sites, while others may have none. The difference in the number of segments and microhabitat study sites per segment depends on the longitudinal variability of the stream and the detail with which this variability is described.

Figure 7 illustrates three different habitat accounting techniques and corresponding microhabitat study site selection strategies. The microhabitat characteristics in the reaches A-B, C-D, and E-F are similar to each other. Reaches B-C, D-E, and F-G are similar to each other, but different from A-B, C-D, and E-F. A large tributary enters at G, changing both the flow regime and the channel structure. A diversion at H changes the flow regime, but not the channel structure.

Figure 7a shows a segment boundary placed at each location where either a change in channel structure or flow regime occurs. This segmentation strategy results in eight segments, each with one microhabitat study site. Figure 7b shows a segmentation strategy based only on changes in flow regime, resulting in three segments. The first segment extends from A to G and is represented by two microhabitat study sites, one between B and C (represented as site two) and one between E and F (represented as site five). The characteristics measured at site two are extended to B-C, D-E, and F-G. Likewise, the characteristics of site five are extended to A-B, C-D, and E-F. Because the channel is the same for the reach G-I, the characteristics measured at site seven are extended over two segments, G-H and H-I.

Figure 7c uses the same segmentation strategy as Figure 7b and the same study site representation for segments G-H and H-I. However, Figure 7c uses only one study site to represent segment A-G. This study site contains elements of both sites two and three, incorporating both types of habitat typical of segment A-G. This strategy results in three segments, represented by only two study sites.

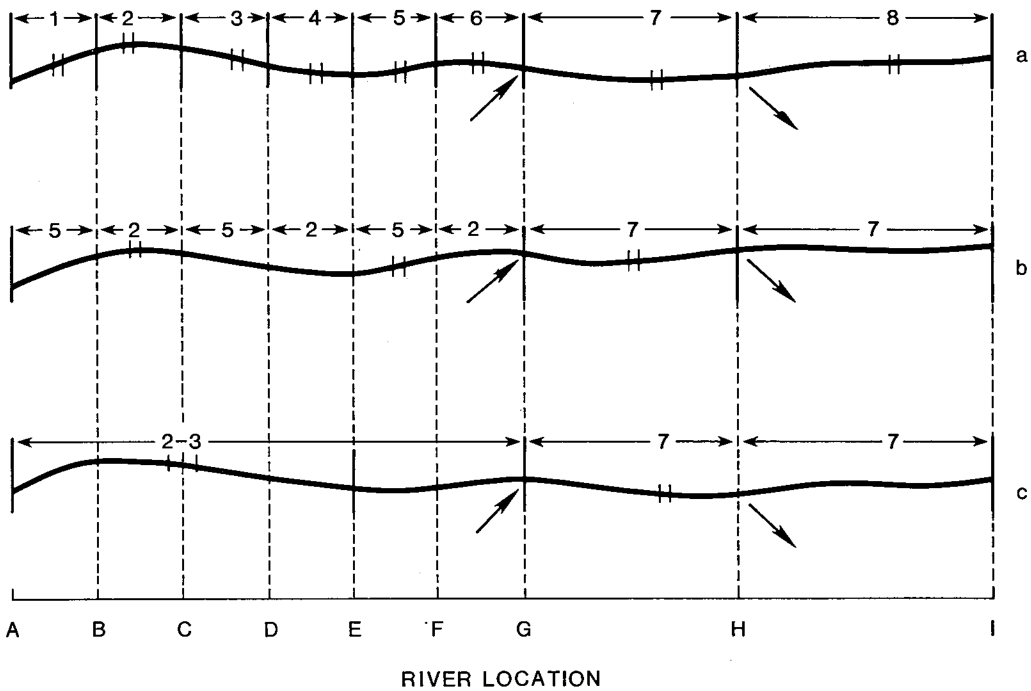


Figure 7. Strategies for designating river segments and selecting study sites to represent each segment. Small hash marks show actual study sites. Dashed lines indicate the reaches used to represent a portion or all of the segment.

Any of the sampling strategies shown in Figure 7 might be employed in a particular study. The highest precision is obtained using the strategy shown in Figure 7a, one microhabitat study site per segment, and a segment everywhere either the flow or the channel structure changes. This technique will also be the most expensive. The strategy shown in Figure 7c will likely be the least expensive, because it uses the fewest study sites. Caution should be used with this sampling scheme if water quality or temperature are likely to become unsuitable for some species, because the biological threshold will move upstream and downstream with changes in flow. The true effect of this movement will be more accurately reproduced by separating the study sites and the portions of the segment represented by each site. This is particularly true when one study site represents good, and another area, poor microhabitat conditions. Little impact is expected when a biological threshold crosses a portion of the segment having poor microhabitat. A large impact is expected when the biological threshold eliminates a subsegment having good microhabitat. A reduction in available habitat will be shown using any of the strategies, but the results are more precise and realistic using those shown in Figure 7a or 7b. The strategy shown in Figure 7b, segmentation based on flow regime and subsegments based on channel structure, is the preferred all-round strategy. Figure 7a is a better strategy for streams having water quality or temperature problems and a gradation of microhabitat conditions throughout the entire study area.

Before establishing study sites, the investigator should determine how the data from those areas will be used in the final analysis. A large scale map of the study area is necessary for selecting study sites and for compiling and analyzing the results. First, the locations of segment boundaries and subdivisions based on changes in flow regime or channel structure are marked on the map. Guidelines for the placement of segment and subsegment boundaries follow in Section 3.1. Second, point and nonpoint sources of pollution or sediment should be marked on the map. Although these points are not used to demarcate a segment boundary, they are necessary to establish a network of macrohabitat (i.e., water quality, temperature, or sediment) sampling sites. Third, locations of both macrohabitat and microhabitat study sites (discussed in Section 3.2) are marked on the map. Finally, a list of species to be evaluated within each segment is compiled and cross-referenced to the map. This list is not used in site selection, but must be referenced to the correct sites in subsequent analyses.

3.1 SEGMENT AND SUBSEGMENT BOUNDARIES

A segment boundary must be placed at all major tributaries, diversions, and other locations where the flow regime undergoes a significant change. A segment or subsegment boundary is also placed wherever a significant change in channel morphology occurs. These locations often coincide or are obvious enough that boundary placement is easy. Other locations reflect more subtle changes, requiring determination of the significance of the change.

3.1.1 Flow Regime

Segment boundaries are placed wherever the stream undergoes a significant change in water supply, most obviously at tributary confluences and at major diversions. However, segment boundaries are warranted only if the accretion or depletion changes the average base flow of the stream more than 10%. Some time-averaged flow, such as mean monthly, should be used rather than an instantaneous flow, because localized precipitation changes the water supply distribution over the short term.

A 10% accretion is easily determined in watersheds with a good stream gaging network. For ungaged streams, the simplest approach is to use the drainage area-precipitation product to obtain an estimate of changes in the volume of runoff. The drainage area of the uppermost subdrainage is measured on a map with a planimeter and the area multiplied by the mean annual precipitation for the subdrainage. The mean annual precipitation can be determined from rainfall atlases or records published by the National Weather Service. This provides the drainage area-precipitation product for that portion of the watershed. The drainage area-precipitation product for the next subdrainage is computed and added to the previous subdrainage, giving a cumulative value for both. The cumulative value is then divided by the value for the first subdrainage. If the ratio exceeds 1.10, a 10% accretion of runoff volume is likely, and a segment boundary should be placed at the confluence of the two streams. This process is continued to the bottom of the watershed, adding to the cumulative drainage area-precipitation product and dividing by the previous value, as illustrated in Table 5.

Table 5. Drainage area-precipitation products for five watershed subdrainages, used to estimate flow accretions to a river.

Drainage	Area x precipitation mi² x inches	(ha x mm)	Cumulative value mi² x inches	(ha x mm)	Ratio
A	720	(4.7×10^6)	720	(4.7×10^6)	--
B	455	(3.0×10^6)	1175	(7.7×10^6)	1.63
C	80	($.05 \times 10^6$)	1255	(8.2×10^6)	1.06
D	210	(1.4×10^6)	1465	(9.6×10^6)	1.16
E	60	(0.4×10^6)	1525	(10.0×10^6)	1.04

In Table 5, there are two places indicated on the mainstem river where a 10% accretion to the volume of flow is likely, one at the confluence of tributary B and the other at the confluence of D. Thus, there are three mainstem river segments based on flow regime changes: one upstream from B, one between B and D, and one below D. These segments apply only to the mainstem river and are totally independent of any segments designated on the tributaries. For example, tributary C joins the mainstem between B and D but does not supply enough water to justify a mainstem river segment boundary. This does not delete tributary C from the study. On the contrary, if tributary C is an important fishery habitat, it must be included in the study area and appropriatly segmented.

The area-precipitation product cannot be used where precipitation records are not available or cannot be estimated. The investigator may choose to determine flow accretions empirically in this case. These determinations can be made by measuring the streamflow above and below each tributary at one point in time. These measurements should be made during a period of steady flow, preferably in the absence of rainfall or snowmelt runoff for at least 1 week prior to the measurements. The best possible stream gaging cross sections and stream gaging techniques should be used because it is necessary to keep the measurement error less than 10%. References describing good stream gaging procedures are listed at the end of this chapter.

Ground water accretions and losses can also result in significant deviations in streamflow. These variations can be detected when measuring streamflow accretions from tributaries. However, large portions of some drainages may not contain any significant tributaries, yet receive inflow from ground water. One or two streamflow measurements should be made in the portion of the mainstem between major tributaries to confirm the effects of ground water. Alternatively, gage records can be examined to determine ground water inflow if the reach lies between two gaging stations. In this case, only records for low precipitation months should be examined.

3.1.2 Channel Morphology

Factors affecting channel morphology along a watercourse include slope, sediment supply, bank materials, vegetation, and flow regime. These factors may change slowly and at a rather constant rate, resulting in subtle differences in the channel structure from headwaters to mouth, or abruptly, resulting in major changes in channel structure. Segmentation of the stream based on flow regime will incorporate some changes in channel morphology, especially changes in channel dimensions, but will not incorporate all of them. Therefore, additional segmentation based on geomorphic characteristics is needed and can be accomplished by adding segments or subdividing existing ones.

Elaboration of the many potential geomorphic characteristics supporting segmentation of stream channels is beyond the scope of this paper. Several texts on geomorphology are listed at the end of this chapter. Perhaps the single best source of information on the geology and geomorphology for a given river system is the Professional Papers Series of the U.S. Geologic Survey (USGS). Other pertinent information is also available in the Water Supply Papers and Hydrologic Atlas Series, published by USGS.

a. Slope. Changes in slope can be detected easily by examining the stream's longitudinal profile, a plot of stream elevation versus distance. A longitudinal profile can be constructed from a topographic map by measuring the river distances between contour lines intersecting with the stream, recording the elevation of the contour lines, and accumulating the distance from the starting point. River distances are measured with a map wheel or a piece of string, starting at either the headwaters or the mouth of the river.

Figure 8 shows a plot of a smooth longitudinal profile; Figure 9 shows an irregular profile. Abrupt changes in slope, such as those shown in Figure 9, are good candidates for segment boundaries or subdivisions. However, the gradual or uniform changes in slope shown in Figure 8 and the higher elevation portions of Figure 9 make segment boundaries less certain. Fitting linear segments to portions of the curve, as shown with the dashed lines, can help overcome this problem. This process is used to delineate areas of steep, moderate, and low slope and should not be used as the sole determinant of segment boundaries or study area selection. However, the approximate locations of segment boundaries can be determined at the points of intersection of the tangential linear segments.

b. Sediment supply and bank materials. Channel morphology is strongly associated with the characteristics of the sediment transported by the river and of the materials composing the banks. Changes in sediment supply, either in terms of size or amount, can result in variations in channel pattern and structure. Several sediment sources should be considered in the placement of segment boundaries: tributaries; glacial deposits; and mass wasting deposits.

A tributary can change the sediment balance of a river by increasing or decreasing the sediment-to-discharge ratio. A tributary contributing a substantial amount of water, but little sediment, will reduce the ratio. Such tributaries should already be marked on the map as segment boundaries because of their influence on flow regime. Other tributaries contribute a disproportionate amount of sediment compared to the amount of water they supply. These tributaries often have little effect on the flow regime, but may cause drastic

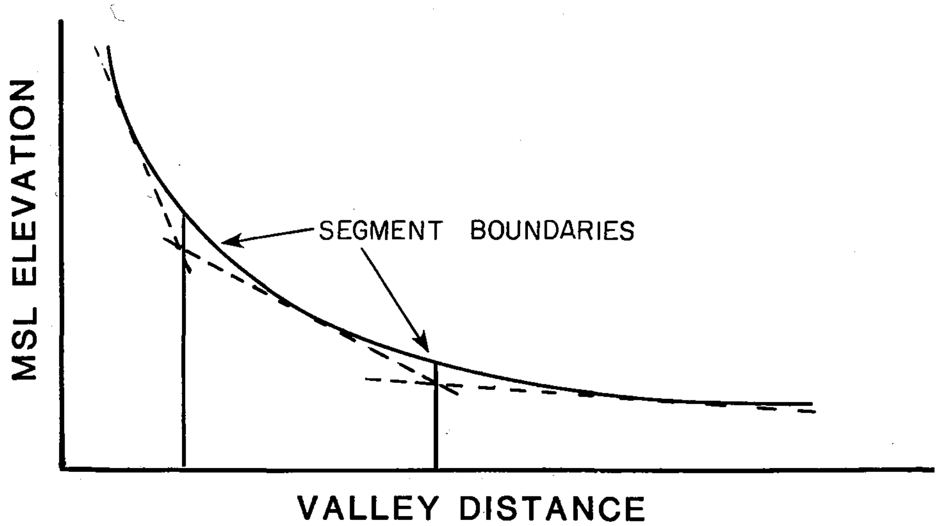


Figure 8. Smooth longitudinal profile typical of streams flowing from headwaters to lowlands with no intervening geological abnormalities. Tangents added to identify potential segment boundaries.

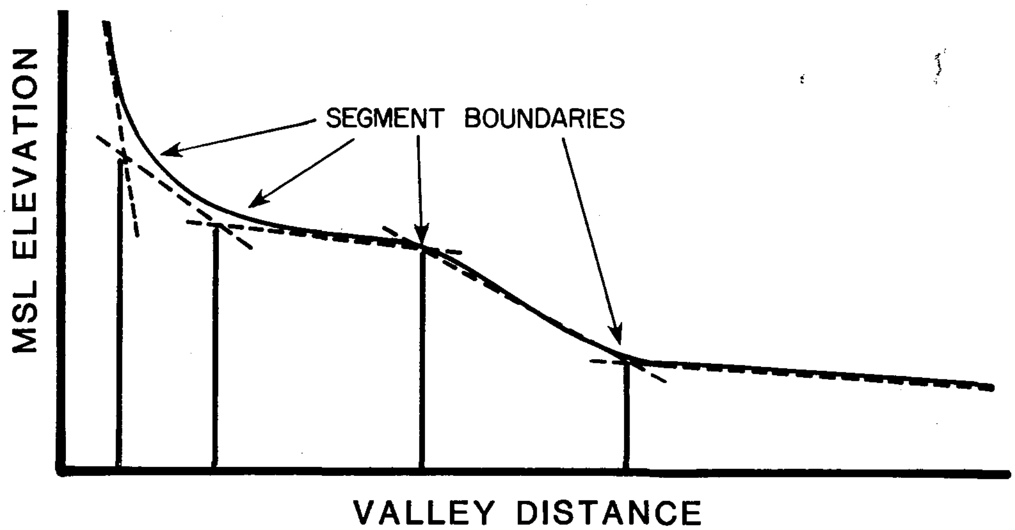


Figure 9. Irregular longitudinal profile of a stream flowing through a canyon located midway between source and mouth. Tangents added to show segment boundaries.

changes in channel pattern. A segment boundary should be placed wherever this situation exists.

Streams flowing through glaciated valleys provide excellent examples of changing channel morphology. At the headwaters end of the valley, there is usually a cirque deposit and evidence of a ground moraine, composed of material deposited beneath the active glacier. The ground moraine is an area of relatively low relief, containing gravels and well rounded boulders as typical materials in the deposit. Vegetation colonizing the ground moraine strengthens the banks, resulting in a meandering, often tortuous, channel pattern. Lower in the valley, lateral moraines occur along the valley margins. Although the stream characteristics in the valley are similar to those upstream from the lateral moraines, tributaries cutting across the lateral moraines are likely to change their appearance considerably. Where the stream cuts through a moraine, its character often changes from a single channel, highly meandering stream to one with multiple channels and lower sinuosity. A segment or subsegment boundary is usually required at the upstream end of the terminal moraine, which marks the farthest downstream advance of the glacier. Another boundary may be desirable at the downstream end, depending on the length of the moraine. The slope of the stream may be steeper across the moraine and the outwash plain downstream than it is elsewhere along the stream; this is often detectable from the longitudinal profile. Section 3.1.4 contains guidelines pertaining to the relative lengths of segments, which will aid in any decisions to subdivide the segment downstream from the moraine.

Mass wasting features, such as rockslides and slumps, affect channel morphology much like glacial deposits. One major difference is that mass wasting products tend to be very angular compared to the rounded moraine material. There may also be relatively little gravel in these deposits. Although these distinctions may not be apparent from map or from channel morphology observations, they often show up as obvious changes in channel substrate characteristics.

3.1.3 Channel Patterns

The channel structure at any location on a river is a reflection of its pattern, generally classified as straight, meandering, or braided (Leopold et al. 1964; Shen et al. 1981). The ratio between channel length and valley length, called sinuosity, is a useful index to the classification of channel pattern. Leopold et al. (1964) suggest that streams having a sinuosity less than 1.5 should be classified as straight or sinuous. Those with sinuosities greater than 1.5 are classified as meandering. A braided channel is divided into many channels which successively divide and reunite, not fitting the definition required to compute sinuosity.

Channels having a sinuosity less than 1.5 are typified by sequences of riffles and pools. However, they may also contain sequences of riffles, runs, and pools. Another typical pattern is a sequence of riffle-pool-island. Finally, a straight channel may contain offset point bars and, at low flow, may resemble a meandering stream more than a straight one. The investigator must be aware that these types of variations can occur within an area of otherwise constant channel characteristics. Sometimes, channel features which appear anomalous (such as islands) are actually part of a larger repetitive pattern.

The typical channel morphology of a meandering stream consists of a triangular cross section at each meander bend, with the apex of the triangle at the outside of the bend. Between meander bends, the stream has a tendency to build a rectangular shaped central bar, called the crossing bar. Meandering channels often exhibit variations similar to those occurring in straight channels. The sinuosity can be used as an index of the magnitude of the change in channel characteristics. Islands, runs, and extensive riffles all tend to increase the distance between pools, resulting in a lowered sinuosity value. Sinuosity is a rather gross indicator of channel pattern and morphology, but a change in sinuosity exceeding 25% is sufficient to warrant a segment or subsegment boundary.

To most observers, braided channels do not appear to have a pattern, much less one that is repetitive. Therefore, the concepts of sinuosity and riffle-pool spacing have little value in these channels. Braided rivers typically have several distinguishing features: a very high sediment load; relatively uncohesive banks; and a very unstable bed. Sediment deposited in midchannel tends to cause channel widening, provided that the banks are easier to erode than the midchannel deposit. If the banks become more resistant by increased vegetation or other mechanism, the central bar will erode instead. Such subtle changes in bank resistance can be detected by computing the ratio between bankfull channel width and depth. The width to depth ratio is probably a more variable index than sinuosity, but a change of more than 25% is sufficient cause to place a segment or subsegment boundary.

3.1.4 Consolidation and Subdivision of Segments

Segment or subsegment boundaries are sometimes poorly defined. Those that are clearly defined, such as by the confluence of a large tributary or an obvious change in channel pattern or slope, take precedence over those less clearly defined. These segment boundaries are easily determined and seldom cause problems for the investigator.

Gradual changes in slope, flow regime, sinuosity, or width-to-depth ratio may result in poorly defined segment boundaries. Consequently, a boundary placed for one of these reasons may not exactly coincide with boundaries placed for other reasons. These boundaries should be consolidated into a single boundary, placed at the midpoint between the two most widely spaced boundaries. As a general rule, a segment should contain more than 10% of the total length of river under study, unless the segment boundaries are clearly defined by changes in flow regime or the segment contains a critical reach (see Section 3.2.2).

Gradual changes in slope or channel pattern may require subdividing the segment. This phenomenon is most common in the transition zones between one well defined channel type and another. The middle segment of Figure 8, an area of transition between high gradient and low gradient, is one example. Such areas are common in foothills and piedmont areas separating mountains and plains and downstream of major sediment sources. The largest supply of sediment occurs closest to the source and the effects of the sediment on channel pattern are attenuated with distance from the source. Therefore, there may be a substantial difference in the channel structure at the top and bottom of the segment, but no clear dividing line within the segment. This causes problems in study site selection because each potential study site looks slightly different, but not radically different, from all other sites in the segment. Several study areas may be needed to adequately describe segments in transition zones. Options for selecting these study areas are discussed in Section 3.2.

3.2 TYPES AND LOCATIONS OF STUDY SITES

There are numerous similarities between study sites established to monitor and model macrohabitat characteristics and those established to evaluate microhabitat. Both are designed to reproduce longitudinal gradations in macrohabitat. The same study sites could be used in an instream flow study to evaluate both types of habitat. However, the objectives and data requirements for water quality and temperature analyses are different from those for sediment transport analysis. Both are different from microhabitat analysis. The investigator has the option of using the same sites for both macro- and microhabitat evaluations or using specific sites for specific analyses. This decision is tempered by the data requirements of a particular analysis and by sampling design considerations specific to each type.

When in doubt, the investigator can adopt the convention of using uniform spacing between study sites. Ideally, this sampling design provides a good representation of longitudinal gradations in both macro- and microhabitats. Uniform spacing of study sites within a segment is an acceptable sampling technique when the segments exhibit smooth longitudinal gradations. Uniform spacing is generally more expensive than nonuniform spacing, discussed in Sections 3.2.1 and 3.2.2. Further, there are enough differences between macrohabitat and microhabitat modeling to cause problems when common sites are used for both. Because different habitat characteristics may exhibit different rates of change within the segment, the use of uniformly spaced sites can result in the collection of unnecessary or redundant data in one instance or inadequate data in another. Therefore, the investigator must understand the sampling strategies for the different types of analyses being conducted and establish study sites for specific objectives.

Measurements for macrohabitat models (i.e., water quality, temperature, and sediment transport) are used in model calibration. Values for constituent concentrations or temperatures at intermediate locations are found by applying different reach lengths, streamflows, and/or loading rates and using the calibrated rate coefficients as determined for the study sites. Thus, what happens at one site is carried downstream to the next. To obtain a more accurate calibration, it is desirable to concentrate study areas where a variable exhibits rapid change or where it approaches a sensitive biological threshold.

Data from microhabitat sites are used to extrapolate the relationship between microhabitat and discharge to a larger reach of stream. The characteristics of each microhabitat site are essentially independent of all other microhabitat sites. No connotation of interpolation is applied to a microhabitat site, whereas this is an important consideration for macrohabitat sites. Thus, microhabitat sites may need to be concentrated in areas where microhabitat exhibits rapid longitudinal change. These sites may not correspond to the places exhibiting rapid changes in such things as temperature or water quality.

3.2.1 Macrohabitat Study Sites

Velz (1970) provides a good description of sampling site design for water quality monitoring and the calibration of water quality models. This discussion is also appropriate for monitoring or modeling sediment transport. Velz discusses the following factors governing the location of sampling sites: the location of control sites; the relative positions of point and nonpoint sources; channel characteristics; river developments; and the assimilation of the organic load.

a. Control sites. The purpose of the control site is to determine the residual loading of the constituent of interest from upstream sources. Placement of the control site is fairly easy in the case of sediment or chemical sources; the control site should be placed a short distance (100 meters or so) upstream from the source. Placement of a control site may be more difficult in the analysis of temperature. Many streams exhibit thermal profiles ranging from "cold," with maximum temperatures less than 18°C, to "warm," with temperatures exceeding 30°C. A transition zone of "cool" (19°C to 29°C) water separates the cold section from the warm. This transition zone shifts upstream and downstream as a function of streamflow and weather. The exact location of the lower boundary of the cold water zone is sometimes difficult to ascertain, but efforts should be made to establish the control station well within this zone. The same rule applies for streams having only cool and warm zones.

b. Point and nonpoint sources. Sampling or monitoring stations should be placed below point sources, regions of nonpoint diffuse input, and confluences of tributaries. Stations should be placed far enough downstream from the source to ensure complete dispersion of the incoming material. This distance may be estimated by equation 3-1, adapted from Ruthven (1971):

$$\text{Mixing length} = \frac{0.058 \times W^2 \times V}{D^{3/2} \times S^{1/2}} \qquad (3\text{-}1)$$

where W = top width of the stream in ft

V = mean velocity in ft/sec

D = mean depth in ft

S = water surface slope for the reach

c. Channel characteristics. Configuration and alignment of the channel are important considerations in the placement of sampling stations. The desirable characteristics of the channel depend on the constituent being sampled. Water quality samples are normally taken at only one location in the river at each station. A straight, regular cross section without excessive turbulence is a good location for taking water quality samples. However, moderate turbulence is a desirable characteristic for suspended sediment sampling stations. Bridges are often used for taking both types of samples, but, depending on the bridge design, they may not be entirely suitable for one or the other. Bridge piers induce turbulence and local scour which may introduce error into the sample. Measurements made from a boat are probably preferable to those made from a bridge with piers.

d. River developments. Dams, diversions, and channel realignments may introduce stratification, bed scouring (or filling), and other problems which cause variations in water quality, sediment transport, or temperature. Velz (1970) states that the greatest variations are introduced by hydroelectric power plants, especially those used for hydropeaking. Another problem associated with dams is the release of waters from the thermocline during periods of drawdown. This may cause erratic fluctuations in temperature, as well as the release of a variety of chemical compounds, dead plankton, and organic matter that tends to concentrate around the thermocline. Measurement of these water quality constituents is certainly not representative of the quality of the water typically released, but it may be the most important from a biological perspective. The investigator should not avoid reaches of streams below dams, but should be aware that they may cause sampling problems. Arrangements should be made with the dam operators to stabilize the flow if a representative sample is desired. Otherwise, an intensive sampling schedule or continuous monitoring is necessary to reflect the cycle (Velz 1970).

e. Waste assimilation characteristics. The main objective in evaluating a nonconservative water quality constituent is to describe its concentration profile along the stream course at various discharges and/or loading rates. This objective applies to temperature profiles as well as chemical concentration profiles. Places along the river where these constituents reach a biologically important concentration, or threshold, are of special interest. Examples of such places are the transition zones from cold-to-cool or cool-to-warm water temperatures and the location of the dissolved oxygen sag. A higher density of sampling stations is advisable in these areas. However, locations of critical water quality conditions migrate up and downstream as a function of streamflow. It is very helpful to have some idea regarding the shape of the profile before study areas are established. This may require a preliminary survey to determine the shape of the profile under normal or anticipated flow regimes. The screening equations in Section 2.3.2. can be very helpful in locating the approximate critical points on the profile.

3.2.2 Microhabitat Study Sites

A microhabitat study site can describe two types of stream reaches in a segment: representative reaches or critical reaches. As the name suggests, a representative reach represents all or part of a segment and must be selected such that it is typical of a fairly large portion of the segment. Critical reaches are usually atypical of most of the river and are selected on the basis of a biological constraint imposed on a species. Microhabitat study sites in representative and critical reaches differ not only in objective, but also in size.

Because a representative reach is defined as being typical of part or all of a segment, it should include at least two entire cycles of riffles and pools or meanders and crossing bars to describe the relative proportions of each in the representative reach. Leopold et al. (1964) state that these cycles are repeated at a spacing of 5 to 7 times the width of the channel. Therefore, a representative reach has a length equal to 10 to 14 times the channel width. A microhabitat site describing a representative reach might include the total length of the reach. However, if the characteristics of the stream throughout the representative reach are very similar, the microhabitat study site needs to describe only one cycle. Thus, a microhabitat study site in a representative reach might encompass the entire reach or only half of it.

Microhabitat study sites in critical reaches vary greatly in size, but should not exceed 10 to 14 channel widths in length. A critical reach at a passage barrier might consist of a single transect across the stream. A microhabitat study site at a critical spawning bar might only run the length of the bar. If the critical reach extends further than 10 to 14 channel widths, the microhabitat study site does not need to cover the entire reach. Rather, the length of the critical reach is determined from ground observations and a microhabitat study site used to characterize the habitat within the reach as described above for a representative reach. Measurements from the microhabitat site are then extrapolated only over the length of the critical reach.

a. Representative reach selection. During the segmentation process, the river is dissected into a series of long segments which are essentially homogeneous. A study site placed anywhere within a segment should theoretically be very similar to any other study site within that segment. Thus, a representative reach is a potential study site, which, when measured in detail, is used to describe the microhabitat for all or a portion of a river segment. Naturally, there will be some variation in microhabitat characteristics within a segment, but when several reaches are selected at random, the probability of selecting a reach "typical" of the segment is greater than selecting an "atypical" reach. The dominant characteristic of a representative reach is that the microhabitat features of the reach are repetitive. Several sampling techniques can be used to select a representative reach: uniform spacing; explicit zonation; or random sampling. None of these techniques is superior in all segments.

Uniform spacing implies that representative reaches are placed at equal distances throughout the segment. This approach is most effective in segments exhibiting gradual and regular change in channel structure or slope from one end of the segment to another. It should not be used in segments having abrupt and irregularly spaced changes in channel structure, such as numerous small landslides. Uniform spacing requires more than one study site to represent a segment and can be more expensive than studies in segments represented by fewer study sites. The least expensive way to use uniformly spaced study sites is to divide the segment into equal thirds and use two study sites, one at each division point. The number of study sites ultimately used may be more a function of time and money than of microhabitat diversity.

Explicit zonation means that changes in channel structure are readily discernible and nonuniformly distributed throughout a segment. This approach subdivides the segment into smaller units, ensuring that at least one representative reach will be located in each type of habitat. These segment subdivisions can be either continuous or discontinuous. A segment having a sequence of riffle-pool-riffle-pool through the top half and riffle-pool-run-island in the lower half is an example of continuous subdivision units. A meandering stream which occasionally abuts a bedrock wall, creating deep scour pools, is an example of a discontinuous subdivision. Study sites can be located in one or more subdivisions by subjective judgment, uniform spacing if the subdivision is continuous, or by random sampling. Of the three techniques, random sampling is preferred.

A representative reach is selected at random in the following manner. First, determine the average channel width of the stream within the segment and multiply by a factor of 10 to 14. A factor of 10 is recommended for simple riffle-pool sequences, 12 for simple meandering streams, and 14 for more complex sequences or braided channels. Second, on a topographic map, mark boundaries of all of these potential or candidate representative reaches along the river at the distances specified in the first step. Eliminate any reaches having bridge crossings, unless a large proportion (greater than 30%) of the reaches have bridge crossings.

Third, sequentially number each candidate reach. Then, using a random number generator, random number table, deck of cards, or other means, randomly select three to five reaches. Fourth, inspect the selected reaches on the ground. Because only one representative reach is needed to represent the microhabitat for the entire river segment when all the candidate reaches are fairly similar, considerations such as access, logistics, and landowner permission may guide the ultimate selection of the study site. However, when the field inspection shows that any of the selected candidate reaches is considerably different from the others, each of the different reaches should be considered as a study site. In this case, each reach is representative of a portion of the segment. These proportions must be determined and the length of river to be represented by each representative reach calculated.

Representative reaches can also be selected by less objective techniques, such as preselection based on the investigator's experience with the river. This approach should not be confused with explicit zonation, which is simply a further subdivision of the segment and is subject to random or uniform reach selection within the subsegment. If the study may become involved in court or administrative hearings, preselection is not recommended because it appears to be a subjective selection technique.

A representative reach should describe the microhabitat for a length of stream considerably larger than itself. As a general rule, a representative reach should represent at least 10% of the total length of stream in the segment. Study areas representing less than 10% of the stream within the segment may be considered critical reaches or may simply be anomolies. Critical reaches should be retained for microhabitat analysis. Anomolous reaches should be abandoned and other, more representative sites chosen.

b. Critical or unique reaches. Critical reaches are portions of rivers containing a particular type of microhabitat that is absolutely essential for the completion of one or more life-stages of a species and absent or in very short supply in the representative reaches. Critical reaches are often associated with migration, spawning and incubation, and development of newly emerged young-of-the-year fish.

Examples of critical reaches for migration (passage) include rapids, culverts, low head dams, and run-of-the-river fish ladders. The reach or point on the river must be negotiable by the fish at some flows in order to be considered critical for passage. If a passage barrier is impassable at all flows (such as a waterfall), it would be a segment boundary, not a critical reach. Several factors must be considered in evaluating a site as a potential critical passage reach. The first is the depth of the section at low flow. The second is the length of the section and the velocity at high flow. The third factor, associated primarily with rapids and low head dams, is the difference in water surface elevation above and below the barrier. The fish may be able to leap over the barrier at some flows but not at others. Passage is often evaluated at representative reaches as well, so a critical passage reach should represent the worst conditions confronting the fish. The final criterion that must be met by a critical passage reach is that passage through the reach must be essential for the successful continuation of the species' productivity throughout the system. Therefore, the critical passage reach concept is applied primarily to species noted for long distance migrations, such as anadromous salmonids, American shad, paddlefish, sturgeon, and striped bass.

A critical reach can also be designated by microhabitat characteristics necessary for spawning and incubation. Generally, such reaches become critical as a result of two factors: (1) the spawning requirements of the species are narrowly defined for one or more stream-related variables; and (2) something has caused a significant alteration of one of those variables. The reduction in the availability of suitable gravels for salmonid spawning due to siltation or degradation is a common example. As more spawning areas are rendered useless, those remaining take on added importance. Sometimes the critical reach is not even located in the mainstem river. The bulk of the spawning activity may occur in the tributaries and appropriate study sites must be established in the tributaries in this case.

Critical reaches can also be designated on the basis of providing rearing areas for young-of-the-year fish. Newly emerged fish larvae are generally poor swimmers and cannot tolerate much, if any, current. Additionally, they may be protected from predators by utilizing very shallow waters. It is not uncommon for these conditions to be absent or in very limited supply in a representative reach during the first month of life of a species. Therefore, these areas should be studied when locations particularly amenable to rearing of very young fish can be identified, and when young of year survival is a significant determinant of adult numbers.

A final type of critical reach is one which, for some reason (often unknown), contains an exceptionally high standing crop of a rare or endangered species. These reaches might be called unique rather than critical. A good example is Black Rocks Canyon on the Colorado River, which has been reported to contain a large population of the endangered humpback chub (C. G. Prewitt 1982; pers. com.). The reasons that the chub congregate there are subject to speculation, but presence of chub in large numbers implies that this reach is important.

3.3 APPORTIONING REACH LENGTHS WITHIN THE SEGMENT

The final exercise in establishing the study area is determining the total length of river represented by a study site, whether in a representative or critical reach. All of the information collected to this point is used to determine these reach lengths. It is recommended that this exercise precede the field work even though the length of stream represented by a study site is not used until the results are compiled. The investigator may find that a potential study area is neither representative nor critical in the process of extrapolating the reach over a larger length of river. Redundant reaches can be eliminated or unrepresented portions of river may be detected and study areas added, if necessary.

A series of ground level photographs taken at each selected representative reach can be very helpful in recalling and comparing the characteristics of the reaches. Large scale aerial photographs, if available, are even better. The location of each selected representative and critical reach should be marked on a topographic map and the approximate total length of stream represented by each type determined. The represented stream length should then be converted from map scale to river distance using a map wheel or piece of string. If a critical passage reach is present, the total length of stream above the blockage should also be determined at this time.

Table 6 contains a checklist of activities related to study area selection. A copy of this checklist is provided in Appendix A for reproduction and use in a actual study.

Table 6. Checklist for establishing study sites.

____________	Topographic maps or suitable substitutes (e.g., aerial photos or other maps) of the study area have been assembled so that entire area is shown on one map.
____________	Tributaries accreting more than 10% to the average base flow below the confluences have been identified and marked on the map.
____________	Diversions removing more than 10% of the total flow of the river above the diversion have been identified and marked on the map.
____________	Ground water sources or diffuse small tributaries, which in aggregate add 10% to the average base flow or add 10% to the drainage area-precipitation product, have been isolated and marked on the map.
____________	Longitudinal profile of stream(s) has (have) been constructed.
____________	Segment boundaries, based on relief, have been determined and marked on the map.
____________	Significant sediment sources, such as moraines, landslides, and areas of sediment-generating land use, have been identified and marked on the map (if applicable).
____________	Locations where channel sinuosity or width to depth ratio changes appreciably (more than 25%) have been identified and marked on the map (if applicable).
____________	Locations where channel shape, channel pattern, bed particle size, or bank vegetation change appreciably have been identified and marked on the map (if applicable).
____________	Stream reaches containing populations of coldwater species and warmwater species, as well as transitional reaches, have been identified and marked on the map (if applicable).
____________	Point sources of pollution or thermal effluent have been located and marked on the map (if applicable).
____________	Areas of land use affecting nonpoint pollution have been identified and marked on the map (if applicable).

Table 6. (Continued)

_________ If water quality is suspected to be a problem, or may be a problem under a proposed action, an expert has been consulted and water quality monitoring or modeling stations have been identified and marked on the map.

_________ If watershed or channel change problems are anticipated, an expert in sediment transport and channel change has been consulted and appropriate actions recommended.

_________ Segment boundaries isolating lengths of stream of less than 10% of the total stream length have been consolidated (remember well defined segment boundaries take precedence over poorly defined boundaries).

_________ Average width of stream within each segment has been determined.

_________ Length of candidate representative reaches has been calculated.

_________ Candidate representative reaches have been marked on the map at appropriate spacing and numbered sequentially from the bottom of the segment to the top.

_________ Candidate reaches having bridge crossings have been eliminated.

_________ Three to five representative reaches have been chosen at random for each segment.

_________ If not random, how were the representative reaches selected? Why?

____

____

_________ Critical reaches, if present, have been identified and marked on the map (may include reaches less than 10% of total stream length in segment).

What is the nature of the critical reach? (e.g., culvert, shallow bar inhibiting passage, or spawning areas).

____

____

_________ Selected reaches have been inspected, redundant reaches eliminated and new reaches added where unrepresented portions of the river are detected.

Table 6. (Concluded)

__________	Landowner permission to work at selected reaches has been obtained (if applicable).
__________	If landowner permission to work at selected reaches is denied or the selected reaches are inaccessible, alternate reaches have been selected (if applicable). If so, how were the alternate sites selected?

____

____

__________	Lengths of stream represented by representative reaches have been determined.
__________	Lengths of stream represented by critical reaches have been determined.

3.4 SUGGESTED ADDITIONAL READING

3.4.1 Geomorphology

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman and Company, San Francisco. pp. 493-712.

3.4.2 Longitudinal Zonation

Hynes, H. B. N. 1970. The ecology of running waters. Liverpool University Press. Liverpool, Great Britain. pp. 383-397.

3.4.3 Stream Gaging Procedures

Buchanan, T. J., and W. P. Somers. 1968. Discharge measurements at gaging stations. USGS Techniques of Water-resources Investigations, Book 3, Chapter A8.

3.4.4 Water Quality

Velz, C. J. 1970. Applied stream sanitation. Wiley Interscience, New York. pp. 398-421.

4. APPLICATION OF THE INCREMENTAL METHODOLOGY

Although the scoping and site selection processes are somewhat routine, the actual application of the Incremental Methodology is very flexible. An application of the methodology typically consists of six steps:

1. Describing the river or system in its present state;

2. Determining the mathematical expressions and functional relationships describing temporal macro- and microhabitat availability of the present system and integrating this information to determine total habitat availability;

3. Incrementally changing one or more of the driving variables in the system and rerunning the model(s) to determine a "new" state of the system in terms of total habitat availability. This step requires a display of total habitat over time with and without the project and subsequent interpretation of the display;

4. Determining alternative courses of action or remedial procedures to correct significant adverse impacts identified in Step 3;

5. Incrementally changing the driving variables to reflect these remedial procedures and rerunning the model(s) to determine the resultant effect on total available habitat. This step can be used like Step 3 to determine effective management alternatives or mitigation efforts to offset an adverse impact. This step requires a display or interpretation of data to quantify the effect of the remedial procedure; and

6. Evaluating the "new" system to make sure that it meets management objectives and to determine its relative permanence. This step is used to examine trade-offs and to ensure that a corrective action does not cause other problems in the future. Economic evaluations of the various alternatives are made at this time, if necessary.

4.1 DESCRIPTION OF SYSTEM IN PRESENT STATE

4.1.1 Microhabitat

Microhabitat consists of two components: channel structure and hydraulic characteristics. The channel structure component includes all microhabitat characteristics inherent to the banks and streambed, independent of the flow. Channel dimensions, relative elevations of the streambed in riffles and pools, longitudinal proportions of riffles, pools, and runs, distribution (both longitudinal and lateral) of different types of cover and substrate, and channel shape and slope are all examples of channel structure characteristics. Although these characteristics remain essentially constant regardless of the streamflow, the hydraulic characteristics change as the flow changes. Hydraulic characteristics refer to the longitudinal and lateral (and sometimes vertical) distributions of depth, water surface elevations and slope, top width, and velocity. Longitudinal changes in microhabitat are measured by placing transects across the stream at the center of each important morphological microhabitat feature (e.g., riffles or pools) and in the transition zones between them. Lateral changes in microhabitat types are measured at points (called verticals) across each transect. Measurements are typically made at one to five different discharges and these data are used to simulate the hydraulic characteristics over the range of unmeasured discharges expected in the channel. The general concepts of microhabitat simulation are included in Chapter 7. Actual specifications for measuring microhabitat structure are in Bovee and Milhous (1978) and Trihey and Wegner (1981). An updated field techniques manual is scheduled for publication and regularly scheduled short courses are offered by the IFG on this subject.

The channel structure is measured at one or more times, typically not over a larger time interval than 1 year. These measurements are assumed to reflect channel structure into the future if the watershed and channel are <u>presently</u> in a state of dynamic equilibrium. Streams undergo lateral migration and riffles, pools, and gravel bars change position over time but, if the channel is in equilibrium, the overall structure and dimensions will remain in approximately the same proportions. If either the watershed or channel is in disequilibrium, then the more complex approaches discussed in Section 2.3.1 must be taken.

Fine bedded alluvial streams often pose a problem in defining the present channel structure. Even in an equilibrium state, these streams change shape frequently. Some changes are cyclic; pools scour during the runoff period, fill during the summer, and then scour again the following year. Separate channel measurements should be made for both conditions in these streams. Some sand bed alluvial streams change shape constantly. The "present" channel structure for these streams should be the one that occurs most often. These streams are frequently braided, so measurement of a typical section (if there is one) may suffice. Alternatively, the same section could be measured several times to define a range of potential channel structures.

4.1.2 Flow Regime

The manner in which the present flow regime is defined depends on the kind of analysis being conducted and the amount of historical streamflow data available. The most desirable definition of the flow regime is a time series of discharges that have occurred over the period of record for the segment, as related to a gaging station. Synthetic flow time series are constructed for streams with short records or no records. The time step used in the series varies according to the problem. Mean monthly values are typically used in water allocation studies from reservoirs. Mean weekly or daily values can be used to determine the impact of a diversion. Hourly values are used for hydropeaking schedules.

Summary time series are often used for instream flow studies. This involves the construction of mean monthly flow hydrographs having a certain probability of occurrence. Normally, the present flow regime defined for this type of study is the median monthly hydrograph. This is a synthetic hydrograph composed of the average monthly flows expected to occur once every 2 years on a recurrence interval curve or the average daily flows exceeded 50% of the time on a daily flow duration curve. (See Section 6.1.1 for details on how to construct both types of hydrographs.) The flow duration curve is preferable in flashy streams, where there may be large differences between the mean and median monthly flows.

The synthetic median monthly hydrograph is also used for ungaged streams or streams with such short gaging records that a flow time series is meaningless. Synthetic hydrographs representing median flow conditions can be assembled with a fair degree of accuracy. The accuracy declines markedly when predictions of less frequent events are attempted.

The median flow hydrograph represents a measure of central tendency for the water supply and is considered a "normal" or typical water supply pattern for the river. However, the biological community structure and carrying capacity may be set by less frequent high or low flows. Therefore, analysis of present conditions also includes hydrographs for high and/or low water years. The recurrence interval selected depends in part on the longevity of the evaluation species. For short-lived fish, like certain minnows, a short recurrence interval, such as 5 years, is used to define the drought or high flow condition that can be expected during the normal life cycle of the species. For longer-lived species a larger interval (usually 10 years) is used. A recurrence interval of 20 years might be used for very long-lived fish, such as sturgeons. Guidelines regarding the use of synthetic hydrographs in various analyses are in Chapter 5.

4.1.3 Water Quality

The present state of water quality is defined by the existing pollutant loading and flow regime. Water quality and temperature affect the total length of stream that is usable by a species. Current species distributions are assumed to remain unchanged under different streamflow conditions, unless water quality and temperature information suggest otherwise. This means that the species distributions marked on the topographic map during the study area selection process delineate areas of suitable water quality and temperature for each species under all flow conditions representing the present state of the system.

It is unlikely that this assumption will remain valid for all studies, unless the study is confined to a small area with little pollution. In many cases, the length of stream having suitable water quality and temperature changes in response to flow regime. There are two techniques that can be used to determine the suitable length under existing conditions. The first is to establish an intensive monitoring network and develop a large empirical data base. Some streams may already have such networks, and the suitable length at different flows can be estimated from the records. The second technique is to use a water quality model to predict temperatures and chemical concentrations at various points along the stream according to streamflow and time of year. The latter approach is advised if a change in water quality is anticipated under the "new" conditions because it is probable that a water quality model will be needed to determine these conditions anyway.

4.2 DETERMINATION OF "NEW" STATE OF SYSTEM

At this point, each study takes on individual characteristics. For example, an instream flow study in an undisturbed watershed, with no pollution sources, is primarily concerned with flow regime and possibly temperature. A very different situation exists where the stream is to be channelized but the flow regime unaltered. Both examples differ from a project that will result in a channel change and a change in flow regime, thermal regime, and water quality, such as dam construction.

Each of the above problems can be analyzed but each requires different procedures. In this context, the Incremental Methodology is simply a process of linking the appropriate analytical methods together to analyze a particular problem. The Instream Flow Group has developed several analytical tools specifically for this methodology. Other tools can be substituted into the process. However, the procedures discussed in this paper represent state-of-the-art tools developed by IFG specifically for stream habitat analysis.

Because of the disparate pathways and analytical procedures available to solve different problems, a simple checklist or "cookbook" approach will not suffice. The guidelines presented in this report take the format of a dichotomous key, which provides the flexibility needed to route the user through the appropriate processes. Each analysis establishes a unique pathway, depending on the starting conditions and the type of problem being addressed. These analyses can be categorized as one of four types:

1. An instream flow study where there are no anticipated changes in macrohabitat features and the main focus is on microhabitat vs. discharge;

2. An instream flow study where macrohabitat features are expected to change and the focus is at both the macro- and microhabitat levels;

3. Studies determining the impact of a proposed action in a system that currently has no macrohabitat or microhabitat problems; or

4. Studies determining the impact of a proposed action in a system that currently has some problems associated with either macro- or microhabitat or rehabilitation studies in previously altered watersheds.

A key to the analytical sequences for these four types of problems is presented in Section 4.5. The key is a tool to help the user build an analytical process specific to a particular problem and a guide to the use of analytical tools to help solve parts of the problem. At certain branches in the key and at places where determinations must be made, a subsequent chapter or section in this manual is referenced that describes specific analytical tools and procedures in detail. Therefore, the user need only refer to those sections in Part II that are germane to a particular problem.

4.3 DETERMINATION OF REMEDIAL MEASURES

Certain splits within the key will guide the user to a series of potential remedial procedures. Changing the flow regime is usually considered first because it may be the easiest and cheapest remedy. It may also be the most difficult to employ in some parts of the country and would be ineffective for certain situations, such as channel alterations. Therefore, the sequence usually contains several remedial techniques which might be employed singly or in combination. The design and selection of remedial measures is one aspect of the IFIM which relies heavily on the imagination, experience, and judgment of the user. We have attempted to outline the more common potential remedial techniques, but have undoubtedly overlooked some.

4.4 ITERATIVE EVALUATION OF THE SYSTEM

Iterative evaluation is designed to help the user arrive at a recommended flow or mitigation plan and to ensure that the system, as designed, will respond as intended. System reevaluation is a necessary part of the application of the methodology. Sometimes it will require some sort of trade-off analysis among two or more conflicting instream uses. The user is cautioned not to automatically select the highest or lowest instream flow requirement among the various uses. Often, the flow recommended for a particular month will not be the most satisfactory for any single use, but will be a compromise satisfying several uses concurrently.

Success in implementing an instream flow recommendation depends on the attitude of the brokering agency and the skill of the proposer in negotiation. Many fisheries managers equate negotiation with capitulation. Anyone who has ever witnessed the negotiation of a labor contract can recognize that this is false. Negotiation is so vital to equal consideration of fish and wildlife values in water planning that IFG has developed a course and has published two information papers (Wassenberg et al. 1980; White et al. 1981) on the subject. Before entering a negotiation setting, the fishery manager should address the following questions:

1. Is this recommendation reasonable when viewed by competing user groups?

2. Are the reasons for each recommendation documented and logical?

3. Have the operational constraints of the action agency been considered?

4. Are there any means to reconcile differences among perceived operational constraints and the instream flow recommendation or mitigation plan? (i.e., Could the system be managed differently to realize both objectives?)

5. Will this recommended flow regime or mitigation plan achieve its objectives under different climatic conditions? How often will it fail to meet its objectives? What are the consequences of failure? Can different recommendations be provided for extreme events?

4.5 PROBLEM SOLVING SEQUENCES

1. The objective of the study is to determine an instream flow regime to be recommended for protection under reservation, permit, or licensing procedure. 2

   The objective of the study is to determine potential impacts of a proposed action (including water withdrawal) and to suggest alternative management actions or rehabilitation plans. 32

2. The watershed and stream system upstream from lowermost point may be in disequilibrium. 3

   The watershed and stream system upstream from lowermost point are in equilibrium, or if previously disturbed, are sufficiently recovered to be considered in equilibrium. 4

3. The effect of watershed disturbance is discernible from stream channel information (e.g., change in width to depth ratio or change in particle size of substrate). 4

   The effect of watershed disturbance is not discernible in stream channel above and below disturbance. 9

4. The stream channel is currently in disequilibrium. 5

   The stream channel is currently in equilibrium. 9

5. The disequilibrium is caused by a change in sediment yield, channelization, runoff, or some combination thereof. 6

   The disequilibrium is caused only by a change in flow regime (i.e., reduction in flood flows). Sediment yield is unchanged. 9

6. Consult expert(s) in watershed sciences, sediment transport, and channel dynamics. 7

7. Resultant channel shape, dimensions, and particle size of bed materials cannot be determined through consultation or other means. 8

   Resultant channel shape, dimensions, and particle size of bed materials can be estimated. 9

8. Stop. If a new channel shape cannot be determined, the application of steady state microhabitat models is invalid. The recommended approach is to apply a generalized percentage of total flow approach (such as the Tennant method) or to conduct periodic analyses with the IFIM to provide interim streamflow protection until the system stabilizes. Final instream flow recommendations should be deferred until that time. Megahan et al. (1980) present evidence that disturbed streams reequilibrate within 5 to 10 years after

cessation of the perturbation. This time period may be reduced by an aggressive rehabilitation or reclamation policy that includes revegetation, flow manipulation, installation of sediment traps, mechanical channel maintenance, or some combination thereof. (Refer to Section 2.3) END

9. Determine equilibrium channel shape, dimensions, and particle size of bed materials. These may be measured directly if the stream is in equilibrium or estimated from channel change models if the stream is not in equilibrium. Retain these data for use in water quality and microhabitat analyses. (See Section 6.2) 10

10. Determine dominant or effective discharge and duration of flow required to maintain equilibrium channel shape and particle size of bed materials. If a flushing flow is required, consult an expert in sediment transport to determine a flow to remove fines without removing gravels. Record flow(s) and duration on Form A (Appendix A) for appropriate month(s). (See Section 6.2) 11

11. Determine median flow for each month for each stream segment. Use the mean monthly flows over the period of record and find the 2-year recurrence interval, or use the average daily flows for the past 10 to 15 years and find the 50% exceedance flow from the flow duration curve. Both statistics are explained in Section 6.1. If large or numerous water withdrawals occur upstream from the gaging station, the flow duration approach is recommended. This approach yields an estimate of water availability which better incorporates water use upstream. 12

12. Determine the 1-in-10 year high and low monthly flows from recurrence interval curves or 10% and 90% exceedance flows for each month from flow duration curves. (see Section 6.1) 13

13. Determine the availability of flow in the segment by correcting values from steps 11 and 12 for water withdrawals and return flows (see water balancing, Chapter 6). If there is a stream gage near the downstream end of a segment, the streamflow records for that reach probably incorporate diversions and return flows adequately. If not, the availability of water within the segment must be estimated by a water balance. In complex systems, a professional hydrologist or hydraulic engineer should be consulted. Record corrected median and 90% exceedance flows on Form A, Appendix A. 14

14. Water quality or temperature is unsuitable for one or more evaluation species in portions of the stream during part or all of the year at flows less than or equal to the median flow for each month. 15

    Water quality and temperature are suitable for all evaluation species throughout the stream during all portions of the year at all flows greater than the 90% exceedance or 1-in 10-year low flows. 23

15. Water quality or temperature conditions could <u>not</u> be improved through some combination of the following:

a) increasing discharge;
b) reducing thermal or waste loading by more advanced treatment;
c) hypolimnetic or multiple level releases from a dam upstream;
d) increasing the shading along the stream; and/or
e) reducing thermal or waste loading by changing land use practices. 16

Water quality or temperature conditions could be improved through one or more of the abovementioned management practices. 20

16. Water quality or temperature is unsuitable for one or more evaluation species in portions of the stream during part or all of the year at the median monthly flow and all lower flows. 17

Water quality or temperature is unsuitable for one or more evaluation species in some portion of the stream during part or all of the year only at some flow less than median monthly flow. 19

17. Water quality or temperature is unsuitable for one or more evaluation species in some portion of the stream all year at the median flow and all lower flows. 18

Water quality or temperature is unsuitable for one or more evaluation species in some portion of the stream segment only during certain times of the year at the median flow and all lower flows. 19

18. Stop. There is something wrong with the study design. Different evaluation species should be used for this portion of stream, the study area should be shortened, or a segment subdivided. Water quality changes are significant enough to alter species distribution. If one of the study objectives is to provide instream flow protection for all species, the segment should be subdivided and different evaluation species used in the new subsegment. If the study objective is to provide flow protection for the original evaluation species, the study area should be truncated where water quality prohibits the existence of the evaluation species. Take appropriate corrective measures and return to Step 14. 14

19. Compute the length of stream within each segment having suitable water quality for each evaluation species (may not be the same for each species) for appropriate months. Compute for a range of flows from the 90% exceedance flow up to and including the median flow for the month. Record the arrayed values on Form B in Appendix A. (See Section 5.1) 21

20. Compute the length of stream within each segment having suitable water quality for each evaluation species (may not be the same for different species) for appropriate months. Compute for a range of flows from the 90% exceedance flow to the 10% exceedance flow, with various combinations of waste management and land use practices. Record the arrayed values (length, flow, and level of treatment) on Form B, Appendix A. Include in this analysis the effect of increasing flow only, with no increase in treatment. (See Section 5.1) 21

21. The species periodicity is not synchronized with the computed thermal regime of the stream segment for some flows within the range analyzed. 22

The species periodicity is synchronized with the computed thermal regime of the stream segment at all flows within the range analyzed. 23

22. Determine the upper and lower threshold flows beyond which the species periodicity chart is not synchronized with thermal regime during appropriate months. This identifies potential limiting flows pending further analysis. When possible, adjust the species periodicity chart for appropriate months and life stages, corresponding to flows causing the change. 23

23. Passage of fish through either a representative reach or a critical reach is essential to species survival or distribution. 24

Passage of fish through either a representative reach or a critical reach is <u>not</u> essential to species survival or distribution. 25

24. Compute a range of flows over the passage barrier which meet depth and velocity tolerances of the target species over at least 10% of the top width of the stream (Section 7.4). In the special case of culverts or long passage barriers, consult section on culverts (Section 7.4.2). Array minimum to maximum passage flows on Form B. Enter zero under Column D, Form B for all flows outside passable range of flows for affected life stage for all microhabitat areas above blockage. Be sure to "zero" affected tributaries, as well as mainstem. Record the total length of stream to next upstream barrier for all flows within the passable range if barriers are considered critical. If passage is evaluated at representative reaches, record the total length of segment represented by the reach for all passable flows. 25

25. Select or develop species and life stage-specific microhabitat criteria. (See Sections 7.2 and 7.3) 26

26. Determine physical habitat availability for each life stage of each target species present in a representative or critical reach for a range of discharges. The range should be at least from the 90% exceedance flow for the lowest flow month to the 50% exceedance flow for the highest flow month. (See Chapter 7) 27

27. Convert weighted usable area per 1,000 ft of stream to weighted usable area per mile and multiply by the number of miles represented by the study reach and having suitable water quality and temperature. Record under Column E, Form B. Add the values for each represented reach in the segment to obtain a segment total for each life stage and discharge. Record under Column F, Form B. (See Section 5.1) 28

28. The instream flow recommendation will be based on predicted change in utilized habitat. 29

The instream flow recommendation will be based on changes in available habitat, treating all life stages equally. 30

29. Compute habitat ratios between appropriate life stages and/or food organisms, based on population and trophic level structure (see Section 5.2.4). Find the smallest available adult habitat value for the monthly hydrograph under consideration (e.g., from Step 13). Compute the minimum amount of subadult or food producing habitat required to support the smallest amount of available adult habitat. Scan the amount of subadult or food producing habitat available (in appropriate months). If the amount of available subadult or food producing habitat is less than the amount required:

1) revise the estimate of adult and other life stage requirements to coincide with the existing life stage limitation; or

2) determine whether or not the habitat availability of the limited life stage can be increased to realize the potential of available adult habitat. (See Section 5.2.3)

Review Chapter 5 on assumptions and limitations of this approach. 31

30. Construct optimization matrices, similar to Table 19, for each month of the year. (Copies of this table are available for reproduction as Form C, Appendix A). Array discharges across the top of the table, corresponding to the probability of exceedance. The range of flows should be from 90% to 50% exceedance flows, at 5 to 10% increments. Array species and life stages appropriate to the month down the left margin of the table. Record the total habitat for each life stage under the appropriate discharge (from Step 27). (Note: habitat ratios should be applied at this time if differential weighting will be given to different life stages.) Record the smallest area in each column at the bottom of the matrix table. The largest area in this row corresponds to the discharge that

minimizes habitat reductions across all life stages or food organisms (see Section 5.2.3a). Review Chapter 5 to understand assumptions and limitations of this approach. 31

31. Following the guidelines in Chapter 5, develop an annual series of recommended flows for each segment that give a zero reduction from existing habitat conditions. Reconcile differences between recommended monthly flows for all segments by a water balance (see Section 6.1.5). Develop several annual series of water-balanced alternatives that approximate the total habitat obtained when the recommended flows in each segment are added separately. These alternatives represent the zero reduction options. Repeat the process for several water-balanced alternatives that result in an approximately 10% reduction in the total habitat computed for the zero reduction. Repeat for 20%, 30%, ..., 100% reductions from the zero reduction option.

Reconcile the differences between flows needed to provide habitat and those needed for channel maintenance (refer to Section 6.2.2). The information developed in Steps 29, 30, and 31 are used in the negotiation of flow regimes. When these arrays have been completed and checked for consistency, the investigator should be well prepared for any negotiation. END

32. Checkpoint. You are attempting to compute the potential impact of a proposed action that may affect any or all of the following: channel structure; bed particle size; channel alignment; cover; flow regime; thermal regime; and/or water quality.

The first problem to be addressed is the distance that a perturbation will be transmitted through the system. Study areas should be set up to bracket the immediately impacted area and should extend upstream or downstream to a point where the effect of the perturbation is no longer discernible. This may require an iterative approach of redefining the limits of the study area. An initial estimate of the area involved in a study should be obtained from the project engineer or a consultant specializing in the subject area under study. This estimate is likely to be revised, so it is important to budget money, manpower, and lead time under the assumption that the study area will be expanded following the initial analysis.

Generally speaking, disturbances causing some form of channel disequilibrium are transmitted the furthest either upstream or downstream. However, channel changes that cause detectable differences in fish habitat are often confined to a length of stream much shorter than the total length involved in the channel change. Alterations in flow regime are attenuated as tributaries enter the stream. If the altered stream is itself tributary to a larger stream, the detectable impact may often stop at the confluence. Changes in many water quality constituents are often effectively attenuated in 3 to 5 day's travel time from the source.

Do not proceed without some estimate of the length of stream involved in the project analysis. Make your own estimate if necessary. The estimate will be revised pending further analysis. 33

33. Establish segment boundaries for the length of river estimated to be affected by the proposed action, as determined in Step 32. Do not include tributaries unless the effects of the action are expected to be transmitted to the tributaries or the analysis is designed to determine operating schedules for a network of reservoirs in a system. Select an appropriate number of representative or critical reaches in each segment. 34

34. Streamflow records for affected segments are unavailable or less than 10 years in length. 35

Streamflow records for affected segments are available for 10 or more consecutive years. 38

35. Streamflow records for affected segments are available but less than 10 years in length. 36

Streamflow records for affected segments are unavailable. 43

36. Examine the streamflow pattern for the period of record and compare with stations having longer periods of record. 37

37. The short period of record includes wet, average, and dry years roughly corresponding to 10%, 50%, and 90% exceedance flows for streams with longer records. 38

The short period of record shows persistence in water supply (consistently wet, consistently average, or consistently dry) compared to range of flows exhibited by streams with longer records. 43

38. Compute the following flow statistics for each affected segment:

a. the flood frequency recurrence interval curve;

b. the average of all daily flows for each month for the period of record (or a portion of the period of record if over 50 years); and

c. the flow duration curve for each month from daily flows for the month over the period of record. 39

(See Section 6.1)

39. Divide mean monthly flow (Step 38b) by median monthly flow (Step 38c). 40

40. The ratio between mean and median flows falls in the range of 0.75 to 1.25. 41

The ratio between mean and median flows is less than 0.75 or greater than 1.25. 42

41. Construct time series of discharges using mean monthly flows for period of record. 44

42. Construct time series of discharges using average weekly or average daily flows for the period of record. (Note: the suggested break-off point between using mean monthly, average weekly, and average daily flows is arbitrary. Average daily flows should certainly be used if the ratio between mean and median flows is around 0.1 or 2.0. Average weekly flows should be used when the ratio is outside the bounds of 0.75 to 1.25. 44

43. A synthetic flow time series must be developed. These may be available from the USGS, construction agency, or project sponsor. Use the same time step in the habitat analysis as in the project operation analysis, except when project operations are based on annual water supplies. The preferred time step is monthly, but seasonal or quarterly time steps are acceptable. Section 6.1 includes some of the techniques used to synthesize hydrographs. Accuracy varies considerably among the techniques and among hydrologic regimes. Flow estimates near the median condition are much more accurate than estimates of extreme conditions, although the difference in accuracy cannot be discerned once the flow time series has been assembled. 44

44. The proposed action may affect sediment yield, water yield, or nonpoint source pollution from the watershed. 45

The proposed action will have no direct effect on the watershed. (See Section 2.3) 48

45. Consult expert(s) in watershed sciences, sediment transport, and channel dynamics. 46

46. The proposed action is sufficient to cause one or more of the following changes (concensus of watershed specialist):

1) any significant change in the frequency of bankfull discharge;

2) a 10% change in median base flow;

3) any discernible change in channel morphology;

4) any discernible change in median particle size of the surface layer of the bed or in the percentage of fines (< 2 mm) in the substrate matrix;

5) any discernible change in bankside vegetation; and

6) any discernible change in water quality. 47

The proposed action will not significantly affect any of the above mentioned factors. END

47. Measure present channel shape, dimensions, bed particle size, and cover distribution in each representative or critical reach selected in Step 33. (See Chapter 7 and Bovee and Milhous (1978) or Trihey and Wegner (1981). 48

48. The proposed action will result in a change in channel structure (shape, alignment, particle size, or cover), either inadvertently or intentionally (i.e., channelization). 49

The proposed action will not result in a change in channel structure (shape, alignment, particle size, or cover). 52

49. The resultant channel shape, dimensions, and particle size of bed materials cannot be determined through consultation or other means. 50

The resultant channel shape, dimensions, and particle size of bed materials can be estimated through consultation or other means. 51

50. Stop! The disturbance involves an unquantifiable channel change. It is virtually impossible to quantify the true impact on the biological community without this information. The assumption of no change must not be made simply to enable an investigator to proceed with some kind of analysis. This is an extremely dangerous assumption. The preferred approach is to intensify efforts to determine the channel change or to instigate remedial measures on the watershed or in the channel that will guarantee that no significant channel change will occur. This may require a second opinion from another channel dynamics specialist. Do not proceed unless these measures have been taken. 49

51. Determine the "new" equilibrium channel structure, dimensions, particle sizes of bed materials, and distribution of cover features. Determine the new length of channel if realignment is anticipated. Retain this information for later use in water quality or microhabitat analysis. 52

52. The proposed action will not alter the flow regime, water quality, or thermal regime. 53

The proposed action will alter flow regime, water quality, or thermal regime. 54

53. Using the present species composition list and species periodicity charts, compute the physical habitat availability for appropriate target species and life stages in the present channel for a range of existing monthly flows from the 90% annual exceedance to the 10% annual exceedance flows. Convert habitat available per 1,000 feet to habitat available per mile and multiply by the number of miles represented by the study reach having suitable water quality and temperature.

Compute the physical habitat availability in the projected channel (Step 51) for the same target species and range of flows used to describe the present conditions. Convert habitat available per 1,000 feet to habitat available per mile and multiply by the number of miles having suitable water quality and temperature. Repeat for all study reaches. 60

54. The proposed action will affect the heat budget of the stream (e.g., thermal pollution, reduction in shading, hypolimnetic release, or alteration in flow). 55

The proposed action will not affect the heat budget of the stream. 57

55. Determine the monthly temperature profiles for the present channel from source of perturbation to lowermost point on study reach. Develop such a profile for each stream segment defined in Step 33 for a range of flows from the present 90% exceedance to the 10% exceedance flow.

Develop the same type of temperature profiles representing the new hydraulic or thermal conditions of the stream segment, including, where applicable:

a) new starting water temperature;
b) new channel configuration;
c) new shade factors; and
d) new flow regime, arrayed from new 90% to new 10% exceedance flows.

Note: Flows in the 80 to 90% exceedance range are often associated with droughts. It may be desirable to input meteorological conditions associated with a drought for the low flows in both the present and new temperature profiles. 56

56. Review periodicity charts and species distribution lists for each stream segment in its present condition. If changes in thermal regime determined in Step 55 are sufficient to alter spawning times, incubation period, or turnover time from fry to juvenile or juvenile to adult, construct a parallel species periodicity chart corresponding to the new thermal regime. The species periodicity charts for both the present and the future conditions may need to be altered for the more infrequent flow events. Retain all sets of species periodicity charts for later use in microhabitat analysis. 57

57. The proposed action will alter the concentrations of water quality constituents in the watercourse (change in loading rates or change in dilution volume) or will alter the reaction rates of nonconservative constituents (change in temperature or stream hydraulics). 58

The proposed action will not alter the concentrations of water quality constituents or their reaction rates. 59

58. Determine the monthly concentration profiles for each affected water quality constituent for the present channel from the source of disturbance to the lowermost point on the study area. Develop such a profile for each stream segment defined in Step 33 for a range of flows from the present 90% exceedance to the 10% exceedance flow.

Develop the same type of concentration profiles representing new hydraulic, thermal, or initial concentration conditions of the stream segment, including the following, where applicable:

a) new loading rates of pollutants, including nonpoint sources where watershed disturbance is a factor;
b) new hydraulic conditions associated with channel or flow regime change;
c) new thermal regime (from Step 55); and
d) new flow regime, arrayed from new 90% to new 10% exceedance flows. 59

59. Record the range of existing flows for the segment, from the 90% to the 10% exceedance flows in Column A, Form B (Appendix A). Record projected flows for the same range of exceedance values on a separate Form B. Be sure to lable forms appropriately for without project or with project conditions. Several forms may be needed to reflect monthly variations in thermal or pollution loading.

Record the length of stream in the segment having satisfactory temperature and water quality (from Steps 55 and 58) for each existing and projected flow value and for each life stage, in Column D, Form B (Appendix A). Be sure to lable forms appropriately for without project or with project conditions. 60

60.a. Compute microhabitat availability for each life stage, for each stream segment under the existing channel configuration and flow regime. Array availability information for the range of flows from the existing 90% exceedance to 10% exceedance flows.

Convert habitat available per 1,000 ft to habitat available per mile and multiply by the number of miles in the stream segment having suitable temperature and water quality (from Form B, without project conditions). Record the total habitat availability for each life stage under without project conditions under Column F, Form B.

b. Compute the physical habitat availability for each life stage, for each stream segment, under projected conditions of channel configuration and flow regime. Array these data for the projected range of flows from the projected 90% to the projected 10% exceedance flows. Convert the projected habitat available per 1,000 ft to habitat per mile and multiply by the number of miles projected to have suitable temperatures and water quality (from Form B, with project conditions). Record total projected habitat availability for each life stage under the appropriate percent exceedance flow for conditions representing alterations due to a proposed action on Form B, with project conditions. 61

61. Combine total habitat vs. discharge function (Step 60a) for existing channel, temperature, and water quality conditions with flow time series from Step 41, 42, or 43 to develop total habitat time series without project. Repeat for all life stages and food organisms. 62

62. Modify flow time series from Step 41, 42, or 43 to reflect project operation. Combine total habitat vs. discharge function (Step 60b) for projected channel, temperature, and water quality conditions with new flow time series to develop total habitat time series with project. Repeat for all life stages and food organisms. 63

63. Impact will be defined in terms of available habitat for all life stages and/or food organisms. 64

Impact will be defined in terms of utilized adult habitat for evaluation species. (see Section 5.2.3) 65

64. Construct habitat duration curve for each life stage with and without project. Integrate area beneath both curves between 50% and 90% habitat exceedance values (see Sections 5.2.2 and 5.2.3). Project impact is defined as the difference in area between these two curves. Review Chapter 5 on assumptions and limitations of this approach. 68

65. Determine habitat ratios among appropriate life stages or food organisms based on population and trophic level structure (see Section 5.2.4). 66

66. Construct a life table similar to Table 12 for the number of years in the habitat time series from Steps 61 and 62. Add extra rows for multiple-year subadult life stages if necessary. Construct one life table for existing conditions and one for each project design alternative. Plot time series of effectively utilized adult habitat for existing and proposed conditions. 67

67. Integrate area beneath utilized habitat curves for existing conditions and each project design alternative. Project impact is defined as the difference in area beneath curves

over the total time series. Note the distinction between this definition and the one in Step 64. Review Chapter 5 on assumptions and limitations of this approach. 68

68. Develop mitigation plan. If water quality or temperature is responsible for the most change (reduction) in habitat availability or utilization, reenter the analysis at Step 52, simulating the system under one or more of the following mitigative measures:

a) Increasing the discharge during appropriate months;
b) Altering the thermal regime by changing the initial water temperature (i.e., multilevel reservoir release), reducing thermal inputs, or increasing the shade factor (i.e., planting trees); or
c) Changing the concentration profiles of water quality constituents by dilution or advanced treatment or changing their reaction rates by modififying temperature or hydraulics.

If physical microhabitat limitations appear to be responsible for most of the habitat reduction, reenter the analysis at Step 60, simulating the system under one or more of the following mitigative measures:

a) Increasing, decreasing, or otherwise redistributing flow over time (this implies storage somewhere in the system; and/or
b) Altering the channel structure to take better advantage of the available flows. Refer to Chapter 8 discussion.

If habitat reductions appear to be correlated to both macro- and microhabitat limitations, experiment with different combinations of all the above listed measures. Prepare a series of alternatives for each mitigation strategy in the same manner as the impact analysis was done. END

5. PREPARATION AND INTERPRETATION OF RESULTS

Chapters 1 through 4 have dealt with setting up and conducting an instream flow or project impact study. Having completed the analytical sequence described in Chapter 4, the investigator will have produced a tremendous volume of information. It is necessary to reduce the volume, while retaining the essence, if this information is to have any utility. The objectives of this chapter are to detail the distillation process and to provide some guidelines regarding interpretation of the results. These two objectives fall under the general category of preparing the investigator for the negotiation process. The goal of negotiation, from the perspective of the fisheries manager, is to retain the most fish habitat possible within the constraints of available water supply and feasible project operation. This chapter discusses a variety of methods which can be used to realize this goal and to prepare negotiating positions.

A secondary objective of this chapter is to show how the IFIM can be used with another habitat analysis methodology developed by the U.S. Fish and Wildlife Service, the Habitat Evaluation Procedures (HEP). HEP was designed to evaluate project impacts and mitigation alternatives and, because the IFIM can be applied to the same types of problems, considerable confusion has resulted regarding the interface between the two methods. The two approaches are conceptually similar, but differ significantly in some respects. The primary utility of the HEP procedures is in the comparison and evaluation of very different types of habitat, such as the replacement of winter range for deer with a reservoir. Output from the IFIM can be used in HEP whenever one of the affected habitats is a river. However, when river flow is the only habitat variable to be affected, output from IFIM can be used alone to conduct mitigation analysis and to develop a flow regime for project operations. The following sections describe points of entry of IFIM output as input to HEP and the use of IFIM output in mitigation planning.

Two types of analyses are commonly performed in an instream flow or project impact study: disjunctive use and conjunctive use analyses. Disjunctive use analyses are made to determine the water requirements for different kinds of instream management objectives. Disjunctive uses require some sort of internal trade-off decision that can only be made by the investigator. One example of a disjunctive use analysis is the determination of water requirements for channel maintenance, as opposed to those for maximizing fish habitat. It is possible that the flow required for channel maintenance may conflict with the flow needed for fish habitat. The investigator must determine whether channel maintenance or fish habitat is more important. A compromise flow may be difficult, if not impossible, to determine. If the stream is controlled, it may be possible to reschedule the time of the channel maintenance flow and reduce the conflict. However, one use or the other must prevail in many cases.

Conjunctive use analysis incorporates inclusive aspects of flow and availability of fish habitat. Much of this chapter deals with the analysis of water availability, physical habitat, and water quality, as related to fish habitat usability. This analysis incorporates all three considerations in such a way that the flow versus habitat relationship is complementary. The objective of a conjunctive analysis is to develop systemwide flow alternatives and corresponding amounts of total habitat. The number of alternatives increases as more streams and segments are incorporated in the analysis.

5.1 INTEGRATION OF MACROHABITAT AND MICROHABITAT

An application of the Incremental Methodoloy will result in one or more sets of habitat-related information. These data usually require some manipulation before they can be interpreted. The first set of data for each life stage and measured study site is a functional relationship between suitable microhabitat area and discharge. A second data set contains relationships between suitable water quality and discharge along a longitudinal profile of the stream. All applications of the method utilize the first set of output data, whereas only some applications necessitate the second set.

The primary output of the physical habitat simulation system (PHABSIM) is a measure of usable microhabitat called weighted usable area (WUA). A description of this model is in Chapter 7. Weighted usable area is a discrete value for each representative or critical reach, each life stage and species, and each flow occurring in the reach. There are numerous ways of displaying this output, but the most common are a summary table and a plot of weighted usable area against discharge. Either display describes a unique functional relationship between microhabitat availability and streamflow for the represented section of stream.

The only time that the microhabitat area vs. discharge function can be used without modification is when a single site is used to describe an entire river, and water quality is not a consideration. The total available habitat for a given life stage at any discharge is defined as the microhabitat area per unit length of stream (unit WUA) multiplied by the length of stream in the segment having suitable water quality and temperature. There are several variations of this basic relationship depending on the characteristics of the segment. These variations are described for the four most common types of segments:

1. Segments represented by one site, water quality suitable throughout;
2. Segments represented by one site, water quality not suitable throughout;
3. Segments represented by multiple sites, water quality suitable throughout; and
4. Segments represented by multiple sites, water quality not suitable throughout.

5.1.1 <u>Segments Represented by One Site, Water Quality Suitable Throughout</u>

The simplest integration of total habitat occurs in river segments where the macrohabitat characteristics of water quality and temperature are satisfactory for all species and life stages, and only one study site is used to describe the entire segment. The total habitat available at a given discharge is simply the product of the available weighted usable area per unit length of stream and the total length of stream within the segment.

$$HA = WUA \times L \tag{5-1}$$

where HA = total stream segment habitat area in ft^2 or m^2

WUA = segment weighted usable area in ft^2/mile or m^2/km

L = length of stream having suitable water quality and temperature, in miles or kilometers

5.1.2 Segments Represented by One Site, Water Quality Not Suitable Throughout

The term L, from Equation 5-1, will not equal the total length of stream in the segment at all discharges when water quality is not suitable throughout the segment. Two pieces of information are needed to determine the value of L for any flow. The first is a longitudinal profile of the concentration of a specific water quality constituent or the temperature under a given set of discharge and constituent load conditions. The second is an evaluation of the tolerances or preferences of the evaluation species to temperature or constituent concentrations.

A water temperature model (see, for example, Theurer 1982), run for a range of discharges from 20 to 65 cfs, might result in a series of longitudinal temperature profiles as illustrated in Figure 10. For this example, suppose that the evaluation species is brown trout, the life stage is adult, and the upper suitable temperature is a weekly average of 23.3° C. The temperature in the entire segment is suitable for adult brown trout at all flows in excess of 40 cfs. However, at 30 cfs, the 23.3° threshold is crossed at 17 miles and at 20 cfs, only about 14 miles of the segment have suitable temperatures.

Equation 5-1 assumes the use of binary water quality criteria; i.e., water quality is either suitable or unsuitable. A variation of this technique is to define a species' preferences and tolerances for a water quality parameter as a curve (Figure 11).

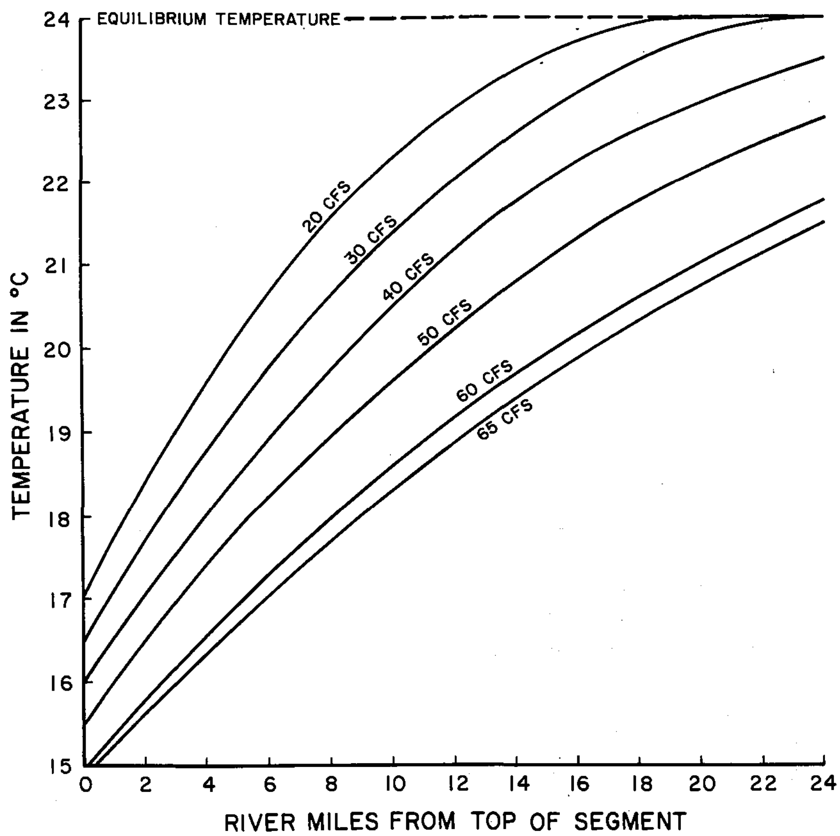


Figure 10. Temperature profiles for a range of August discharges from 20 to 65 cfs.

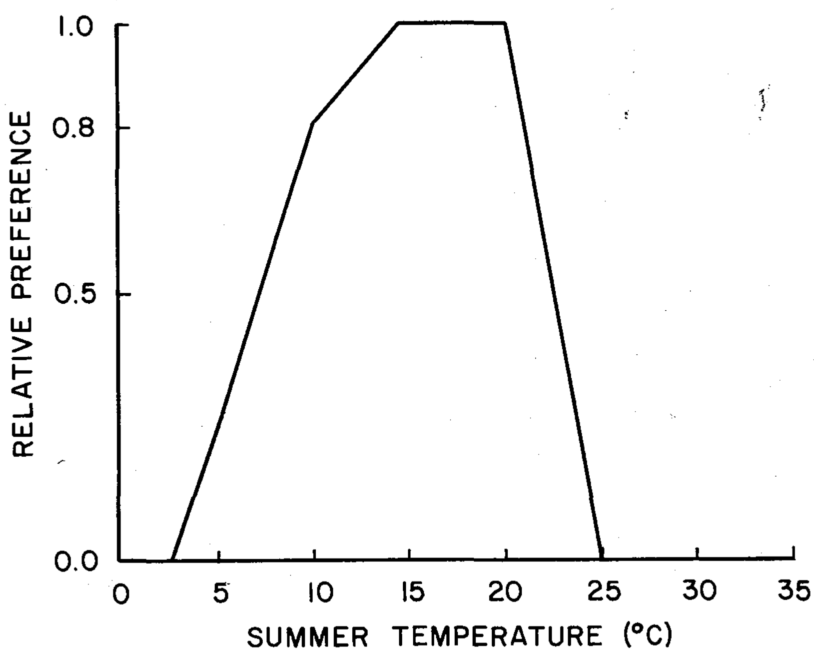


Figure 11. Example of a temperature preference curve.

The equation used to compute total habitat area in the segment using the type of criteria illustrated by Figure 11 is:

$$HA = WUA \times L_1 \times PF_1 + WUA \times L_2 \times PF_2 + WUA \times L_n \times PF_n \qquad (5\text{-}2)$$

where

HA = the total habitat area in ft^2 or m^2

WUA = segment weighted usable area in ft^2/mile or m^2/km

$L_1, L_2 \ldots L_n$ = a unit length of stream within the segment

$PF_1, PF_2, \ldots PF_n$ = a preference factor for the water quality or temperature of each unit length of stream

Water quality models used in the Instream Flow Incremental Methodology, most notably the Stream Simulation and Analysis Model (SSAM IV, Grenney and Kraszewski 1981), can be used to predict longitudinal concentrations of various water quality constituents and water temperatures at different discharges. Other water quality models may also be used, if it is more convenient to do so. The user must select and evaluate the water quality and temperature criteria that determine the usable length of a section. There are several sources of water quality criteria for the types of constituents that can be modeled by SSAM IV. The most current set of water quality criteria published by the U.S. Environmental Protection Agency is contained in Quality Criteria for Water, otherwise known as the red book (U.S. Environmental Protection Agency 1976).

Another source of water quality criteria is A Review of the EPA Red Book: Quality Criteria for Water (Thurston et al. 1979). In addition, each State has the option of setting its own water quality standards if they are more stringent than the Federal standards. Each of these sources contains criteria for the common water quality constituents although they may not contain criteria for the more exotic compounds that sometimes enter streams. However, most water quality models do not deal with exotic chemicals and the study of these materials is beyond the scope of an instream flow study.

The user must decide whether to evaluate water quality constituents independently or in combination. The job is easier when the constituents are evaluated individually because the criteria are simply matched with the predicted concentration of each constituent. If the synergistic effects of two or more constituents are evaluated, the determination is more difficult. The user must also determine whether the criteria reflect average daily (or even monthly) conditions or short term extremes. The SSAM IV water quality model can predict water quality concentrations under either time frame, although predictions of mean conditions are more accurate.

5.1.3 Segments Represented by Multiple Sites, Water Quality Suitable Throughout

The relationship between habitat availability and streamflow is determined by measuring the habitat at a representative or critical reach. There may be more than one representative reach in the segment, if habitat types vary within the segment. Therefore, a stream length within each segment must be assigned to each representative or critical reach. This stream length is called a represented segment length and is determined from topographic maps, aerial photographs, and from field inspection (ground truth). Figure 12 and Table 7 illustrate this process. Table 7 is a completed Form A (Appendix A) containing a rather detailed description of the geography and hydrology of the segment. Segments and reaches must be uniquely identified and data kept organized if two or more segments are used in the analysis.

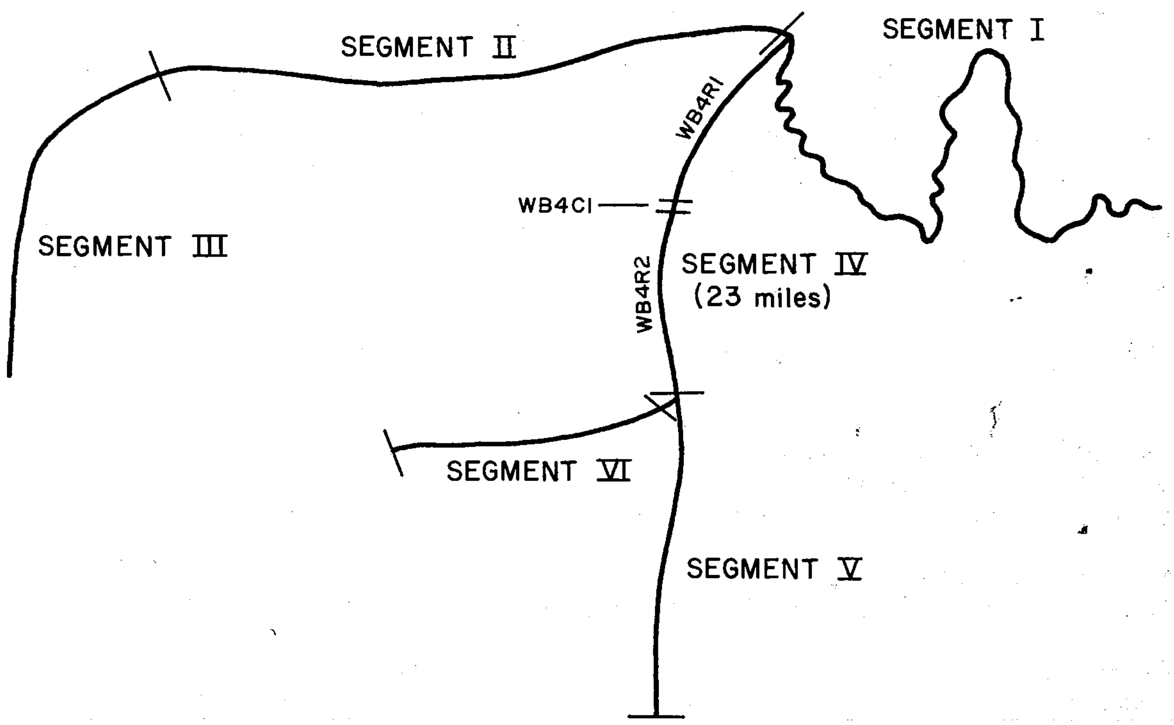


Figure 12. Map of a segmented stream network showing locations of three represented segment lengths in segment IV.

Table 7. Example of segment related information contained in Form A (Appendix A).

Stream name: West Branch Smith River

Segment number: IV

Segment boundaries: upstream river mile 23 downstream river mile 0

Number of representative reaches in segment: 2

Number of critical reaches in segment: 1

Nature of critical reach(es): spawning ______ ______

Passage barriers downstream? yes ____ no x

Computation of represented segment lengths:

Study site ID	River miles to bottom of represented section from lower segment boundary	River miles to top of represented section from lower segment boundary	Length of segment represented
WB4R1	0	15	15 miles
WB4C1	15	16.5	1.5 miles
WB4R2	16.5	23	6.5 miles

Streamflow characteristics:
Dominant discharge for segment (attach flood frequency recurrence interval curve) 150 cfs

Monthly streamflow distribution:
[attach monthly flow duration or recurrence interval curves (12)]

Exceedance probability	O	N	D	J	F	M	A	M	J	J	A	S
	Month											
10%												
50%	30	25	28	30	32	50	35	180	240	90	40	25
90%												

The total habitat for a given flow, species, and life stage in a segment with multiple study sites is computed by Equation 5-3:

$$HA = WUA_1 \times L_1 + WUA_2 \times L_2 + \ldots WUA_n \times L_n \qquad (5\text{-}3)$$

where HA = total habitat area in ft^2 or m^2

WUA_1 = weighted usable area per unit length of stream represented by the first study site

L_1 = the length of stream represented by the first study site

WUA_n = weighted usable area per unit length of stream represented by the n^{th} study site

L_n = the length of stream represented by the n^{th} study site

5.1.4 Segments Represented by Multiple Sites, Water Quality Not Suitable Throughout

Equation 5-3 is also used to compute the total habitat in a segment having multiple sites and unsuitable water quality through some portion of the segment. As discussed in Section 5.1.2, the value of L for one or more of the represented sections may not equal the total length of the section.

The water quality profile is an overlay for the entire segment, parts of which are represented by different reaches. It is necessary to match the length of stream having suitable temperatures with the appropriate represented section. This can be done by marking the represented section boundaries on the profile (Figure 13).

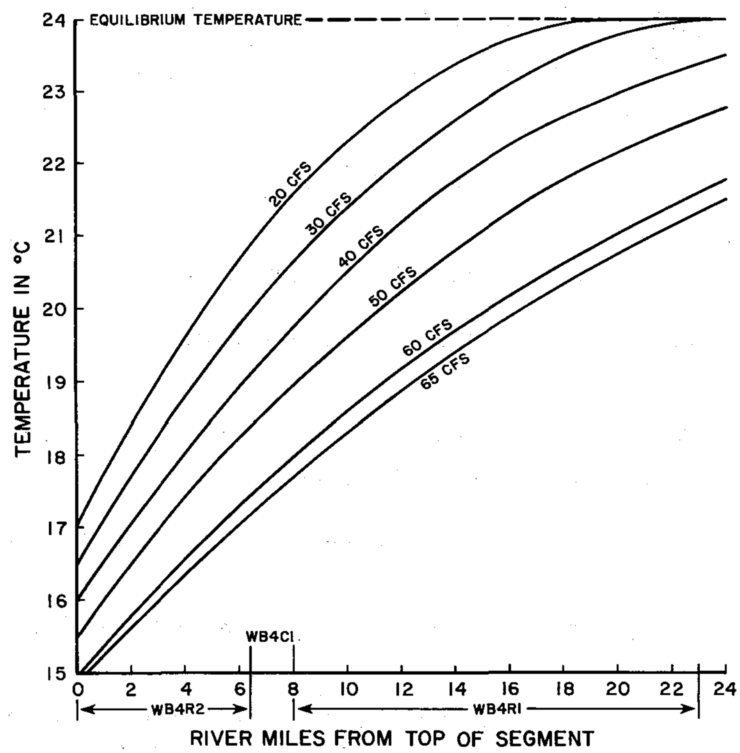


Figure 13. Example of temperature profile overlaid on a segment having multiple study sites (from Figure 12).

Each represented section, as shown in Figure 13, can be treated as a "mini-segment," using Equation 5-1 or 5-2 to compute total habitat area and then summing the values for all the sections. Figure 14 shows the relationship between unit weighted usable area and discharge for the three represented sections of segment IV (Figure 12). The computation of the total habitat in this segment for adult brown trout from 10 to 150 cfs is shown in Table 8. The results from Table 8 give total segment habitat areas for one life stage at one time of the year. The same process must be repeated for each life stage and evaluation species. It is also likely that the process will have to be repeated for other time periods. Total habitat should be computed for summer and nonsummer conditions, at the very least, and may need to be computed monthly during the summer. The results from each set of computations are summarized and entered on Form B in Appendix A. It is anticipated that this process will eventually be computerized. At present, the more tedious hand calculations must be performed.

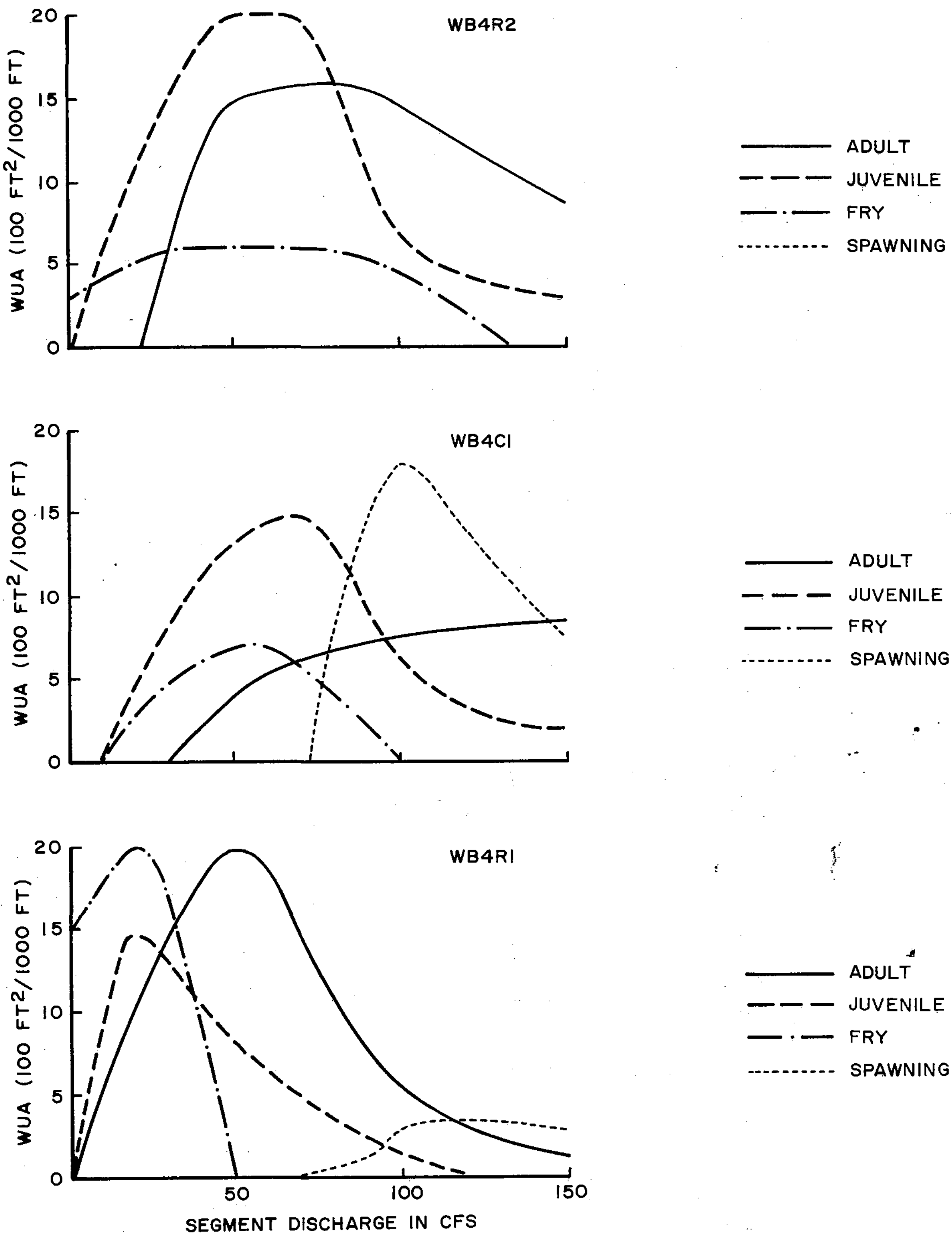


Figure 14. Weighted usable area for brown trout vs. discharge for three study reaches in segment IV of example.

Table 8. Computation of total habitat for adult brown trout in a segment having three study sites and unfavorable temperature conditions.

	WB4R2			WB4C1			WB4R1			
Segment Discharge	Unit WUA (ft²/mile)	Usable length (miles)	Section subtotal (ft²)	Unit WUA (ft²/mile)	Usable length (miles)	Section subtotal (ft²)	Unit WUA (ft²/mile)	Usable length (miles)	Section subtotal (ft²)	Segment total (ft² × 1,000)
10	0	6.5	0	0	1.5	0	3,170	2.0	6,340	6.3
20	0	6.5	0	0	1.5	0	5,800	5.5	31,900	31.9
30	2,640	6.5	20,600	0	1.5	0	7,920	9.0	71,300	91.9
40	6,870	6.5	44,600	1,070	1.5	1,600	9,500	14.0	133,100	179.3
50	7,920	6.5	51,500	2,130	1.5	3,200	10,560	15.0	158,400	213.1
60	8,030	6.5	52,200	2,670	1.5	4,000	9,770	15.0	146,500	202.7
70	8,300	6.5	53,900	3,170		4,800	7,660	15.0	114,900	173.6
80	8,450	6.5	54,900	3,430		5,150	5,540	15.0	83,100	143.2
90	8,180	6.5	53,200	3,700		5,550	3,700	15.0	55,500	114.3
100	7,870	6.5	51,100	3,960		5,900	2,640	15.0	39,600	96.6
110	7,130	6.5	46,300	4,220		6,300	2,110	15.0	31,700	84.3
120	6,340	6.5	41,200	4,360		6,500	1,580	15.0	23,700	71.4
130	5,810	6.5	37,800	4,490		6,700	1,190	15.0	1,7900	62.4
140	5,280	6.5	34,300	4,620		6,900	920	15.0	13,800	55.0
150	4,490	6.5	29,200	4,750		7,100	790	15.0	11,850	48.2

5.1.5 Optional Conversion of IFIM Output to HEP Input

The Habitat Evaluation Procedures (HEP) are based on the premise that present and future habitat conditions can be displayed with two variables: a habitat suitability index and the surface area of a habitat type. These two variables are combined into an index of habitat availability, called a habitat unit:

$$HU = HSI \times A \tag{5-4}$$

where HU = habitat units for an evaluation species, a group of species, or a life stage

HSI = a dimensionless habitat suitablity index bounded by 0.0 and 1.0, where 0.0 represents no habitat and 1.0 represents optimal habitat

A = the surface area of a specific habitat type

One difference between total habitat area (HA) computed with IFIM and habitat units (HU) with HEP, is the number of life stages and species represented by the index. Total habitat area (HA) is computed separately for each life stage in the IFIM, but habitat units may represent one life stage, a species, or several species. If habitat units are used to represent a single life stage, then HU and HA are virtually synonymous.

When habitat units refer to multiple life stages, one approach to using IFIM output in the Habitat Evaluation Procedures is to convert total habitat area for each life stage into a habitat suitability index. This conversion can be made by dividing the total habitat area by the surface area of the segment, as suggested in the HEP manuals (U.S. Fish and Wildlife Service 1980). Besides the obvious redundancy of converting one measure of total habitat area into another, there are several reasons that this conversion is not recommended.

First, the IFIM output is very precise; this precision is lost when an output is reduced to a single, average value. Second, the extensive data collection and processing for IFIM is probably a waste of time and money if all that is desired is an average value for an HSI. Third, the principal reason for computing an HSI is to determine habitat units and, ultimately, habitat unit-years. There are better ways to determine habitat unit-years from IFIM output than reducing it to a single HSI. These techniques are discussed in Sections 5.2.2 and 5.2.3.

5.2 HABITAT DISPLAY AND INTERPRETATION

Figure 14 shows a typical habitat display provided by the PHABSIM program. This display is useful because it shows changes in physical habitat for each life stage of the evaluation species as the discharge is raised or lowered in the segment. Unfortunately, this information is usually insufficient for the formulation of recommendations regarding instream flow requirements or mitigation plans. The points on the curves that seem to have the most importance are places where the curve reaches a maximum value or zero. The maxima and minima are often unrealistic representations of the amount of habitat actually available in the stream. For example, if there was an inexhaustible supply of water and any desired amount could be reserved for instream flow, the logical choice would be to pick a flow which would provide the most habitat. Referring to Figure 14, the maximum amount of adult habitat occurs at 90 cfs in section WB4R2, at 150 cfs in section WB4C1, and at 60 cfs in section WB4R1. Fry habitat is completely eliminated in section WB4C1 at all flows exceeding 100 cfs and in WB4R1 at all flows exceeding 50 cfs. This example illustrates several concepts related to the development of water allocation and mitigation plans:

1. A flow that is beneficial to one life stage may be detrimental to another life stage;

2. A flow that is beneficial to one species may be detrimental to another;

3. Various life stages and species may require different amounts of water at different times of the year;

4. A flow that maximizes usable habitat in one part of the stream may not provide very much usable habitat in another part of the same stream; and

5. More water does not necessarily mean more habitat.

Some of these issues are resolved by examining several sections at once and determining the total habitat for a segment over a range of flows. Figure 15 is a plot of the total adult brown trout habitat in segment IV as a function of discharge under summer and nonsummer conditions. Total habitat for adult brown trout is maximized in this segment at a flow of 50 cfs, but there is no spawning habitat available in this segment at this flow (Figure 14). Obviously, the relationship between total habitat and discharge is an essential piece of information, but not the only one. Some knowledge about the annual water supply is at least as important as the habitat - discharge relationship. Furthermore, spawning, incubation, and rearing of fry are usually seasonal activities and adult fish may not live in the stream year-round. Therefore, knowledge about species periodicity is also required.

Riverine impact analysis and instream flow studies differ from other types of environmental analyses in one significant manner. Changes in habitat in either case must be quantified not only in regard to amount, but also in regard to frequency. All the habitat display and interpretation techniques in this chapter incorporate the concept of frequency, either as a probabilistic or stochastic process. A probabilistic process is considered time independent, whereas a stochastic process is time dependent. Most hydrologic events are stochastic in character but are reduced to probabilistic terms to simplify analysis (Chow 1964).

The display and interpretation techniques that follow are arranged from simple to complex. In addition, one interpretation technique may complement

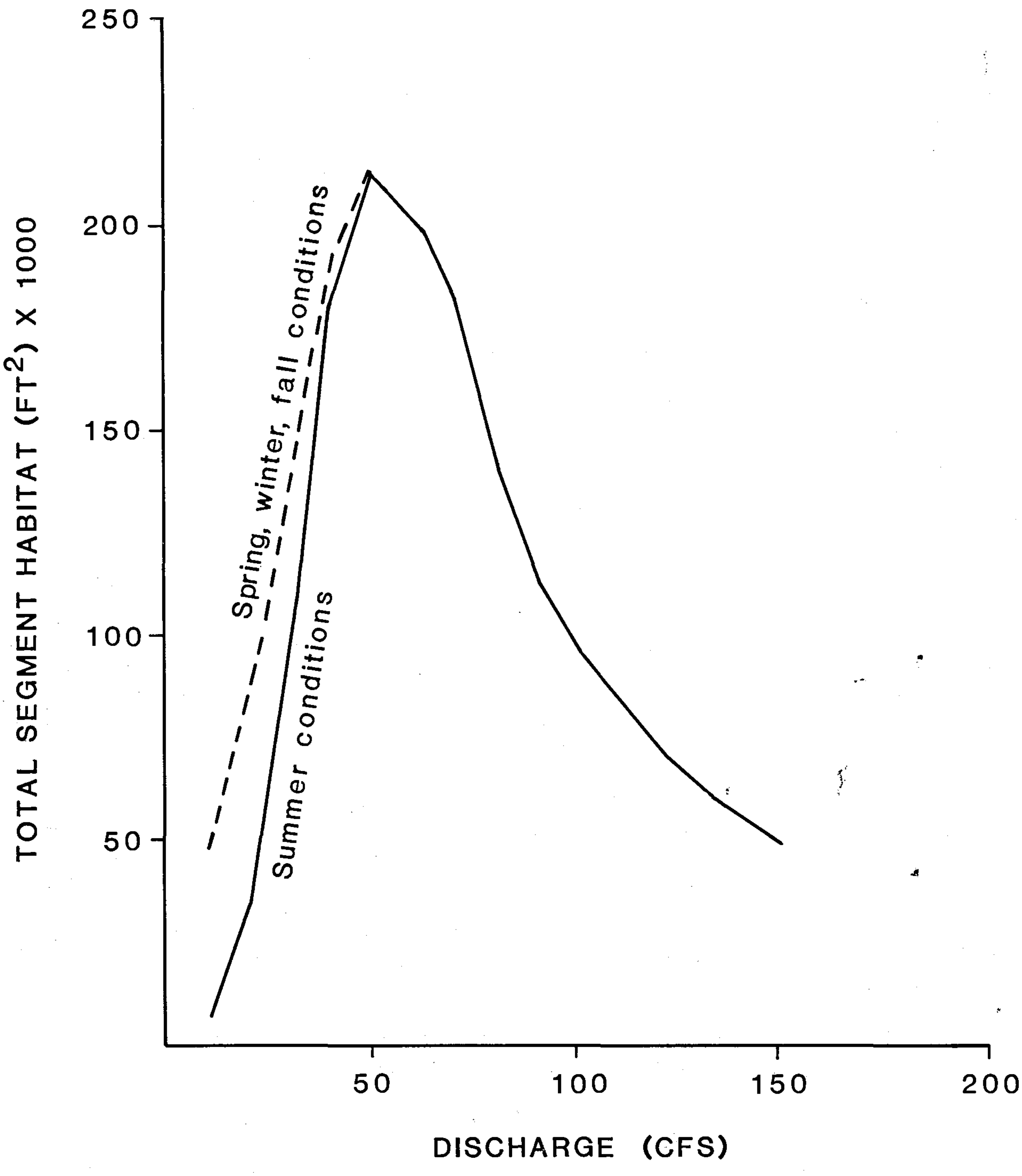


Figure 15. Total adult brown trout habitat in segment IV as a function of discharge under summer (solid line) and nonsummer conditions (dashed line).

or supplement another so the investigator has a variety of options to choose from. The goal of any interpretive technique is to make it easier to solve problems, as was the case when the three habitat functions (Figure 14) were combined into a single function (Figure 15). The law of diminishing returns can operate at any level of analysis; i.e., a more complex analytical technique may not result in a better or easier solution than would a simpler technique. The essential difference between simple and complex techniques is that simple techniques are usually based on one or two large assumptions. Complex solutions require more, but usually smaller, assumptions. Therefore, the investigator should understand three things before selecting an interpretive technique:

1. The complexity of the problem;

2. The complexity of the solution technique; and

3. The assumptions inherent to the solution technique.

The best interpretive technique for a problem is the one that provides an insight into the problem and suggests a solution without requiring assumptions the investigator is unwilling to accept or defend.

5.2.1 Optimization Techniques

Optimization techniques are used to determine combinations of conditions which yield the best mix of benefits or which minimize negative impacts. Such techniques are often used by environmental engineers to determine the amount of treatment required of waste dischargers to meet water quality standards without imposing stricter requirements (and economic liabilities) on those the furthest downstream. A similar approach can be used in an instream flow study to select the flow for a particular month of the year that has the least detrimental effect on different organisms.

The flow which gives the best mix of habitat availability for any month can be determined by using an optimization matrix. Matrices are developed for each month of the year as follows. First, the range of flows which have occurred during that month over the period of record are arrayed across the top of the matrix according to the probability of exceedance read from the flow duration curve for the month. The typical range of exceedance probabilities for instream flow studies is from 90-95% to 50%. The calculation of flow exceedance is discussed in Chapter 6.

The second step is to array the life stages of each evaluation species present in the stream segment during the month of interest down the left side of the matrix. Third, referring to the habitat vs. discharge curves (i.e., total segment habitat as in Figure 15), record the total habitat for each life stage corresponding to the flows entered at the top of the table. Table 9 represents a completed optimization matrix. A blank copy of this matrix is provided in Appendix A.

Table 9. Analysis of habitat availability over a range of flows for the month of August. Record total habitat for each life stage beneath each recorded discharge.

Evaluation species and life stage	Discharge (% exceedance)				
	20 cfs (90%)	30 cfs (80%)	40 cfs (70%)	50 cfs (60%)	65 cfs (50%)
Brown trout					
Fry	15,840	29,100	38,100	26,100	25,600
Juvenile	49,650	87,000	113,100	127,500	123,800
Adult	31,944	91,900	179,300	213,100	193,300
Minimum HA value in column	15,840	29,100	38,100	26,100	25,600

To determine the optimum flow for the mix of life stages and species, scan each column and record the smallest value at the bottom of the column. After recording the minimum value for each column, scan across this row of numbers and circle the largest number. This value corresponds to the flow which maximizes the habitat in least supply.

A matrix is developed for each month of the year by changing the flows across the top of the table and life stages down the side to reflect the water supply and species' utilization of the segment over time. Finally, a hydrograph of the circled flows is constructed. This hydrograph represents the "preferred scenario" because the flows recorded in the hydrograph will minimize habitat losses and, concurrently, meet the criterion for water availability. During negotiations, counter proposals will be made for different amounts of water than the recommended flow regime. It is important to remember that the recommended flow regime is one that currently exists, or could exist, in the stream. Any counter proposal for less than the recommended flow for a month represents a deviation from the amount of habitat currently available. The amount of deviation can quickly be determined from the tables. Months where the available flow greatly exceeds the recommended flow can also be identified from the matrix tables. During these months, water could be removed from the stream with no loss, and possibly a gain, in habitat.

The optimizing flow in Table 9 is 40 cfs, with fry habitat the assumed limiting factor. Adult and juvenile habitat are maximized at 50 cfs. This illustrates the need to examine the whole table, not just the bottom row of numbers, especially if habitat for some life stage or species is of special concern. This is particularly evident in the habitat reduction that occurs between 40 cfs and 30 cfs. Fry habitat is reduced by slightly over 20% with this flow reduction, but adult habitat is nearly halved.

Two assumptions are inherent in the use of the optimization matrix as exemplified by Table 9. First, the habitat requirements for each month are assumed independent of all other months. The best way to avoid this assumption is to analyze habitat in time series, as discussed in Section 5.2.2 The second assumption implied by Table 9 is that all life stages and species have the same relative spatial requirements. This assumption can be avoided by weighting the total habitat area for each life stage according to its relative space requirements or for each species according to its priority from a management perspective. The use of relative spatial requirements, called habitat ratios, in the optimization matrix is illustrated in Table 10, where a ratio of 5:1 was assumed between adults and fry and a ratio of 1.5:1 between adults and juveniles. (Adults are assumed to require 5 times more space than fry and 50% more than juveniles). The matrix approach optimizes the habitat minima, so the weighting factors are applied to the two subadult life stages. A loose interpretation is that 38,000 square feet of fry habitat could ultimately produce enough adults to fully utilize 190,000 square feet of adult habitat. Derivations of habitat ratios, and their implications, are discussed in Section 5.2.4

Table 10. Optimization analysis of habitat availability using weighting factors to reflect relative spatial requirements among life stages. Fry and juvenile habitat from Table 9 weighted by factors of 5 and 1.5, respectively.

Evaluation species and life stage	Discharge (% exceedance)				
	20 cfs (90%)	30 cfs (80%)	40 cfs (70%)	50 cfs (60%)	65 cfs (50%)
Brown trout					
Fry	79,200	145,500	190,000	130,500	128,000
Juvenile	74,475	130,500	169,650	191,250	185,700
Adult	31,944	91,900	179,300	213,100	193,000
Minimum HA	31,944	91,900	169,650	130,500	128,000

Although the optimizing flow in Table 10 is the same as the one determined in Table 9, significant interpretations can be made regarding the other flows, particularly the flow increment from 40 cfs to 30 cfs. When the habitat areas are evaluated from the perspective of unequal space requirements, the reduction in adult habitat appears to have added significance and is probably a better representation of the true impact.

5.2.2 Time Series Analysis and Habitat Duration Curves

A time series is a sequence of events, arranged in order of occurrence. The discharges listed for a station in the USGS Water Supply Papers constitute a time series of streamflow data. Every discharge flowing through a segment has an associated area of habitat. A time series of habitat data can be constructed by interfacing a time series of streamflow data with the functional relationship between streamflow and habitat (Figure 16).

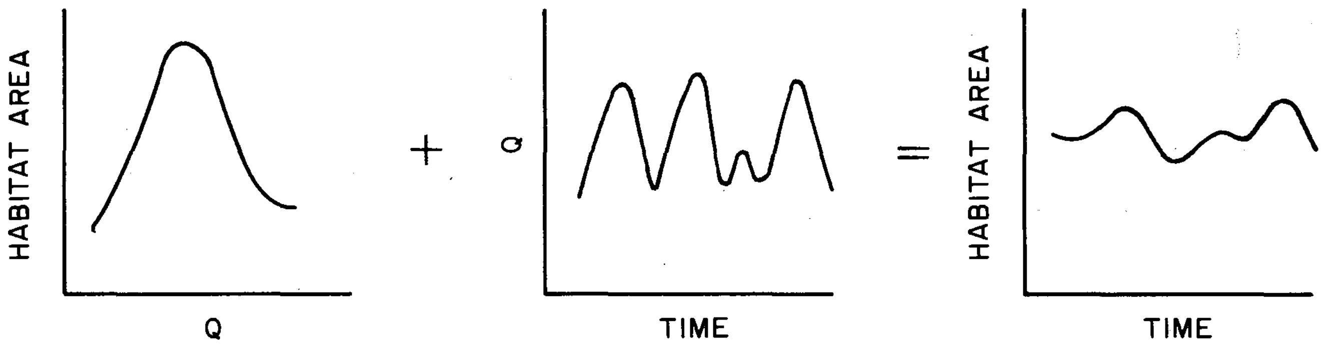


Figure 16. Development of a habitat time series.

A time series of habitat data can be used independently from other interpretive techniques. It can also be used in conjunction with other techniques to enhance or verify their conclusions. Any time step from hours to years can be used to generate a habitat time series. Normally, time series are presented in graphic, rather than tabular, form, so that the recent history of habitat conditions in the stream under study is more easily interpreted. The relative difference in amount of habitat available during normal and extreme events is more obvious on a time series plot than in a table. Furthermore, the effects of stochastic variations in flow are much more dramatic in time series (e.g., a 25 year flood followed by a 10 year drought).

Whether IFIM output is used in HEP, or used independently, the net effect of a proposed alteration should be expressed as an integration of habitat area (equivalent to habitat units) over time. Numerical integration of habitat area over time is quite easy because the habitat time series generated with the IFIM uses small, equal time steps, treating each habitat value for the time step as a measure of central tendency. A habitat time series generated this way represents the habitat area per unit time as a rectangle (Figure 17). Because the time steps are of unit width (e.g., 1 month, 1 day, 1 hour) the area of each rectangle is the product of the height of the rectangle (habitat area) and unity (the time step). The total area beneath the curve can be determined simply by summing the habitat areas over all the time steps:

$$HUY = \frac{\Sigma\ HA_m}{12} \text{ or } \frac{\Sigma\ HA_d}{365} \qquad (5\text{-}5)$$

where HUY = habitat unit years

HA_m = habitat area (or habitat unit) for one month

HA_d = habitat area (or habitat unit) for one day

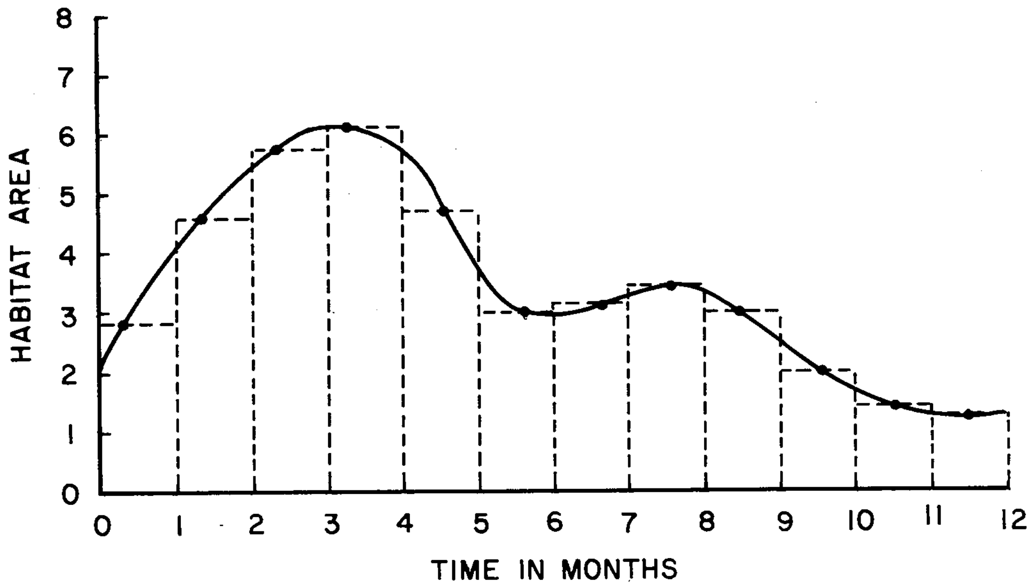


Figure 17. Principle of numerical integration of habitat unit years for a time series.

Numerical integration of a time series is tedious unless it is done on a computer. The area under the curve can also be determined with a planimeter. An unusual, but highly accurate technique, is to cut the curve out and weigh it on a high precision balance. These techniques require calibration by determination of the area or weight represented by a unit measure of habitat and time.

Figure 18 is a copy of Form C, used in the HEP analysis to compute habitat unit years. The results of an IFIM time series, if integrated as described above, may be entered directly in block 8 of Form C. Use of these integration techniques eliminates the need to fill in blocks 5, 6, and 7.

a. Impact analysis using habitat time series. One method of quantifying an impact is to generate habitat time series with and without a project and calculate the difference in area beneath both curves. Figure 19 shows two habitat time series representing alternative hydroelectric peaking schedules for Glen Canyon Dam on the Colorado River. The numerical integration of this time series by 6-hour periods is in Table 11. Schedule B provides about 10% fewer total habitat hours than Schedule A (Table 11). However, this difference may be somewhat misleading, because the greatest impact of reducing habitat occurs when habitat minima are reduced. Fish populations reach their greatest densities and, therefore, experience greatest stress when habitat availability is lowest. Habitat reductions during periods of greater availability may be inconsequential if the population has adjusted to the habitat minima. Examination of the dips in the curves on Figure 19 indicates that Schedule B will result in habitat reductions approaching 50% during some of these periods.

Form C. Calculation of Average Annual Habitat Units available for an evaluation species under a proposed action.

<table>
<tr><td colspan="4">1. Study</td><td colspan="5">2. Study area</td><td colspan="6">3. Proposed action</td></tr>
<tr><td rowspan="3">4. Evaluation species</td><td colspan="14">5. HSI and area by target year (TY)</td></tr>
<tr><td colspan="2">Baseline (TYO)</td><td colspan="2">TY1</td><td colspan="2">TY</td><td colspan="2">TY</td><td colspan="2">TY</td><td colspan="2">TY</td><td colspan="2">TY</td></tr>
<tr><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td><td>HSI</td><td>Area</td></tr>
<tr><td colspan="12">6. Calculations</td><td colspan="3">7. Habitat Units between target years</td></tr>
<tr><td colspan="12">6A.</td><td colspan="3"></td></tr>
<tr><td colspan="12">6B.</td><td colspan="3"></td></tr>
<tr><td colspan="12">6C.</td><td colspan="3"></td></tr>
<tr><td colspan="12">6D.</td><td colspan="3"></td></tr>
<tr><td colspan="12">6E. Total from additional target years</td><td colspan="3"></td></tr>
<tr><td colspan="12">Sum of Habitat Units</td><td colspan="3">8.</td></tr>
<tr><td colspan="7">9. Life of project</td><td colspan="8">10. Average Annual HU'S
Block 8 ÷ Block 9</td></tr>
</table>

Figure 18. Copy of Form C from the Habitat Evaluation Procedures.

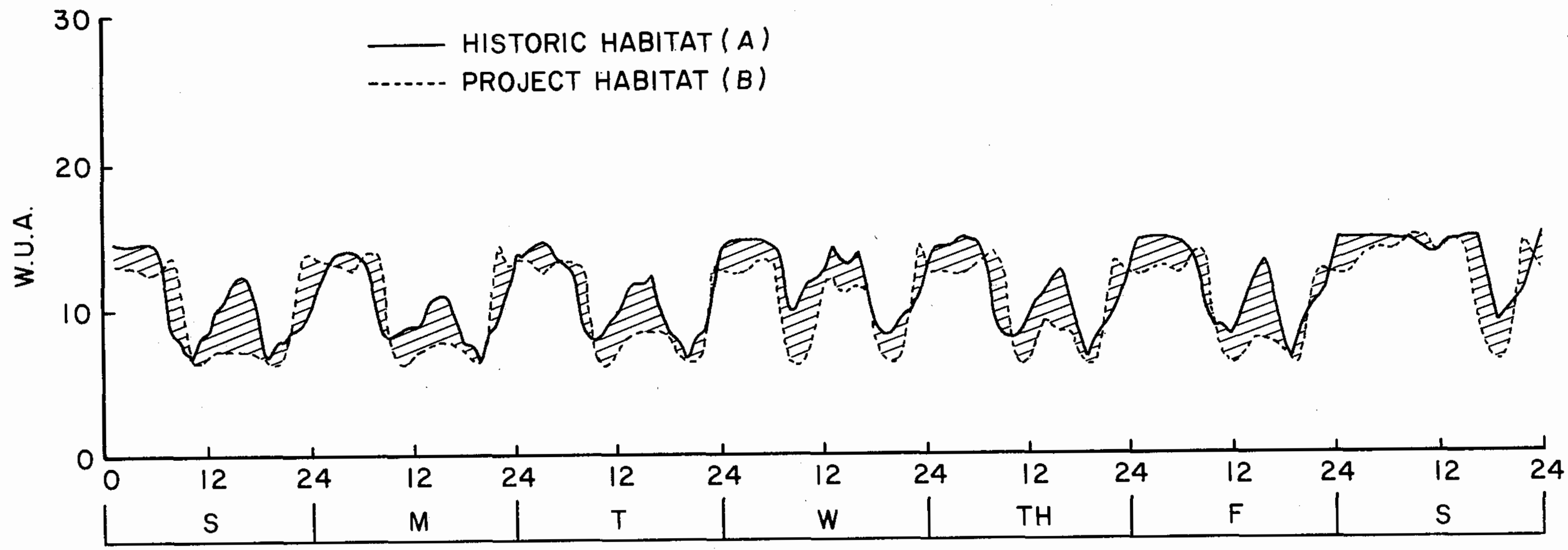


Figure 19. Hourly habitat time series for Schedule A and Schedule B hydropeaking schedules below Glen Canyon Dam.

Table 11. Numerical integration of two habitat time series for alternative hydropeaking schedules below Glen Canyon Dam. Schedule A is the existing alternative and Schedule B is proposed.

Day	Hours	Sum of habitat area-hours per 6 hour period	
		Schedule A	Schedule B
Sunday	0000-0600	85.5	76.5
	600-1200	50.5	61.0
	1200-1800	66.0	42.5
	1800-2400	48.5	56.5
Monday	0000-0600	82.0	78.0
	0600-1200	53.5	54.5
	1200-1800	60.0	44.0
	1800-2400	55.0	61.0
Tuesday	0000-0600	83.0	80.0
	0600-1200	55.5	57.5
	1200-1800	66.0	50.5
	1800-2400	55.5	50.0
Wednesday	0000-0600	89.5	75.5
	0600-1200	71.5	48.0
	1200-1800	77.0	67.5
	1800-2400	60.0	56.5
Thursday	0000-0600	89.0	75.5
	0600-1200	56.5	62.5
	1200-1800	67.5	50.5
	1800-2400	56.5	56.5
Friday	0000-0600	89.5	76.5
	0600-1200	62.0	63.5
	1200-1800	66.5	45.0
	1800-2400	61.0	59.5
Saturday	0000-0600	90.0	81.5
	0600-1200	87.0	87.5
	1200-1800	85.5	71.0
	1800-2400	68.5	61.5
Total		1,938.5	1,750.5

One technique for examining this type of impact is to integrate over a partial time series. The portion beneath the dips in the curve is the only area of curve included in the integration. Figure 19 shows two daily habitat minima, with durations of about 6 hours. Table 12 shows the results of integrating across these 6 hour minimum habitat time periods. In this case, Schedule B will result in a 16% reduction in minimum habitat available over the time series. Although this is a better representation of the true impact of implementing Schedule B, a different answer would have been obtained if 4-hour periods had been used rather than 6, or if Saturday had been left out of the analysis. Analysis of impacts in rivers requires the evaluation of frequency in addition to amount. Frequency evaluations can be made using a habitat duration curve, as described below.

b. Impact analysis using habitat duration curves. A habitat duration curve is a cumulative frequency plot that shows the probability of a certain amount of habitat being equalled or exceeded during a time period. It is constructed in much the same way as a flow duration curve, except that habitat frequency is used instead of flow frequency. The habitat area - discharge function is usually bell shaped and two or more discharges, each with different probabilities of occurrence, can produce the same total amount of habitat. The probability of having a certain amount of habitat available at any time is a function of the combined probabilities of having the associated flows in the stream.

Construction of a habitat duration curve is illustrated in Table 13 and Figure 20. The first step is to array the habitat areas from the time series from highest to lowest. Second, the number of times (i.e., the frequency) that each habitat area occurs in the time series is tallied and each frequency divided by the total number of values to determine the percent of time that each value has occurred. A cumulative percentage is computed, starting with the highest value and adding subsequent percentages. This results in a series of plotting points representing the probability of a given habitat value being equalled or exceeded. These points are then plotted on probability paper.

Figure 20 is a habitat duration curve for the time series example from Figure 19. Curve A represents the typical shape of most duration curves. Curve B is atypical and represents a bimodal distribution of habitat over time. The area of greatest interest beneath these curves is the portion representing probabilities of exceedance between 50% and 90%. The median habitat value has biological significance because it represents a measure of central tendency. Habitat values with exceedance probabilities greater than 90% (sometimes greater than 95%) represent extreme conditions of limited habitat. It is assumed that more extreme conditions may not occur frequently enough to have much significance. This assumption may be invalid, and a method of testing it is discussed in Section 5.2.3.

Both Schedules A and B in Figure 20 result in about the same median habitat value. This is not too surprising, given the time series from which the duration curves were derived. As mentioned in Section 5.2.2a., the real impact of implementing Schedule B is on the low habitat values. This impact is illustrated by the shaded portion of Figure 20. One technique of quantifying the impact of Schedule B is to determine the area of the shaded portion between curves A and B, using the numerical techniques discussed in Section 5.2.2a. Based on this integration, the difference in area between

Table 12. Numerical integration of two partial habitat time series for alternative hydropeaking schedules below Glen Canyon Dam. Schedule A is the existing schedule and Schedule B is proposed.

	Schedule A	Schedule B
Sunday	50.5	41.0
	48.5	40.5
Monday	52.0	40.0
	47.5	43.0
Tuesday	54.0	46.5
	49.5	44.0
Wednesday	71.5	47.0
	57.0	49.5
Thursday	54.0	49.0
	54.0	44.5
Friday	57.0	44.0
	56.0	45.5
Saturday	87.0	86.5
	64.5	50.5
Total	803.0	671.5

Table 13. Computation of habitat duration from two habitat time series for alternative hydropeaking schedules below Glen Canyon Dam. Schedule A is the existing schedule and Schedule B is proposed.

Habitat units	Frequency (hours)		Percent of time		Percent of time equalled or exceeded	
	A	B	A	B	A	B
15.0	28	5	16.7	3.0	16.7	3.0
14.5	16	5	9.5	3.0	26.2	6.0
14.0	9	9	5.3	5.3	31.5	11.3
13.5	4	19	2.4	11.3	33.9	22.6
13.0	7	14	4.1	8.3	38.0	30.9
12.5	8	24	4.8	14.3	42.8	45.2
12.0	10	8	6.0	4.8	48.8	50.0
11.5	5	2	3.0	1.2	51.8	51.2
11.0	11	1	6.5	0.6	58.3	51.8
10.5	6	0	3.6	0.0	61.9	51.8
10.0	11	4	6.5	2.4	68.4	54.2
9.5	7	5	4.1	3.0	72.5	57.2
9.0	10	3	6.0	1.8	78.5	59.0
8.5	14	10	8.3	6.0	86.8	65.0
8.0	9	7	5.3	4.1	92.1	69.1
7.5	7	11	4.1	6.5	96.2	75.6
7.0	3	17	1.8	10.1	98.0	85.7
6.5	3	15	1.8	8.9	99.8	94.6
6.0	0	9	0.0	5.3	100.0	99.9

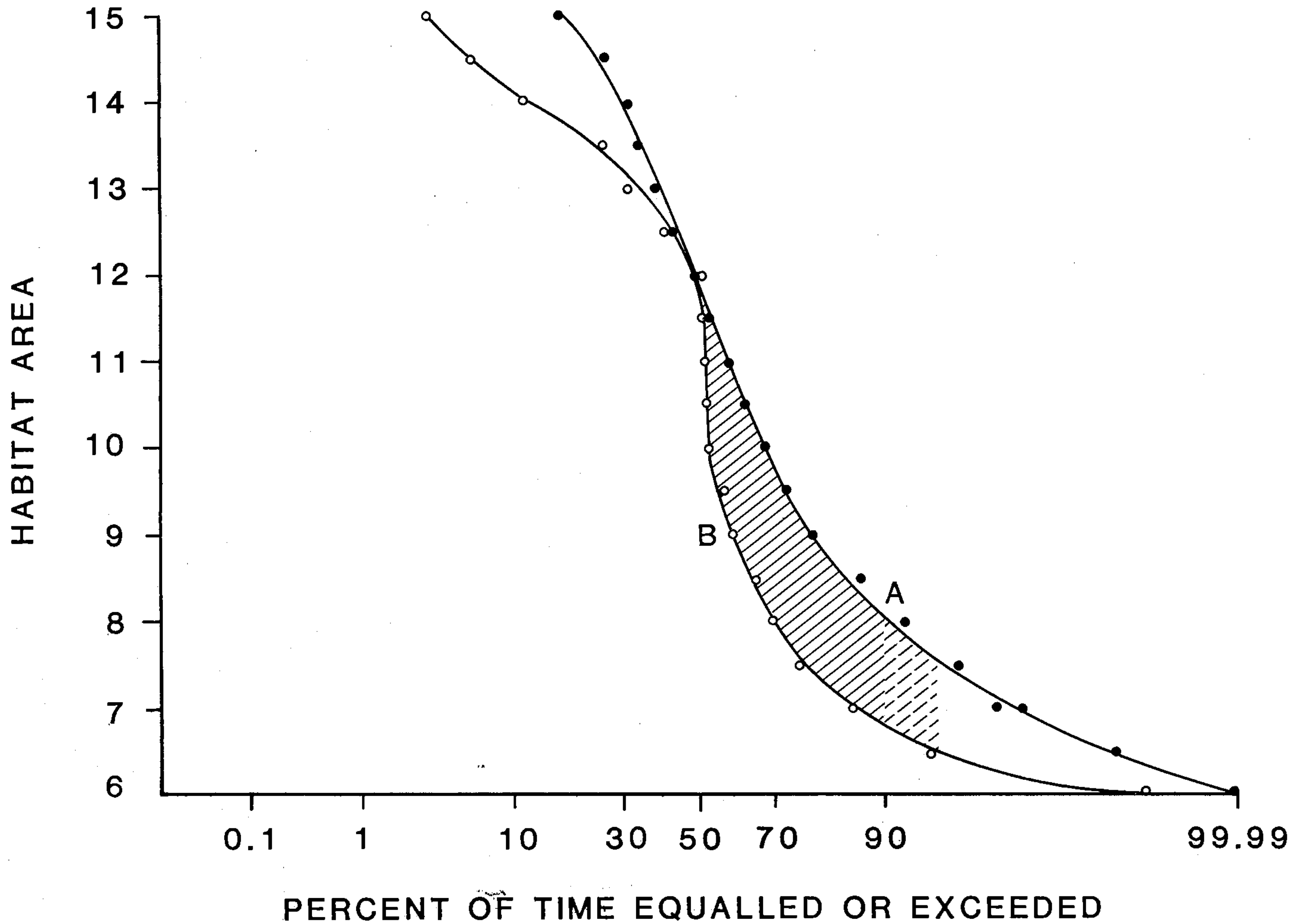


Figure 20. Habitat duration curve for the time series shown in Figure 19.

curves A and B is 16.2%, the same reduction computed in Section 5.2.2a. Although both techniques arrived at the same answer, the habitat duration technique is less arbitrary and will give much more consistent results than using a partial habitat time series. Another use of the habitat duration curve is to help express an impact in terms of frequency, rather than amount. In Figure 19, the minimum habitat available under option A is around 7 units (70,000 ft^2). This minimum value is equalled or exceeded 98.5% of the time under option A, but only 85.5% of the time under option B (Figure 20). This means that habitat values lower than seven units occur only 1.5% of the time under option A, but nearly 15% of the time under option B. Thus, option B increases the probability of reducing habitat availability below the previous minimum by a factor of ten.

5.2.3 Effective Habitat Time Series

Although integration of the habitat area over a time series or habitat duration curve is an accurate method of quantifying an impact, the results are often hard to interpret because a time series is produced for each life stage. The resulting time series plot resembles the example shown in Figure 21. Evaluating and interpreting the variable effects of changes in streamflow on the habitat of four life stages, concurrently, can be very confusing. One way to avoid this confusion is to base the quantification of the impact on a single curve. This is quite easy if one life stage is known (or can be assumed) to be limiting. In many cases, a limiting life stage cannot be identified, or more typically, different flow events cause different life stages to be limiting. This phenomenon can be observed in Figure 21 during year 4, a major drought, and year 8, a major flood. The drought flow has a significant effect on habitat for adults, juveniles, and spawning. The flood flows affect fry and juvenile habitat, but have relatively minor influence on adult and spawning habitat. The assumption that the same life stage is always limiting is probably not valid in very many streams.

This problem can be overcome by using the habitat ratio concept, introduced in Section 5.2.1, to construct a time series of effectively utilized habitat, defined as the amount of adult habitat that can potentially be used during any year.

Each value for subadult habitat in the time series represents a potential amount of adult habitat that can be utilized at some time in the future. For example, assume that the habitat ratio between juveniles and adults is 0.8:1.0. In year zero, there are 25 units of juvenile habitat. This translates to the potential recruitment of enough juveniles to occupy 31 units of adult habitat in the following year (25/0.8 = 31.25). Utilized (effective) adult habitat consists of two parts, the part that is occupied by adults surviving from the previous year and the part that will be occupied by adults recruited from the juvenile cohort. The portion of the adult habitat occupied by surviving adults can be calculated by multiplying the net effective habitat for the previous year by the average annual adult survival rate. This represents the adult habitat needed if there was no recuitment.

Starting at year zero and assuming adults are initially at carrying capacity, the amount of spawning habitat needed the next year is computed. The adult habitat from year zero is multiplied by the adult:spawning habitat ratio. This is the first step shown in Table 14, which illustrates all of the

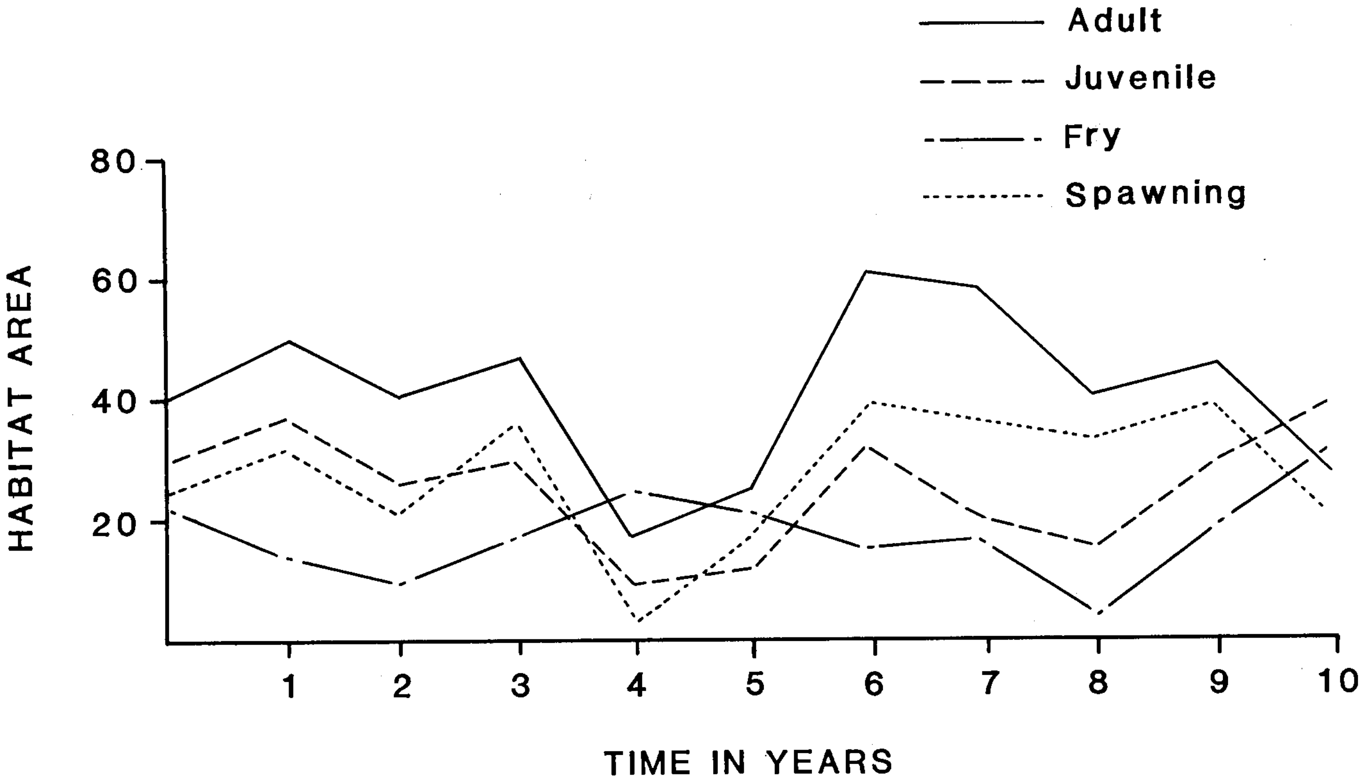


Figure 21. Example of a habitat time series for four life stages of a species over a ten year period.

Table 14. Computation procedure used to construct effective habitat time series.

Life Stage	Year 1	2	3	4	5	6	7	8	9	10
Adult @ t-1	40[a]	50	40	45	18	21.5	21	28.5	35.7	30
Spawning										
Available	32	20	25	2	5	40	44	48	50	32
Effective	8	10	8	9	3.6	4.3	4.2	5.7	7.1	6
Limit	8	10	8	2	3.6	4.3	4.2	5.7	7.1	6
Fry										
Available	15	10	15	25	22	12	10	8	5	14
Effective	12	15	12	3	5.4	6.5	6.3	8.6	10.7	9
Limit	12	10	12	3	5.4	6.5	6.3	8	5	9
Juvenile										
Available		28	30	10	24	32	20	15	14	36
Effective		32	27	32	8	14	17.2	16.8	21.4	13.4
Limit		28	27	10	8	14	17.2	15	14	13.4
Adult										
Recruit			35	34	12.5	10	18	21.5	18.8	17.5
Carryover			+20	22	9	11	10.5	14.2	17.9	15
Total			55	56	21.5	21	28.5	35.7	36.7	32.5
Available	50	40	45	18	25	61	58	46	30	50
Net Effective			45	18	21.5	21	28.5	35.7	30	32.5

[a]From year zero, Figure 21.

steps involved in computing effective habitat. The amount of spawning habitat needed to accommodate all the spawners from the previous year is the effective spawning habitat. Each life stage in Table 14 is represented by three rows; one for the actual habitat available (HA), one for the effective habitat (EH), and one for the habitat limit (L), which is the lower of the other two values. During year zero, the actual adult habitat is 40 units, and the spawning habitat ratio was 0.2:1. This means that eight spawning units are needed to perpetuate an adult population at carrying capacity for 40 adult units. The actual spawning habitat available during year 1 is 32 units. Thus, spawning for this year is limited by the number of spawners, not the amount of spawning habitat.

The next step is to determine the amount of fry habitat needed to support eight units of spawning habitat. The ratio of fry habitat to spawning habitat is 1.5:1. Therefore, 12 units of fry habitat can be utilized during year 1. Fifteen units are available, so the effective limit is 12 units (left hand side of Table 14, beneath year 1).

The 12 units of fry habitat are carried forward to the next year in order to determine the amount of juvenile habitat needed to support the cohort. The ratio of required juvenile to fry habitat is 2.67:1. This step is illustrated in the diagonal column from year 1 to year 2 on Table 14. Twelve units of fry habitat will produce enough juveniles to occupy about 32 units of juvenile habitat. However, only 28 units are available during year two; this value becomes the limit to be carried forward (see juvenile, year 2, Table 14).

The juveniles from year 2 mature and are recruited during year 3. The habitat ratio for adults to juveniles is 0.8:1, so one unit of juvenile habitat requires 1.25 adult units. This step is illustrated below year 3, near the bottom of Table 14. The 28 units of juvenile habitat from year 2 require 35 units of adult habitat in year 3. This is the effective adult habitat for recruitment. This is not the total effective adult habitat, however. Some adult habitat is needed to accommodate carryover adults from year 2. The effective adult habitat from year 2 is assumed to be the amount of available habitat, 40 units. Adult mortality is given as 50%, so 20 units of adult habitat would be needed for the survivors from year 2. The total amount of habitat that could be occupied in year 3 is 55 units, the sum of the recruitment and carryover requirements. However, only 45 units are available during year 3. The lower of these two values (required or available habitat) is recorded at the bottom of the table as the net effective adult habitat.

The net effective adult habitat for each year is recorded at the top of the form as the beginning value for the next year and used to compute the required amount of spawning habitat. In this case, the 45 units of effective habitat from year 3 is recorded under year 4 in the row labeled "Adult @ t-1." The effective habitat units for at least the first 3 years (0, 1, and 2) are relatively meaningless because adult habitat availability is assumed to equal effective habitat until year 2. Note that the effective adult habitat value is the value carried forward to compute the spawning habitat needed the next year.

The time lag between year zero and the first year for which effective habitat can be computed is extended if juveniles take several years to mature. Several rows in the table must be allocated to juveniles when this occurs.

Effective juvenile habitat is computed the same way as adult carryover when each age group of juveniles uses the same habitat type in the same ratio. That is, the effective juvenile habitat for one year equals the effective juvenile habitat from the previous year times the survival rate. However, fish are likely to require proportionately more space as they grow larger. In this case, the ratio between juvenile I and juvenile II is determined and habitat values calculated the same way as between fry and juvenile, shown in Table 14.

The effective adult habitat values from Table 14 are plotted in Figure 22 to illustrate the additional interpretive power gained by this exercise. The actual adult habitat available is also plotted for comparison. Years 0-2 should be excluded from this comparison, as discussed earlier. There is less area beneath the effective adult habitat curve than below the available adult habitat curve. The determination of habitat unit years for HEP or for other types of impact analysis is more accurate when the effective habitat curve is used. The effective habitat time series also documents the extent of the impact of an extreme event. Such an event is the 1-in-10 low water year during year 4, illustrated in Figures 21 and 22. Three life stages (adult, juvenile, and spawning,) were adversely affected that year. Available adult habitat rebounds slightly in year 5, but cannot be fully utilized due to the combined effects of low amounts of adult and juvenile habitat during the previous year. Year 6 shows a dramatic increase in available adult habitat but, because of the combined effects of low spawning habitat in year 4 and low recruitment and carryover from year 5, the effective habitat remains depressed. Full habitat recovery does not occur until year 9. Thus, the effects of one low water year carry over for six years.

a. <u>Impact analysis using effective habitat method.</u> Figure 23 shows a 20-year habitat time series under historical flow conditions, for four life stages of an evaluation species. Streamflows are clustered near median water year conditions (40-60% exceedance) during years zero through 3, 10 through 13, and 15 through 20. A prolonged drought occurred during years 4 and 5, with one year of low water at year 14. Years 7 through 9 had a higher than average water supply, and year 17 was an extremely high water year (10% exceedance).

As an example, assume that a water project is proposed on the river to supply municipal and agricultural water requirements. Two alternative water diversion schedules (A and B) are proposed by the construction agency. The same amount of water would be diverted at all times (i.e., constant withdrawal) under Schedule A. Schedule B calls for accelerated diversion and off-channel storage during above average water years, constant withdrawal during normal water years, and no withdrawal during droughts. Water from storage would be used to make up shortages whenever streamflow approached the 90% exceedance level. A habitat time series was developed by imposing projected diversions on the historical flow regime for both Schedules A and B (Figures 24 and 25, respectively). Calculations of the effective habitat under historical conditions and under Schedules A and B are in Tables 15 through 17, respectively. The resulting effective habitat time series for all three scenarios are plotted in Figure 26. Integration of the area beneath the three curves shows that Schedule A would result in an overall reduction in effective habitat of 24.2%. Schedule B results in a 16.8% reduction. Schedule B appears to be preferable to Schedule A, although consideration of mitigation alternatives should not stop here as this example falls short of a complete mitigation study.

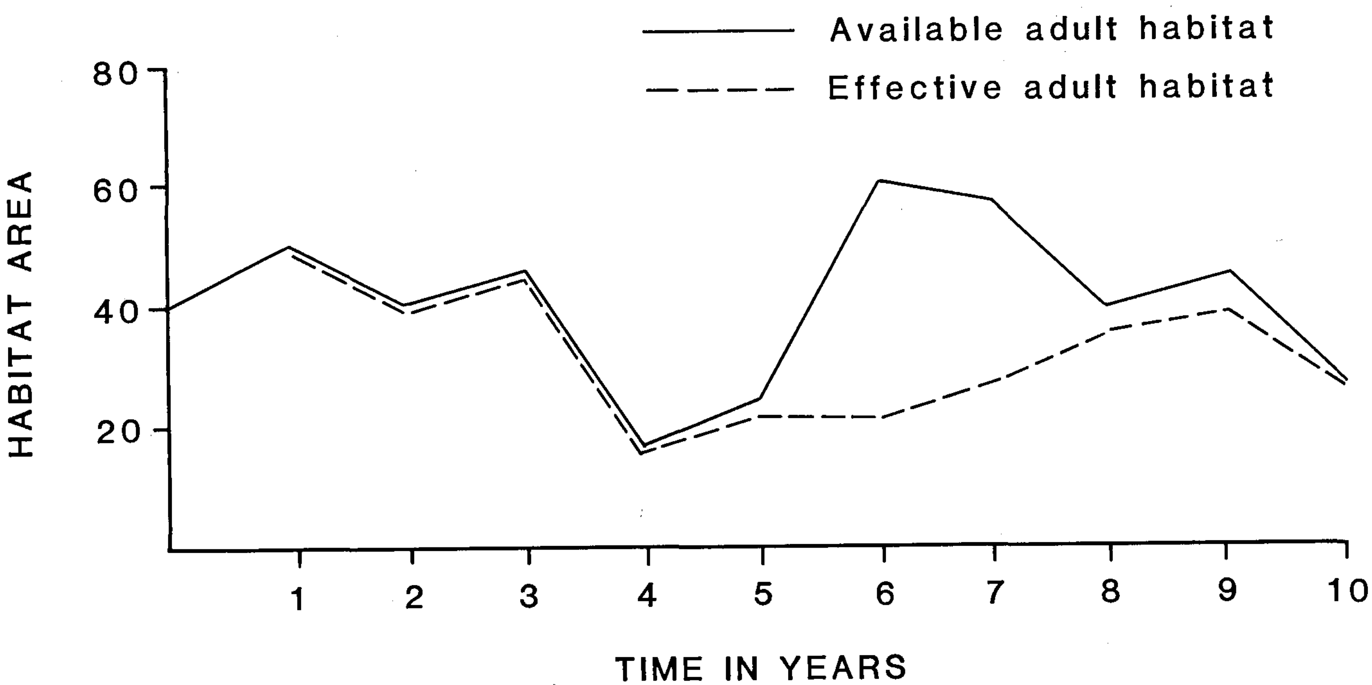
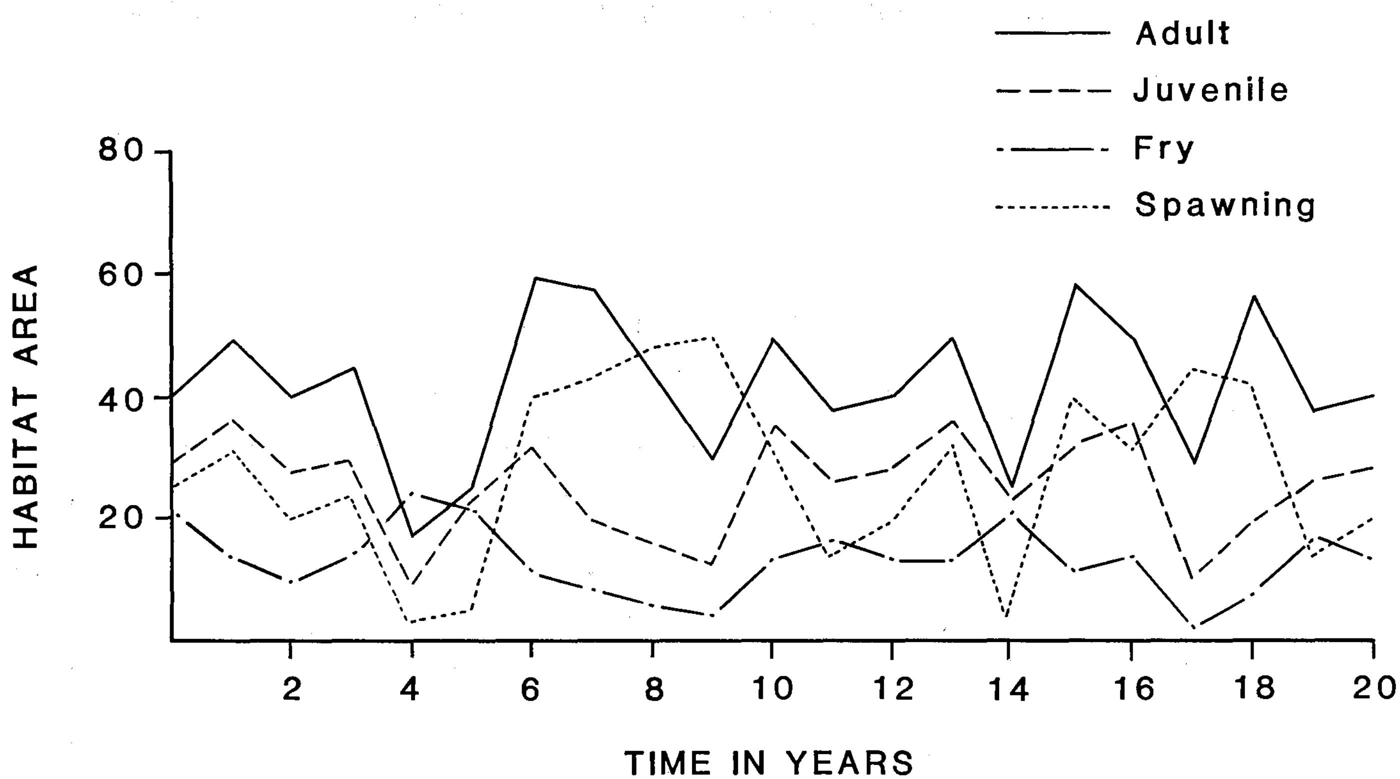


Figure 22. Comparison of available and effectively utilized adult habitat over a ten year period.



Flow exceedence probability (%)

50	65	60	90	80	40	30	25	20	50	70	60	50	80	40	50	10	30	70	60

Figure 23. Habitat time series for four life stages of a species under historical flow conditions.

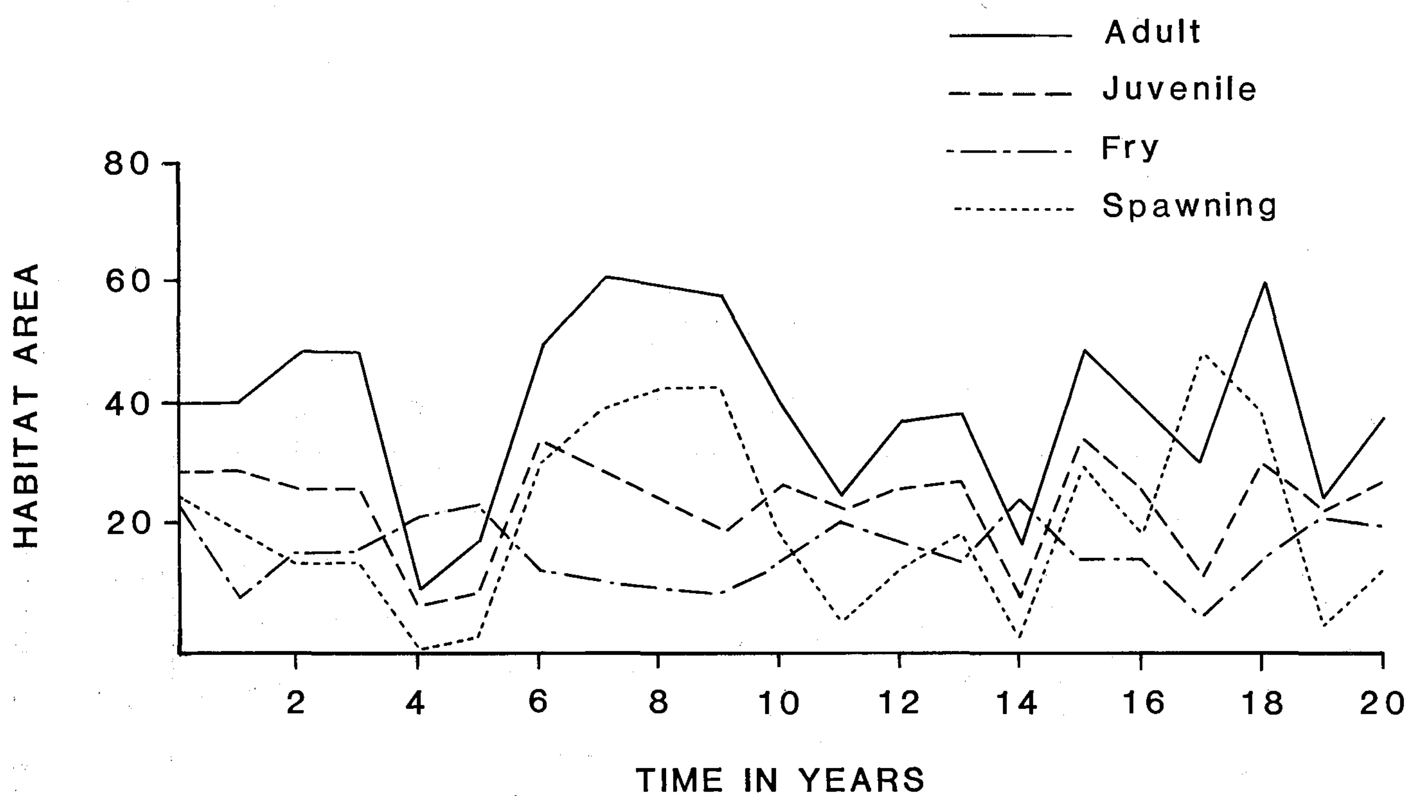


Figure 24. Available habitat time series for operating Schedule A (constant withdrawal alternative) imposed on historic flows shown in Figure 23.

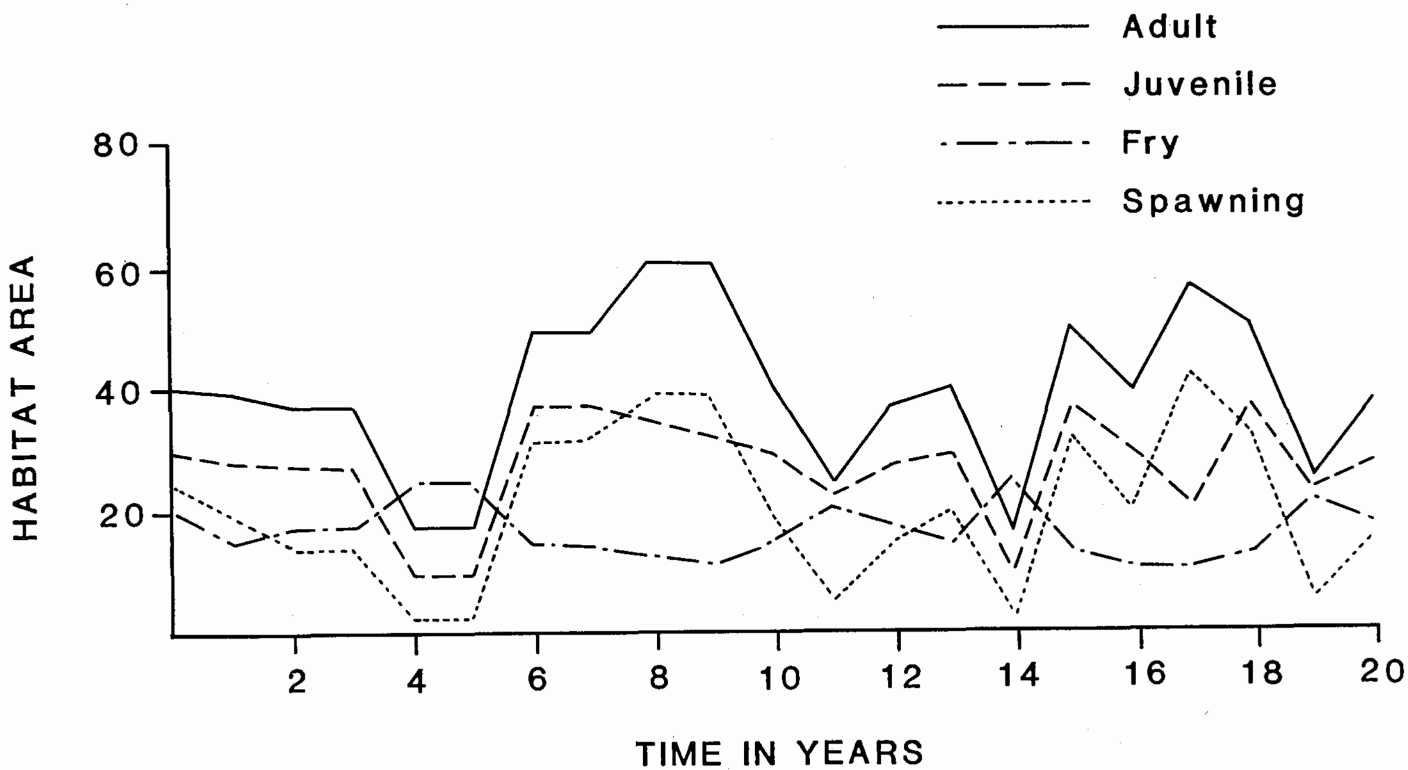


Figure 25. Available habitat time series for operating Schedule B (variable withdrawal alternative) imposed on historic flows shown in Figure 23.

Table 15. Computation of effective habitat under historical flow conditions with no project.

Life Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Adult t-1	40	50	40	45	18.0	21.5	21.0	28.5	35.7	30.0	32.5	32.9	40.0	50.0	25.0	42.5	46.2	30.0		
Spawning																				
Available	32	20	25	2	5.0	40.0	44.0	48.0	50.0	32.0	15.0	20.0	32.0	5.0	40.0	32.0	45.0	43.0		
Effective	8	10	8	9	3.6	4.3	4.2	5.7	7.1	6.0	6.5	6.6	8.0	10.0	5.0	8.5	9.2	6.0		
Limit	8	10	8	2	3.6	4.3	4.2	5.7	7.1	6.0	6.5	6.6	8.0	5.0	5.0	8.5	9.2	6.0		
Fry																				
Available	15	10	15	25	22.0	12.0	10.0	8.0	5.0	14.0	18.0	15.0	14.0	22.0	12.0	14.0	3.0	10.0		
Effective	12	15	12	3	5.4	6.5	6.3	8.6	10.7	9.0	9.8	9.9	12.0	7.5	7.5	12.8	13.9	9.0		
Limit	12	10	12	3	5.4	6.5	6.3	8.0	5.0	9.0	9.8	9.9	12.0	7.5	7.5	12.8	3.0	9.0		
Juvenile																				
Available		28	30	10	24.0	32.0	20.0	15.0	14.0	36.0	28.0	29.0	36.0	24.0	32.0	36.0	10.0	20.0	28.0	
Effective		32	27	32	8.0	14.0	17.2	16.8	21.4	13.4	24.0	26.0	26.4	32.0	20.0	20.0	34.0	8.0	24.0	
Limit		28	27	10	8.0	14.0	17.2	15.0	14.0	13.4	24.0	26.0	26.4	24.0	20.0	20.0	10.0	8.0	24.0	
Adult																				
Recruit			35	34	12.5	10.0	18.0	21.5	18.8	17.5	16.7	30.0	32.5	39.5	30.0	25.0	25.0	12.5	10.0	30.0
Carryover			20	22	9.0	11.0	10.5	14.2	17.9	15.0	16.2	19.0	20.0	25.0	12.5	21.2	23.1	15.0	18.8	14.4
Total			55	56	21.5	21.0	28.5	35.7	36.7	32.5	32.9	49.0	52.5	64.5	42.5	46.2	48.1	37.5	28.8	44.4
Available	50	40	45	18	25.0	61.0	58.0	46.0	30.0	50.0	32.0	40.0	50.0	25.0	60.0	50.0	30.0	58.0	38.0	40.0
Net Effective			45	18	21.5	21.0	28.5	35.7	30.0	32.5	32.9	40.0	50.0	25.0	42.5	46.2	30.0	37.5	28.8	40.0

Table 16. Computation of effective habitat with historical conditions altered to reflect a constant withdrawal of water (proposed Schedule A).

Life Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Adult t-1	40	40.0	50.0	50	10	15.0	7.5	13.8	21.9	28.5	28.1	25.0	38.0	40.0	18.0	21.5	20.8	28.4		
Spawning																				
Available	20	15.0	15.0	0	2	32.0	40.0	42.0	42.0	20.0	5.0	15.0	20.0	2.0	30.0	20.0	50.0	40.0		
Effective	8	8.0	10.0	10	2	3.0	1.5	2.8	4.4	5.7	5.6	5.0	7.6	8.0	3.6	4.3	4.2	5.7		
Limit	8	8.0	10.0	0	2	3.0	1.5	2.8	4.4	5.7	5.0	5.0	7.6	2.0	3.6	4.3	4.2	5.7		
Fry																				
Available	10	15.0	15.0	22	24	12.0	11.0	10.0	10.0	15.0	20.0	18.0	15.0	25.0	15.0	15.0	5.0	15.0		
Effective	12	12.0	15.0	0	3	4.5	2.3	4.1	6.6	8.6	7.5	7.5	11.4	3.0	5.4	6.5	6.3	8.5		
Limit	10	12.0	15.0	0	3	4.5	2.3	4.1	6.6	8.6	7.5	7.5	11.4	3.0	5.4	6.5	5	8.5		
Juvenile																				
Available		28.0	28.0	8	10.0	35.0	30.0	25.0	20.0	28.0	23.0	27.0	28.0	10.0	35.0	28.0	12.0	30.0	24.0	
Effective		26.7	32.0	40	0.0	8.0	12.0	6.0	11.0	17.5	22.8	20.0	20.0	30.4	8.0	14.4	17.2	13.4	22.7	
Limit		26.7	28.0	8	0	8.0	12.0	6.0	11.0	17.5	22.8	20.0	20.0	10.0	8.0	14.4	12.0	13.4	22.7	
Adult																				
Recruit			33.3	35	10	0.0	10.0	15.0	7.5	13.8	21.9	28.5	25.0	25.0	12.5	10.0	18.0	15.0	16.7	28.4
Carryover			25.0	25	5	7.5	3.8	6.9	11.0	14.3	14.0	12.5	19.0	20.0	9.0	10.8	10.4	14.2	14.6	12.5
Total			58.3	60	15	7.5	13.8	21.9	28.5	28.1	35.9	41.0	44.0	45.0	21.5	20.8	28.4	29.2	31.3	40.9
Available	40	50.0	50.0	10	18	50.0	61.0	60.0	58.0	40.0	25.0	38.0	40.0	18.0	50.0	40.0	30.0	60.0	25.0	38.0
Net Effective			50.0	10	15	7.5	13.8	21.9	28.5	28.1	25.0	38.0	40.0	18.0	21.5	20.8	28.4	29.2	25.0	38.0

Table 17. Computation of effective habitat with historical conditions altered to reflect a variable withdrawal of water (proposed Schedule B).

Life Stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Adult t-1	40	40	38.0	38.0	18.0	18.0	19.0	20.8	28.4	33.2	37.4	25.0	38.0	40.0	18.0	21.5	20.8	28.4		
Spawning																				
Available	20	15	15.0	2.0	2.0	32.0	32.0	40.0	40.0	20.0	5.0	15.0	20.0	2.0	32.0	20.0	42.0	32.0		
Effective	8	8	7.6	7.6	3.6	3.6	3.8	4.2	5.7	6.6	7.7	5.0	7.6	8.0	3.6	4.3	4.2	5.7		
Limit	8	8	7.6	2.0	2.0	3.6	3.8	4.2	5.7	6.6	5.0	5.0	7.6	2.0	3.6	4.3	4.2	5.7		
Fry																				
Available	15	18	18.0	25.0	25.0	15.0	15.0	12.0	11.0	15.0	20.0	18.0	15.0	25.0	12.0	10.0	10.0	12.0		
Effective	12	12	11.4	3.0	3.0	5.4	5.7	6.2	8.5	10.0	7.5	7.5	11.4	3.0	5.4	6.5	6.2	8.5		
Limit	12	12	11.4	3.0	3.0	5.4	5.7	6.2	8.5	10.0	7.5	7.5	11.4	3.0	5.4	6.5	6.2	8.5		
Juvenile																				
Available		28	28.0	10.0	10.0	38.0	38.0	35.0	32.0	30.0	23.0	28.0	30.0	10.0	38.0	30.0	20.0	38.0	23.0	
Effective		32	32.0	30.4	8.0	8.0	14.4	15.2	16.7	22.7	26.7	20.0	20.0	30.4	8.0	14.4	17.2	16.7	22.7	
Limit		28	28.0	10.0	8.0	8.0	14.4	15.2	16.7	22.7	23.0	20.0	20.0	10.0	8.0	14.4	17.2	16.7	22.7	
Adult																				
Recruit			35.0	35.0	12.5	10.0	10.0	18.0	19.0	20.8	28.4	28.8	25.0	25.0	12.5	10.0	18.0	21.5	20.8	28.4
Carryover			20	19.0	9.0	9.0	10.8	10.4	14.2	16.6	18.7	12.5	19.0	20.0	9.0	10.8	10.4	14.2	17.9	12.5
Total			55	54.0	21.5	19.0	20.8	28.4	33.2	37.4	47.1	41.3	44.0	45.0	21.5	20.8	28.4	35.7	38.7	40.9
Available	40	38	38	18.0	18.0	50.0	50.0	60.0	60.0	40.0	25.0	38.0	40.0	18.0	50.0	40.0	58.0	50.0	25.0	38.0
Net Effective			38.0	18.0	18.0	19.0	20.8	28.4	33.2	37.4	25.0	38.0	40.0	18.0	21.5	20.8	28.4	35.7	25.0	38.0

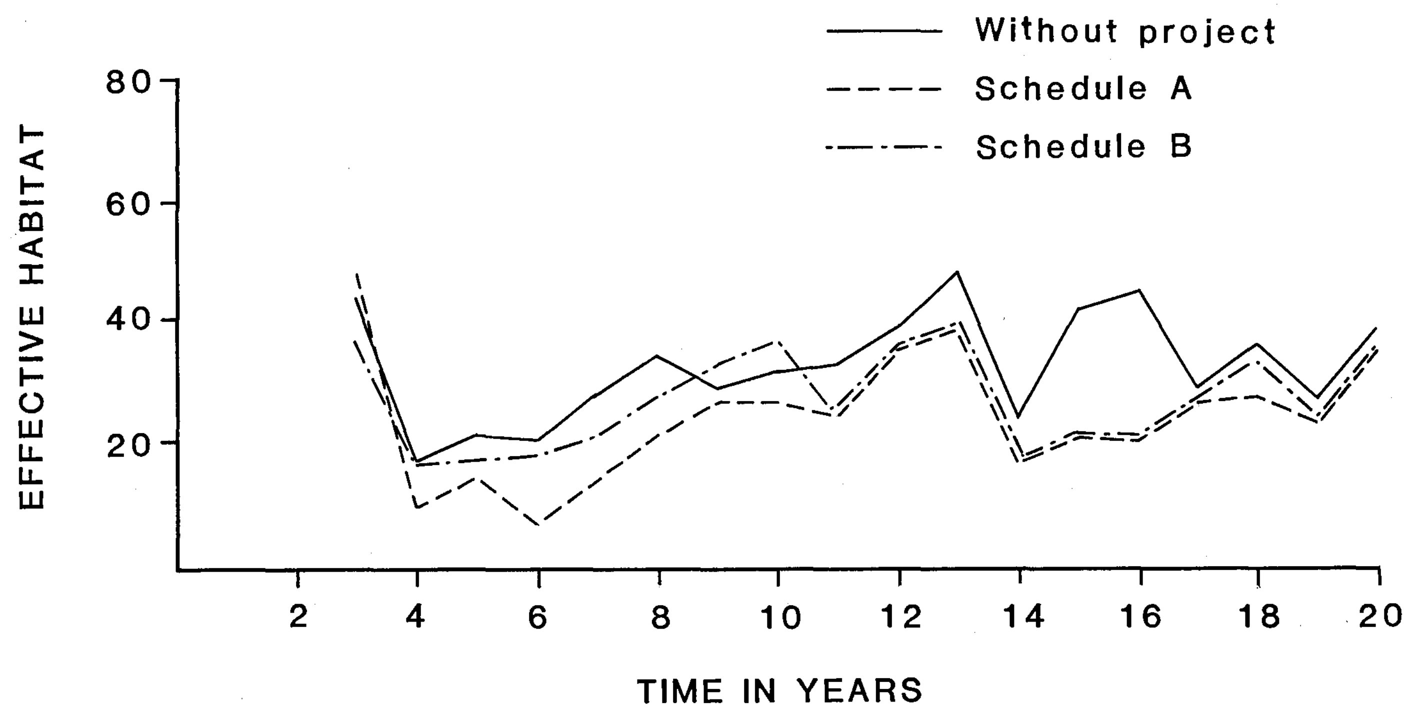


Figure 26. Effective habitat time series for historic flow regime, constant withdrawal alternative, and variable withdrawal alternative.

Historical conditions, as illustrated in Table 15, include two types of events that suppressed effective habitat to a level below the amount of available habitat for adults. Drought flows in years 4, 5, and 14 resulted in a reduction in habitat for spawning, juveniles, and adults. The depression in adult habitat has its initial impact during the year of the drought, and secondary impacts on effective spawning habitat, recruitment, and carryover for several years after the drought. This can be seen during years 4 and 5 on Table 15. During year 4, there was less spawning habitat available than what could have been utilized. There was more spawning habitat available in year 5 than would be utilized, because insufficient spawning adults carried over from year 4. The reduction in spawning habitat in year 4 was manifested in effective recruitment habitat during year 6. Juvenile habitat was also reduced in year 4, and the effect on usable adult habitat carries over to year 5. The first year of the drought was so severe that the effective habitat during the second year of drought was lower than the available habitat, even though not much habitat was available. The net effect of year 4 (roughly a 1-in-10 year occurrence) was to reduce the adult population below habitat capacity for a period of 4 years. The same type of effect occurred at year 14, but, in this case, the available adult habitat was reduced by high flows 3 years later, so the recovery period was shorter.

High flow events that occurred in years 9 and 17 (Table 15) had the greatest impact on fry and juvenile habitat and a moderate impact on adult habitat. Spawning habitat was actually increased under the high flow conditions. Available fry habitat was reduced well below the amount that could be used in year 9. The eventual effect of that reduction was low recruitment in year 11. Juvenile habitat was also affected in year 9, with that impact carried over into year 10. The greatest impact occurred in year 10, as a result of the combined effects of reduced juvenile habitat and adult carryover from the previous year. There was a similar occurrence in year 17, but, in this case, the reduction in fry habitat appeared to have the greatest impact, which carried over to year 19.

Carryover effects should be examined in the evaluation of possible mitigation alternatives. Relatively little could be done under this project design to mitigate drought situations, aside from not making them worse. However, something can be done about floods. Schedule A will result in drought conditions that are more severe and more frequent, but will not reduce the severity of flood conditions enough to realize many benefits with regard to fry and juvenile habitat. Schedule B, on the other hand, will increase the frequency and severity of moderately low water years, most notably years 11 and 19. These years correspond to 70% exceedance flows under historical conditions. The primary impact appears to be a reduction in available adult habitat and its carryover effects, including amount of subsequent spawning. Juvenile habitat for those years would be limited below the effective level, but not as severely as adult habitat. Therefore, it is likely that diversion of low flows having historical probabilities greater than 70% will cause a reduction in habitat, especially for adults and juveniles. Storage and diversion of high flows will have a beneficial effect, illustrated by the reduction of the high flows occurring in years 8 and 9. This flow reduction will increase the availability of adult habitat and remove the limitations on fry and juveniles that was evident in historical conditions (Table 15, years 8 and 9). The effective habitat in years 9 and 10 (Figure 26) are benefits from reducing the high flows. The same benefits are not evident in year 17, historically a 1-in-10 high water year. This is because the drought conditions in year 14 are more severe under Schedule B, and the population did not have time to recover.

Several mitigation alternatives worthy of further investigation are evident. The most significant impact under historical conditions with or without the project is the loss of juvenile and adult habitat during drought periods. A biologically significant drought (for this example) can be defined as any water year when the water supply has a probability of exceedance of 70% or higher. Therefore, one step in the development of a mitigation plan is to institute flow protection at the 70% level, with particular emphasis on adult and juvenile habitat. Some severe droughts will be unavoidable, even with storage. It appears that water years having exceedance probabilities greater than 80% can induce spawning limitations. Flow protection for spawning seems justifiable during low water years having 70% to 80% probabilities of exceedance. Data in Tables 15 through 17 indicate that low flows are never limiting to fry. Thus, one remedial approach might be to stock fingerlings during extremely low flow years.

There are several methods that can be used to increase the amount of juvenile and adult habitat in low water years. One technique is the alteration of the channel to improve the structural characteristics of the habitat, thereby increasing the habitat potential at lower flows (see Chapter 8). This alternative is costly but, depending on the value of the water and the fishery, the economics of this mitigative approach are often quite attractive. The underlying cause of the reduction in habitat must be determined before the feasibility of habitat improvement can be determined. The cause of the reduction can be identified by reviewing the calculation of total segment habitat area, discussed in Section 5.1. Channel improvement will help only when physical microhabitat (i.e., weighted usable area) undergoes a major reduction at low flows. Channel improvement will do little, if anything, to correct the problem when water quality is the main cause of the reduction in total habitat area. Reduction in waste loading may correct some water quality problems. The solution may be more difficult if the water quality problem is temperature-related. Increased shading along the stream may help control water temperatures. However, trees along the bank remove water from the river and this solution may not be desirable in some streams. Irrigation return flows tend to be warm, and elimination of this heat source by implementing sprinkler irrigation may be a feasible solution.

Reduction in total habitat is often the result of a combination of factors, such as channel structure, waste loading, and reduced water supply. Therefore, the remedy may require a combination of mitigation measures. One possible remedy is to examine the temporal distribution of the water supply throughout the year and the redistribution of that supply during critical time periods. This is the subject of an instream flow study, discussed in Sections 5.2.1 and 5.2.3b. An instream flow study should accomplish several goals. First, a water allocation plan should be developed so that a monthly instream flow requirement is met and protected. Secondly, critical months and habitat types during the year should be identified. Months (or places) where water could be diverted without reducing available or effective habitat and the amount of diversion should be determined.

b. <u>Instream flow recommendations using effective habitat time series.</u> Monthly instream flow recommendations can be made using the optimization techniques shown in Section 5.2.1. However, the biggest drawback to using the optimization matrix approach is the lack of a connection between the recommendations for different months. This problem can be overcome by using habitat ratios and a variation of the effective habitat time series. A monthly habitat time series is used instead of an annual series, and the flow regime developed corresponds to a water year having a specified exceedance probability. The basic approach starts by finding the smallest amount of adult habitat available during the year. Then, the habitat ratios for other life stages are used to compute the amount of subadult habitat needed to support the minimum available adult habitat. Comparison of the subadult habitat needed and the amount available will quickly reveal whether there is enough to support the available adult habitat. If one or more life stages appear to be limiting, then the actual habitat of the most limiting life stage is used as a starting point and the required amounts of habitat for other life stages calculated, based on this limit. The flows corresponding to the respective habitat requirements can be found from the habitat area vs. discharge function, as developed in Section 5.1.

The approach to determining required habitat by life stage is illustrated below, using the habitat areas for four life stages of a species over a range of flows encompassing the 50% to 90% annual exceedance probabilities for a stream (Table 18). The habitat ratios used in this example are:

Fry:Spawning = 1.5:1.0
Juvenile:Fry = 2.67:1.0
Adult:Juvenile = 1.25:1.0
Spawning:Adult = 0.1:1.0

Two habitat area values are listed for each flow in Table 18, one for summer conditions (influenced by temperature) and one for fall, winter, and spring conditions. The summer conditions apply for June, July, and August. Table 19 contains the monthly discharges corresponding to a median (50% exceedance) water year and the available habitat areas for each life stage, by discharge and month.

This species spawns in April and May with the bulk of the spawning activity in early May. The eggs incubate approximately 7 weeks with emergence completed around the first week in July. Fry are not normally present in the stream during the high runoff period. The species is sexually mature by age III.

The minimum amount of adult habitat occurring during a median water year is 20 units (Table 19) in August. At least 80% of this amount (16 units) of juvenile habitat is needed to support this adult value, based on the adult to juvenile habitat ratio. The actual amount of juvenile habitat available is less than 16 units in May (11), June (6), and August (13). At least 2.25 units of fry habitat are needed to support the minimum available juvenile habitat (6.0/2.67 = 2.25). The amounts of spawning and fry habitat do not appear to be a problem under median flow conditions.

Table 18. Total habitat areas for four life stages of an evaluation species over a range of flows, for summer (S) and nonsummer (NS) conditions. (One habitat area unit = 1,000 ft^2.)

Discharge	Spawning	Fry		Juvenile		Adult	
	NS	NS	S	NS	S	NS	S
10	0.2	18.0	0.0	16	4	12	5
20	1.0	15.0	0.5	18	8	16	10
30	2.0	13.0	2.0	24	11	24	16
40	4.0	11.0	4.0	26	13	28	20
50	5.0	9.0	6.0	25	16	32	25
60	6.0	7.0	7.0	25	18	34	27
70	6.5	6.0	6.0	24	20	36	30
80	6.5	5.0	5.0	24	21	38	33
100	7.0	4.5	4.5	21	21	40	35
120	7.5	4.5	4.5	18	18	42	40
140	8.0	4.0	4.0	15	15	45	45
160	8.5	3.0	3.0	13	13	45	45
180	8.0	2.0	2.0	11	11	45	45
200	7.5	1.5	1.5	9	9	42	42
220	7.0	1.0	1.0	8	8	40	40
240	6.5	0.7	0.7	6	6	38	38
260	6.0	0.5	0.5	5	5	32	32
280	5.0	0.2	0.2	4	4	30	30
300	4.0	0.0	0.0	3	3	25	25

Table 19. Monthly discharges and habitat areas for four life stages of an evaluation species, corresponding to a median water year.

Month	Discharge (cfs)	Habitat Units[a]			
		Spawning	Fry	Juvenile	Adult
October	30		13	24	24
November	25		14	21	22
December	28		13	22	23
January	30		13	24	24
February	32		13	24	25
March	50		9	25	32
April	35	3		25	26
May	180	8		11	45
June	240			6	38
July	90		4.5	21	34
August	40		4.0	13	20
September	25		14.0	21	24

[a]one habitat unit = 1,000 ft^2

The recommended flow regime can be developed in one of two different ways. The first way is to build a flow regime around the currently limited life stage (juveniles), without adjusting the flows to raise the limit. Using this method, flows which provide 1.5 units of spawning habitat, 2.25 units of fry habitat, and 7.5 units of adult habitat would be consistent with a 6-unit limitation on juvenile habitat. The discharges which would provide these amounts of habitat are taken from Table 18 and displayed as a recommended flow regime in Table 20.

Table 20. Monthly flow recommendations for a median water year based on limited habitat type with no change to the current limit.

Month	Flow (cfs)	(Lifestage)	Month	Flow (cfs)	(Lifestage)
October	10	juvenile-adult	April	25	spawning
November	10	juvenile-adult	May	25	spawning
December	10	juvenile-adult	June	240	juvenile
January	10	juvenile-adult	July	15	juvenile
February	10	juvenile-adult	August	15	juvenile-adult
March	10	juvenile-adult	September	10	juvenile-adult

A second approach to designing an instream flow regime is to increase the amount of limiting habitat, thereby increasing the utilization of other habitat types. This is one area where instream flow reservations under State law can deviate significantly from operational design associated with mitigation plans. This is true because there can be considerably more flexibility in the design of operational schedules for a project, which usually implies physical control of the water, than in the instream flow reservation process. Habitat limitations may occur in free flowing streams (i.e., the reservation process) over which there is no control. In the example in Table 19, juvenile habitat is limited by high flows in June. This is an example of an instance where the limit could be raised, even in an instream flow reservation, by allowing diversion of high flows during June. This option would not necessarily require storage or physical control of the water.

The recommended June flow could be lowered to 180 cfs, the same as the existing May flow, increasing the limited juvenile habitat from 6 units to 11. The extent to which high flows can be reduced is limited, with or without storage. There is also a limit on the amount of habitat increase that would be reasonable without physical control of the water. The most juvenile habitat needed is 16 units, based on the adult habitat available in August; this could be accomplished by recommending a June flow of about 130 cfs (from Table 18). However, this represents a significant reduction in the channel forming or channel maintenance flow. Therefore, an analysis of the flow needed to maintain the integrity of the channel is advisable. Realistically, the most juvenile habitat that could be made available is about 13 units. This is the amount available to juveniles in August and this limit cannot be changed without increasing the flow. The option of raising the limit through an increased flow might be feasible in the design of project operations for a mitigation plan, but probably could not be accomplished through instream flow reservations.

A recommended flow regime for a median water year is presented in Table 21, based on the assumptions that the juvenile habitat limit can be raised to 13 units by decreasing the May and June flows and that these flow reductions will not affect the channel structure.

Table 21. Monthly flow recommendations for a median water year, based on increasing amount of limiting habitat type and adjusting other habitat types accordingly.

Month	Flow (cfs)	Lifestage (habitat units required)	Month	Flow (cfs)	Lifestage (habitat units required)
October	20	adult (16)	April	35	spawning (3.)
November	20	adult (16)	May	35	spawning (3.)
December	20	adult (16)	June	160	juvenile (13)
January	20	adult (16)	July	40	juvenile (13)
February	20	adult (16)	August	40	juvenile (13)
March	20	adult (16)	September	20	adult (16)

The methods for developing recommended instream flows illustrated in Tables 20 and 21 meet all the requirements for an instream flow recommendation: A flow is recommended for each month, the reason for the flow documented, and the consequences of not meeting a recommended flow determined. The first two of these requirements are also met by the optimization matrix. However, the third criterion is met only by the methods illustrated in Tables 20 and 21, where flow requirements for all the months are linked. It is interesting to note that the flows recommended in Table 21 represent only a 16% increase over the water supply needed to provide the flows in Table 20, but result in more than twice the amount of utilized habitat.

The construction of an instream flow regime discussed above is a probabilistic process. This means that the water supply estimate is based on a known probability of occurrence. The example above showed the development of flow recommendations for median water months. The same process should be repeated for months having water supply exceedance probabilities greater than 50%. This provides a series of alternative negotiating positions in the event that the flows recommended for the median condition are unacceptable to other parties involved in the negotiation.

One issue that may surface during the negotiation process is the validity of a flow recommendation based on a water supply having a fixed probability of occurrence. The operation of the system when the natural water supply falls below the instream flow requirement or reservation is of crucial interest to those responsible for water allocation. The problem can be resolved by development of several instream flow recommendations, one for median flow conditions and one or more for high and low water years. This approach has been successfully employed in several cases, but it does have a few drawbacks. The first drawback is that many authorities involved in water allocations prefer only one set of operating rules, not two or three. Many prefer one discharge as a minimum flow. Even the concept of different monthly flow requirements may be resisted in some cases. The degree of resistance depends, in part, on the legislative system in the state for reserving or allocating water. Resistance to multiple allocation schedules is also based on the inability to forecast lean water years. This is less of a problem where storage exists in the system and the water supply for the next year is fairly certain. The water supply in unregulated systems can often be estimated 4 to 6 months in advance, particularly where snow pack is the major contributor to streamflow. The acceptance of multiple water allocation schedules is likely to be higher as the ability to forecast low water supplies improves. It may be necessary to evaluate instream flow requirements across years, incorporating the stochastic variation in streamflow in the recommended flow regime, where it is difficult to predict the water supply.

The actual and effective habitat time series presented in Section 5.2.3a represent the habitat response to these stochastic events. It would be difficult at best to derive a monthly flow regime based only on the annual time series of habitat shown in Figure 23. However, the effective habitat time series reflects changes in the potential utilization of habitat as a consequence of stochastic events which span several years. The effective habitat time series can be reduced to probabilistic terms, incorporating the effects of random events on potential habitat utilization. This is accomplished using a habitat duration curve of the effective habitat time series.

The effective habitat time series tends to be a smoother curve than the actual habitat time series. This is due to the lag in the effects of low habitat availability and the fact that effective habitat does not immediately recover to the level of increased available habitat. Therefore, the median effective habitat over a relatively long time series represents an equilibrium condition. Habitat utilization may fluctuate but will tend to assume the median condition under the historical range of high, medium, and low water conditions.

The goal of an instream flow recommendation may be to prevent the equilibrium point from shifting downward. In this case, the median effective habitat is determined using the habitat duration curve technique illustrated in Section 5.2.2. This value is assumed to be the "limiting" adult habitat. The required habitat amounts, and the corresponding streamflows for subadult life stages, are computed following the procedures described above.

5.2.4 Methods of Deriving Habitat Ratios

Previous sections have demonstrated the value of habitat ratios in the interpretation of habitat data. It is also apparent that some problems can be solved by simple techniques without the use of habitat ratios. When the abundance of a species is always controlled by a single life stage or by the food supply, only the limiting life stage or appropriate food organisms must be evaluated. However, this situation is more likely the exception rather than the rule in most stream habitat analyses. More typically, the limiting life stage cannot be identified, the food supply cannot be proved inadequate, or different life stages and food organisms respond differently to variations in the flow regime. The purpose of using habitat ratios is to estimate the appropriate balance of habitat types so potential limitations can be identified. If habitat ratios are not used, one or more of the following assumptions must be made:

1. The limiting life stage can be identified with certainty:

2. The life stage having the least amount of habitat is always limiting; and/or

3. All life stages and food organisms have the same relative spatial requirements.

The use of habitat ratios may require a reexamination of the traditional expression of limiting factors in riverine ecosystems in terms of space, food, reproduction, or recruitment. Each of these potential limiting factors can be defined in terms of an inadequate amount of habitat for the limiting life stage or food organism compared to the habitat available for other life stages and trophic levels. An underlying assumption of the IFIM is that stream populations of fish that are sensitive to changes in streamflow or habitat structure are, at some time, limited by space. This assumption can also be stated as carrying capacity is limited by the habitat available for one of the life stages, or for some other organism that the species relies on for food, such as forage fish or invertebrates.

Interpretations of the output from the IFIM are facilitated if the following logic is accepted. Each life stage or food organism has certain preferences and tolerances for different habitat conditions. These conditions occur in varying amounts in each stream. Rather than thinking of a stream as being food limited, or spawning limited, the investigator should consider the stream as having an imbalance between food producing or spawning habitat, compared to the amount of habitat available to the adult life phase of the evaluation species. This allows the comparison of adult habitat available under a particular flow regime or project design with the subadult or food producing habitat needed to support it. If the available habitat for another life stage or trophic level is less than the required amount, then that life stage or trophic level may be limiting. This translates to a limiting habitat type, around which the instream flow recommendation or mitigation plan can be based.

Several methods can be used to derive habitat ratios among life stages and trophic levels: professional judgement, historical and empirical evidence, and mathematical derivation. Ratios derived by professional judgement are not necessarily less accurate than those obtained from the more deductive methods, but it is often difficult to identify the assumptions on which the ratios are based. Variations of these methods can be used to derive habitat ratios among life stages or between trophic levels. However, there are significant differences in the procedures followed and the factors considered for life stage habitat ratios and those for different trophic levels. The derivation of life stage ratios preceeds the discussion of trophic level ratios in each of the following sections because trophic level relationships are usually more complicated.

a. Professional judgement, historical evidence, and comparisons among streams. Habitat ratios can be determined on the basis of professional judgement, historical evidence, and comparisons between streams. The three methods are so interrelated that they have been combined under one discussion. Professional judgements are usually formulated from experience the investigator has gained from examining numerous streams over a period of time.

Life stage ratios can be bounded with respect to adult habitat. The space requirement for any life stage is a function of the total biomass and the density of the cohort. Density, in the context of the IFIM, refers to the number or weight of fish per unit weighted usable area. In this respect, density is different from standing crop, which is computed on the basis of surface area. A life stage with a small biomass or a high density requires proportionately less space than one with a large biomass or a low density. Generally, the adult life stage has the largest biomass and lowest density and, therefore, the habitat ratios between subadult and adult life stages will nearly always be less than 1:1. The most likely exceptions are when adults defend a very large spawning territory (spawning density is very low) or when juveniles comprise the bulk of the biomass, as may be the case with salmon. If the investigator can estimate the approximate distribution of the total biomass among the various cohorts, and their relative densities, a reasonable estimate of the appropriate habitat ratios can often be derived by professional judgement and experience. This judgement is made easier by the fact that the ratios are bounded: juveniles need less space than adults but usually more than fry. Care must be employed when applying these bounds to very fecund species because they frequently produce a large quantity of fry. The biomass of fry may temporarily exceed that of juveniles, but because of the high fry mortality associated with these species, this condition does not last very long. The assumption that each life stage requires twice as much space as the previous life stage might not be accurate, but it is more accurate than assuming equal space requirements.

Most professional fisheries biologists would prefer some empirical evidence to reinforce their judgements. Such evidence can be obtained from the stream under study and by comparisons made with other streams. The habitat areas in the stream under study can be simulated over a time series, as discussed in Section 5.2.2. This will provide the ratios among the various habitats, by life stage, that have historically existed in the stream. These ratios vary from year to year because they reflect the available, rather than required, habitat for each life stage. However, habitat ratios can be derived by taking the average of the historical habitat ratios over the time series. For example, the average of the ratios between fry and juveniles in Figure 21 (Section 5.2.3) is 0.7:1.0, with a standard deviation of 0.69. The standard deviation is an important statistic with this method. Large standard deviations from the average habitat ratio indicates that the habitat types used in the ratio are affected differently by natural fluctuations in the flow regime. Therefore, one life stage is likely to be more limited under one set of streamflow conditions and the other life stage more limited under a different set of conditions.

The use of historical habitat ratios is strengthened immensely if a very weak or very strong year class can be tracked over the habitat time series. Referring again to Figure 21 as an example, suppose that year class 2 is weak but the year classes from years 6 and 7 are strong. The ratios between fry and juvenile habitat availability in this case are computed for the year class, across years (i.e., fry habitat from year 2 with juvenile habitat from year 3, with adult habitat from year 4). The habitat ratios for the weak year class are:

adult (year 1):spawning (year 2) = 2.0:1.0
spawning (year 2):fry (year 2) = 2.0:1.0
fry (year 2):juvenile (year 3) = 0.3:1.0
juvenile (year 3):adult (year 4) = 1.67:1.0

The habitat ratios for year class 6 are:

adult (year 5):spawning (year 6) = 0.625:1.0
spawning (year 6):fry (year 6) = 3.33:1.0
fry (year 6):juvenile (year 7) = 0.6:1.0
juvenile (year 7):adult (year 8) = 0.43:1.0

and for year class 7:

adult (year 6):spawning (year 7) = 1.38:1.0
spawning (year 7):fry (year 7) = 4.4:1.0
fry (year 7):juvenile (year 8) = 0.67:1.0
juvenile (year 8):adult (year 9) = 0.5:1.0

Each of the ratios are then examined for patterns. The correct ratio between adult habitat and spawning habitat is not apparent from this example. The ratios for adult to spawning habitat for years 6 and 7 were 2.0:1.0 and 0.625:1.0, respectively, and 2.0:1.0 for year 2. Obviously, neither the number of spawners nor the amount of spawning habitat had any effect on year class strength. Similarly, ratios of 3:1 and 4:1 between spawning and fry habitat were associated with large year classes, but a ratio of 2:1 was associated with the weak year class. It is concluded that the appropriate spawning:fry ratio has not been found either, because the cohort from year 2 had proportionately more fry habitat than spawning habitat, compared to years 6 and 7. However, in both years associated with the strong year classes the ratios between fry and juvenile habitat were around 0.6:1.0 to 0.7:1.0, and the ratios between juvenile and adult habitat around 0.4:1.0 to 0.5:1.0.

Habitat ratios derived from historical evidence by tracking year class strength provide strong relationships that would be difficult to criticize. Unfortunately, this method requires a history of year class strength that will be lacking in many streams. In some cases, this history can be reconstructed from the present age structure of the population. The present age structure may not be too informative if weak or strong year classes are not evident. The most serious problem with this approach is that it may not be possible to determine all the habitat ratios needed, as was the case in the previous example.

The examination of other streams in the vicinity of the study stream can also be useful in the derivation of habitat ratios, particularly if one or more of the streams contains a population that is limited by a known habitat type. In this case, variation over space is substituted for variation over time. Because this approach examines different populations at one point in time, year class tracking is not directly applicable. The investigator must take several precautions in the selection of streams used in this analysis. First, all of the streams should be virtually identical, with respect to water quality and temperature, as these factors affect the basic productivity of the water and are likely to alter the habitat ratios. Second, the study streams must exhibit a large variation in the types and proportions of physical microhabitat conditions. A pattern of habitat ratios associated with streams having good and poor populations should emerge when enough streams have been examined. The main problem with this approach is that many streams may need to be studied (physical habitat measurement and simulation as well as population - age structure estimates) before these patterns become apparent. Unless the derived habitat ratios can be directly related to a known life stage limitation, the ratios found in the various streams are assumed to equal the required ratios. Ratios between available habitat amounts are not necessarily the same as ratios between required habitat amounts.

Similar approaches can be used to estimate appropriate habitat ratios between a fish population and its food supply. One of the oldest habitat ratios in existance was probably derived through a combination of professional experience and comparisons of numerous streams. A familiar concept to many fisheries scientists is that the ideal stream has an equal proportion of riffles and pools. Assuming that the food organisms are primary consumers living in the riffles and that the fish are secondary consumers living in the pools, the habitat ratio implied by this concept is 1:1 between fish and food producing habitat types. This ratio might be appropriate in many trout streams where the fish are primarily secondary consumers. However, this ratio might not be appropriate between invertebrate habitat and adult bass habitat because the adult bass is a tertiary consumer. One of the complicating factors in relating the habitat of a fish at one trophic level with the habitat of a forage fish or macroinvertebrate at another is the efficiency of energy transfer from one trophic level to the next. Odum (1957) estimated that only about 10% of the available energy at a trophic level was transferred to the next higher level. A second complication is that the rate of production is often many times higher in the lower trophic levels than in higher levels (Mann 1967). Whereas proportions of biomass in a population can be used to estimate life stage ratios, proportions between production rates determine the appropriate habitat ratios between trophic levels. Assuming that the production rates are equal and that the energy transfer efficiency is 10%, the implied habitat ratio between the habitat for a food organism and a fish species is 10:1. Since the production rates of fish rarely approach the production rates of macroinvertebrates, a 10:1 ratio may be considered an upper bound of the potential ratios. Conversely, a 1:1 habitat ratio, under the assumption of 10% energy transfer efficiency, implies an invertebrate production rate that is 10 times higher than that of the fish. Although this difference is probably reasonable in some streams, it is likely too high for many others. Therefore, a 1:1 ratio between fish and food producing habitats can be considered a lower boundary of the potential ratios. The actual ratio for any stream probably falls between 1:1 and 10:1. A third complication is caused by competition of two or more species for the same food base. The habitat ratio is computed between the habitat for one species and the habitat for a food organism or group; it does not account for the presence of another species that uses the same food source. A possible solution to this problem is in Appendix B, a discussion of total community food requirements and production rates.

As is often the case, the simplest method of deriving trophic level habitat ratios may also be the best. This method involves a comparison of streams having different proportions of food producing and fish habitat. The various habitat types are simulated for each stream over the growing season and the average ratio between food producing habitat and the habitat for a life stage or species is computed. Then, the condition factor is used to evaluate the adequacy of the food supply over the growing season. The condition factor is computed as:

$$K = \frac{100\ W}{L^3} \tag{5-6}$$

where W = the weight of the fish in grams

L = the length of the fish in centimeters

The comparison of several streams having different proportions of fish and food producing habitat types will reveal a relationship between the habitat ratio and the condition factor, providing that food is the limiting factor in at least some of the streams. If food is not limiting in any of the streams, then this factor can probably be ignored in the habitat analysis for an instream flow or impact study.

Great care must be exercised in the use of the condition factor and in the selection of "calibration" streams. Several factors in addition to food supply, notably water quality and temperature, can affect the condition factor. Therefore, these conditions must be satisfactory in all the streams used in the comparison. The condition factor also varies among species and tends to be higher during summer than at other times of the year (Allen 1951; Weatherley 1972). Therefore, it is recommended that the condition factor be determined during July or August. The condition factor must also be species specific if it is to be used to judge the adequacy of the food supply. A value of K = 1.0 is suggested for trout, but long and slender species, such as ling (Lota lota), could be in excellent condition with a K value less than 1.0. Short, round fish could be on the verge of starvation and still have a K value of 1.0 or higher.

Finally, the streams used in the comparison must be as similar as possible in terms of primary production and allochthonous input (organic matter derived from outside the stream). Great care must be used in the classification and selection of these streams. A suggested approach to this classification is to measure the accumulation of chlorophyll A on glass slides left in the streams for two weeks. The slides should be placed at equal depths in all streams to remove variations due to light penetration.

b. Mathematical derivation of habitat ratios. The mathematical derivation of habitat ratios has several advantages over the simpler empirical approaches. First, the logic for requiring a particular habitat ratio between two life stages is fully displayed when the ratio is mathematically derived; habitat requirements are demonstrated, not inferred. Second, the risk of not obtaining a ratio between two or more life stages, as occurred in the example in Section 5.2.4a, is less when habitat ratios are derived mathematically. Finally, the calculated ratios depict required habitat amounts; they are not simply ratios of the amount of habitat available. The disadvantages of mathematically derived habitat ratios include the amount of data required for their calculation and the difficulty in obtaining these data. These disadvantages may make the mathematical derivation of trophic level habitat ratios prohibitive.

The determination of habitat ratios requires information on the population structure, fish density, food production, and mortality rates. This technique utilizes the same basic logic as a population or ecosystem model. However, simplifying assumptions are made to reduce data requirements, distinguishing this technique from a traditional population model. The first of these assumptions is that an idealized steady state population may be attained under a particular flow regime and if a satisfactory flow regime were developed, that flow regime would be delivered year after year. This assumption is untrue for virtually all free flowing streams, but is used to evaluate the potential, rather than actual, production of the stream.

The second assumption is that the potential carrying capacity of each life stage or food organism is a function of weighted usable area. The weighted usable area needed for each life stage depends on the numbers or biomass of that life stage needed for recruitment to the next life stage, the maximum numerical or biomass density of the life stage, and the annual survival rate of the life stage. Growth and mortality of each life stage are assumed constant over the year, allowing the use of annual growth and mortality rates.

This assumption, more than any other, separates this method from a traditional population model.

Despite such simplifications, the information requirements for determining the appropriate habitat ratios are significant. Such information may be available in the literature, but is probably derived from diverse areas and may not be directly applicable to the stream under study. The best data are derived empirically from the study stream or from "calibration" streams that have been classified according to the methods in Section 5.2.4a. The data required for this process are:

1. The weight-age relationship for the population;

2. The periodicity (see section 2.5) of the population;

3. The life span and age of maturity of adults;

4. Average fecundity per spawning female;

5. Maximum density of spawning pairs (D_s) per unit spawning WUA (WUA_s);

6. Survival of eggs to the fry stage (S_E);

7. Density of fry (D_F) per unit WUA for fry in kg/m² or lb/ft² (numerical density may be substituted);

8. Survival of fry to juvenile stage (S_F);

9. Density of juveniles (D_J) per unit WUA for juveniles in kg/m² or lb/ft² (numerical density may be substituted);[1]

10. Survival of juveniles to adult stage (S_J);[1]

11. Density of adults (D_a) per unit adult WUA, in kg/m² or lb/ft²; and

12. Annual survival of adults (S_a).

[1] If juveniles reside in the stream for more than one year, it may be desirable to compute ratios for different age groups based on different densities and survival rates as the fish grow.

The first step in determining habitat ratios by life stage is to establish a target WUA value for adults and a related adult carrying capacity. This step may take two forms. The first is to select the smallest value of adult WUA which occurs during a year or under a particular management plan, and multiply this value by the density of adults. The second form is to arbitrarily determine an adult biomass and, using the same density value, compute the amount of adult WUA needed to support it. Equation 5-7 defines the relationship between adult WUA and adult carrying capacity:

$$B_a \equiv WUA_a \times D_a \qquad (5\text{-}7)$$

where B_a = the biomass of adult fish in lbs or kg

WUA_a = the weighted usable area for adults in ft² or m²

D_a = the density of adults at carrying capacity in lbs/ft² or kg/m²

The next step is to compute the juvenile recruitment needed to sustain this biomass of adults under steady state conditions. Only a portion of the total available adult WUA will be occupied by newly recruited adults; the rest will be occupied by surviving adults. Therefore, only enough juveniles to fill that portion of the adult habitat vacated through adult mortality are needed. The distribution of the adult biomass among the age classes must be computed to determine the recruitment necessary to sustain the steady-state biomass. The weight-age relationship and adult survival rate are used to make this determination.

The total biomass of adults can be determined by

$$B_a = (W_1)(NI) + (W_2)(NII) + (W_3)(NIII) + \ldots (W_n)(N_n) \qquad (5\text{-}8)$$

where B_a = the biomass of adult fish in g or lbs

$W_1, W_2, W_3, \ldots W_n$ = the average weights of individuals within each age class in g or lbs

$NI, NII, NIII\ldots, N_n$ = the number of adult fish in each age class

However, the number of second year adults equals the number of first year adults times the average annual survival rate for adults

$$NII = (NI)(S_a) \qquad (5\text{-}9)$$

where NII = the number of second year adults

NI = the number of first year adults

S_a = the average annual survival rate for adults

Likewise, the number of third year adults equals the number of second year adults times the average annual survival rate for adults

$$NIII = (NII)(S_a) \qquad (5\text{-}10)$$

By combining equations 5-9 and 5-10, it can be seen that the number of third year adults equals the number of first year adults times the survival rate for the first year, times the survival rate for the second year. If the annual survival rates are fairly constant, this concept reduces to

$$NIII = NI\ (S_a)^2 \qquad (5\text{-}11)$$

Substituting equation 5-11, equation 5-8 may be rewritten as

$$B_a = (W_1)(NI) + (W_2)(NI)(S_a) + (W_3)(NI)(S_a)^2 + \ldots (W_n)(NI)(S_a)^m \qquad (5\text{-}12)$$

where B_a = the biomass of adult fish in g or lbs

$W_1, W_2, W_3, \ldots W_n$ = the average weights of individuals within each age class in g or lbs

S_a = the average annual survival rate of adults

m = the maximum adult life span of the population (total years minus years to maturity)

NI = the number of first year adults recruited from juvenile life phase

Equation 5-12 is solved for NI to determine the number of first year adults needed to maintain the adult population in its current age structure, at a biomass of B_a. If NI is the number of juveniles needed for recruitment at the end of the juvenile stage, then the number of juveniles needed at the beginning of the juvenile stage is:

$$N_J = NI/S_J \qquad (5\text{-}13)$$

where N_J = the number of juveniles needed at the beginning of the juvenile stage

NI = the number of first year adults recruited

S_J = the average annual survival rate of juveniles

By the same logic, the number of successfully hatching fry needed is:

$$N_F = N_J/S_F \qquad (5\text{-}14)$$

where N_F = the number of fry needed at the beginning of the fry stage

N_J = the number of juveniles needed at the beginning of the juvenile stage

S_F = the average annual survival rate of fry

The number of eggs needed is:

$$N_E = N_F/S_E \qquad (5\text{-}15)$$

where N_E = the required number of eggs spawned

N_F = the number of fry needed at the beginning of the fry stage

S_E = the survival of eggs to fry (hatching success)

Finally, the number of redds, nests, or spawning pairs is:

$$N_S = N_E/F \qquad (5\text{-}16)$$

where N_S = the number of redds, nests, or spawning pairs

N_E = the required number of eggs

F = the average number of eggs per redd, nest, or spawning female

The necessary amount of spawning habitat can then be computed:

$$WUA_S = N_S/D_S \qquad (5\text{-}17)$$

where WUA_S = the weighted usable area required for spawning to provide the recruitment to sustain the original biomass, Ba

N_S = the number of redds, nests, or spawning pairs needed

D_S = the maximum density of redds, nests, or spawning pairs that can be accommodated without interference with spawning or survival of embryos

After determining the required number of individuals to be replaced in each life stage, the determination of the desired ratios among WUA values for each life stage is fairly simple. The required number of individuals at the beginning and end of each life stage is multiplied by the average individual weight for the respective time periods to determine the maximum biomass of that cohort. The largest amount of WUA for the cohort is required when biomass is at the maximum. This value is found by dividing the maximum cohort biomass by the density value for that cohort. For example:

$$WUA_J = B_{Jmax}/D_J \qquad (5\text{-}18)$$

where WUA_J = the maximum required WUA for juveniles in ft^2 or m^2

B_{Jmax} = the maximum biomass of the juveniles in kg or lb

D_J = the density of juveniles at carrying capacity in kg/m^2 or lbs/ft^2

A safety factor should be applied to the computed WUA requirements before arriving at a final set of WUA ratios among the various life stages. The safety factor is analogous to the principle of overdesign in structural engineering. The purpose of the habitat ratio is to ensure an adequate amount of subadult habitat. After the best estimate of this requirement is determined, the safety factor is added as an extra precaution. Depending on the user's confidence in the coefficients leading to the ratios, this safety factor varies from 10 to 25%. For example, if the calculations indicate that 500 ft^2 of juvenile habitat are needed to support 1,000 ft^2 of adult habitat, a safety factor is applied to the juvenile WUA before computing the final ratio. A 25% margin of safety would result in a desired ratio of 625 to 1,000 (0.625:1) rather than the computed 500 to 1,000 (0.5:1) ratio.

The following example illustrates the mathematical derivation of habitat ratios. For example, suppose a brown trout population exhibits the following periodicity: Spawning occurs in November, followed by a 60-day incubation period. The first swim-up fry are observed in early March (termed Fry 1). By July, the fry have grown to fingerling size (termed Fry 2). The Fry 1 and Fry 2 stages both use the same type of habitat, but have different densities and survival rates. The Fry 2 stage lasts until the next March, at which time the fingerlings are recruited to the juvenile phase. Juveniles are recruited to the adult phase after 1 year. The adult stage lasts 3 years, with no fish surviving beyond age V. Vital statistics for the population are in Table 22.

Table 22. Vital statistics for a sample fish population used in the mathematical derivation of habitat ratios.

Life stage	Weight range over time period (g)	Annual survival	Density at carrying capacity (g/ft²)
Egg	--	.15 (s_e)	(D_{sp}) 125[a]
Fry 1	.4-9	.20 (s_{f1})	(D_{f1}) 14
Fry 2	9-45	.25 (s_{f2})	(D_{f2}) 11
Juvenile	45-140	.20 (s_j)	(D_j) 5
Adult II	140-320	.50 (s_a)	(D_a) 6
Adult III	320-500	.50 (s_a)	(D_a) 6
Adult IV	500-600	.50 (s_a)	(D_a 6

[a]Based on 1 redd per 12 ft² and 1,500 eggs per redd; value is in numbers per ft² rather than grams per ft².

Step 1: Determine target adult WUA and adult biomass at carrying capacity. Assume the minimum WUA_a for the year equals 7,500 ft². The biomass which could be supported at carrying capacity density, from Equation 5-7, would be

$$WUA_a \times D_a = Ba$$

$$7{,}500 \text{ ft}^2 \times 6 \text{ g/ft}^2 = 45{,}000 \text{ g}$$

Step 2: Compute the weight distribution among adult age classes, and solve for the number of juveniles needed for recruitment.

From Equation 5-12, the distribution of the 45,000 g at the time of recruitment is as follows:

$$W_1 \times NI + (s_a) \times (W_2) \times (NI) + (s_a)^2 \times (W_3) \times (NI) = B_a$$

$$140NI + (.5) \times (320) \times (NI) + (.5)^2 \times (500) \times (NI) = 45{,}000 \text{ g}$$

solving for NI, the number of juveniles needed for recruitment is:

$$140NI + 160NI + 125NI = 45,000$$

$$NI = 106$$

Step 3: Compute the number of fry needed to provide the required number of juveniles. The number of juveniles at the beginning of the juvenile phase is (by Equation 5-13)

$N_J = NI/S_J = 106/0.2 = 530$ juveniles at the beginning of the juvenile life stage

The number of fingerlings (F2) required is:

$N_{F2} = N_J/S_{F2} = 530/0.25 = 2,120$ fingerlings at the beginning of the F2 life stage

The number of swim-up fry (F1) required is:

$N_{F1} = N_{F2}/S_{F1} = 2,120/0.2 = 10,600$ hatched fry

Step 4: Compute the required number of eggs and redds.

$N_E = N_{F1}/S_E = 10,600/0.15 \simeq 71,000$ eggs

The number of redds required is:

$N_r = NE/\text{eggs per redd} = 71,000/1,500 = 47$ redds

Step 4: Compute the appropriate WUA values to support the available adult WUA for each life stage at its maximum biomass.

Life Stage	Initial biomass	Final biomass
Juvenile	45 g x 530 = 23,850 g	140 g x 106 = 14,840 g
Fry 2	9 g x 2,120 = 19,080 g	45 g x 530 = 23,850 g
Fry 1	.4 g x 10,600 = 4,240 g	9 g x 2,120 = 19,080 g

The required WUA for each life stage is then:

Juvenile = 23,850 g/5 g/ft² = 4,770 ft² Juvenile WUA

Fry 2 = 23,850 g/11 g/ft² = 2,168 ft² Fry WUA (July to March)

Fry 1 = 19,080 g/14 g/ft² = 1,363 ft² Fry WUA (March to July)

Spawning = 47 redds x 12 ft²/redd = 564 ft² spawning WUA

Step 5: Apply safety factor and compute desired ratios between each life stage and adult. The following calculations assume a 25% safety factor.

$$\frac{WUA_J}{WUA_a} = \frac{(4,770 \times 1.25)}{7,500} = \frac{5,962}{7,500} \approx \frac{0.8}{1}$$

$$\frac{WUA_{F_2}}{WUA_a} = \frac{(2,168 \times 1.25)}{7,500} = \frac{2,710}{7,500} \approx \frac{0.4}{1}$$

$$\frac{WUA_{F_1}}{WUA_a} = \frac{(1,363 \times 1.25)}{7,500} = \frac{1,703}{7,500} \approx \frac{0.2}{1}$$

$$\frac{WUA_{sp}}{WUA_a} = \frac{(564 \times 1.25)}{7,500} = \frac{705}{7,500} \approx \frac{0.1}{1}$$

Step 6: Compute the desired ratios between adjacent life stages.

$$\frac{WUA_a}{WUA_J} = \frac{7,500}{5,962} \approx \frac{1.25}{1}$$

$$\frac{WUA_J}{WUA_{F_2}} = \frac{5,962}{2,710} \approx \frac{2.0}{1}$$

$$\frac{WUA_{F_2}}{WUA_{F_1}} = \frac{2,710}{1,703} \approx \frac{1.6}{1}$$

$$\frac{WUA_{F_1}}{WUA_{sp}} = \frac{1,703}{705} \approx \frac{2.4}{1}$$

Habitat ratios between trophic levels can also be derived mathematically, in theory. In practice, the derivation of trophic level habitat ratios by comparisons of different streams is a more practical approach. The following discussion is included to help the investigator derive appropriate habitat ratios from professional judgement and experience in the event that comparisons of different streams cannot be made. A more rigorous discussion of this subject is in Appendix B.

The characteristic that distinguishes trophic level habitat ratios from life stage ratios and makes accurate mathematical derivation difficult is that trophic level ratios are based on production rates. Production, especially of macroinvertebrates, is very difficult to measure in streams and varies greatly from stream to stream. Mann (1967) quotes production to biomass (P/B) ratios that vary by an order of magnitude depending on the life span of the organism and the rate of predation.

Production can be defined as the product of the production to biomass ratio and the average biomass:

$$P = (P/B) \times B \qquad (5\text{-}19)$$

where P = production in g/m^2/unit time

P/B = the ratio between production and biomass

B = the average biomass in g/m^2 measured for a specified time period

Combining Equations 5-7 and 5-19

$$P_i = WUA_i \times D_i \times (P/B)_i \qquad (5\text{-}20)$$

where WUA_i = the weighted usable area for an organism in ft^2 or m^2

D_i = the biomass density of the organism in g/ft^2

Assuming that a fish feeds exclusively on a food organism with 100% cropping efficiency and that all of the food energy consumed is utilized, the amount of food produced must equal the amount consumed if the fish is to maintain its growth rate.

By equation 5-21

$$P_i = WUA_i \times D_i \times (P/B)_i = WUA_F \times D_F \times (P/B)_F = P_F \qquad (5\text{-}21)$$

where P_i = the production rate of the food organism

WUA_i = the weighted usable area for the food organism

D_i = the biomass density of the food organism

$(P/B)_i$ = the production to biomass ratio for the food organism

WUA_F = the weighted usable area for the fish

D_F = the biomass density of the fish

$(P/B)_F$ = the production to biomass ratio for the fish

P_F = the production rate of the fish

Thus, the habitat ratio between the fish and the food organism, under the above assumptions, is:

$$\frac{WUA_i}{WUA_F} = \frac{D_F \times (P/B)_F}{D_i \times (P/B)_i} \quad (5\text{-}22)$$

However, the cropping rate cannot be 100% without eliminating the food item (in fact, the production to biomass ratio of the food item will increase as the cropping rate increases). Therefore, additional food producing habitat must be provided because of incomplete cropping. Furthermore, only about 10% of the energy at one trophic level is transferred to the next higher (Odum 1957) so the ratio in Equation 5-22 needs to be increased by a factor of 10. Finally, the food organism may comprise only a fraction of the total diet of the fish, so the ratio must be reduced accordingly. Incorporating all of these factors, Equation 5-22 can be written as

$$\frac{WUA_i}{WUA_F} = \frac{D_F \times (P/B)_F \times K}{0.1\ D_i \times (P/B)_i \times CR} \quad (5\text{-}23)$$

where K = a constant for the portion of food item, i, in the diet of the fish

CR = the cropping rate of the fish on the food item

other terms have been defined previously

The derivation of habitat ratios by comparisons among streams as discussed in Section 5.2.4a is preferred over the use of Equation 5-23 unless each of the coefficients in the equation can be determined for the stream under investigation. The primary use of Equation 5-23 is in helping a user derive habitat ratios by professional judgement. Each of the terms in Equation 5-23 should be considered in making these judgements and if reasonable estimates of these terms can be made, a habitat ratio can be derived directly. However, the user is advised that the ratio is only as accurate as the terms used to derive it.

There are two opposing criticisms of the mathematical derivation of habitat ratios (either life stage or trophic level ratios). The first criticism is that a large amount of data is needed to compute the ratios. This fact cannot be denied, but if the data are obtained from the stream under investigation, the ratios should be very reliable. However, many investigators will not be able to collect these data in routine applications of the methodology. The best solution to this problem is to spur the interest of the research community to develop a large data base. In the interim, the investigator may need to rely on data from the literature. Although this is a poor second choice, some of these data are available for different parts of the country. If this option is chosen, production studies are better sources of data because the growth and mortality rates are related to density. This relationship is typically missing from age and growth studies. A list of possible literature sources is contained in Section 5.3.

The second criticism of habitat ratios is that they ignore the phenomena of compensatory growth and survival. This is true only when average annual growth, survival, and densities are used. Density dependent habitat ratios can be derived if the relationships between growth, survival, and density are known. However, the determination of density dependent growth and mortality rates is an order of magnitude more difficult than the determination of average annual values. The assumption of constant average annual values is necessary to reduce data requirements. The purpose of deriving habitat ratios is to enable the investigator to determine the appropriate amounts of habitat for various life stages or food organisms so that management emphasis is placed on the correct habitat type. Habitat ratios are not used to predict abundance or production of fish; these predictions can only be made with density dependent growth, mortality, and production data.

5.3 SUGGESTED ADDITIONAL READING

5.3.1 Water Quality

American Public Health Association. 1980. Standard methods for the examination of water and wastewater, 15th Edition. Am. Pub. Health Assoc., Am. Water Works Assoc., Water Poll. Cont. Fed., Washington, D.C. 1134 pp.

Grenney, W. J. and A. K. Kraszewski. 1981. Description and application of the stream simulation and assessment model: Version IV (SSAMIV). Instream Flow Information Paper 17. USDI Fish. Wild. Serv. FWS/OBS-81/46. 199 pp.

Theurer, F. D. 1982. Instream water temperature model. Instream Flow Information Paper 16. USDI Fish. Wildl. Serv. (in preparation). 131 pp.

Thurston, R. V., R. C. Russo, C. M. Fetterolf, T. A. Edsall, and Y. M. Barber (eds.). 1979. A review of the EPA Red Book: Quality criteria for water. Am. Fish. Soc., Water Quality Section, Bethesda, Maryland. 313 pp.

U.S. Environmental Protection Agency. 1976. Quality criteria for water. U.S. Environmental Protection Agency, Washington, D.C. 256 pp.

Velz, C. J. 1970. Applied stream sanitation. Wiley Interscience, New York. 619 pp.

5.3.2 Fish Production Statistics

Allen, K. R. 1951. The Horokiwi Stream: a study of a trout population. Fish. Bull. N.Z. 10:1-238.

Backiel, T. and E. D. LeCren. 1967. Some density relationships for fish population parameters. pp.261-293. In S. D. Gerking (ed.). The biological basis of freshwater fish production. John Wiley and Sons, New York.

Brown, M. E. 1946. The growth of brown trout (Salmo trutta Linn.) I. Factors influencing the growth of trout fry. J. Exp. Biol. 22:118-129.

Buck, D. H. and C. F. Thoits, III. 1970. Dynamics of one-species populations of fishes in ponds subjected to cropping and additional stocking. Ill. Nat. Hist. Surv. Bull. 30(2):68-165.

Carlander, K. D. 1969. Handbook of freshwater fishery biology (Vol. 1). Iowa State University Press, Ames, IA. 752 pp.

__________. 1977. Handbook of freshwater fishery biology (Vol. 2). Iowa State University Press, Ames, IA. 431 pp.

Cooper, E. L. 1953. Mortality rates of brook trout and brown trout in the Pigeon River, Otsego County, Michigan. Prog. Fish. Cult. 15(4):163-169.

Eipper, A. W. 1961. Vital statistics of trout populations in New York farm ponds. Can. Fish. Cult. 29:13-14.

Gerking, S. D. 1954. The food turnover of a bluegill population. Ecology 35(4):490-497.

__________. 1962. Production and food utilization in a population of bluegill sunfish. Ecol. Monog. 32:31-78.

Hartman, W. L. 1959. Biology and vital statistics of rainbow trout in the Finger Lakes region. N.Y. Fish and Game J. 6(2):121-178.

Leclerc, J. and G. Power. 1980. Production of brook charr and ouananiche in a large rapid, tributary of the Caniapiscau River, Northern Quebec. Env. Biol. Fish. 5(1):27-32.

Mann, K. H. 1967. The cropping of the food supply. pp. 243-257. In S. D. Gerking (ed.). The biological basis of freshwater fish production. John Wiley and Sons, New York. 495 pp.

__________, R. H. Britton, A. Kowalczewski, T. J. Lack, C. P. Mathews, and I. McDonald. 1970. Productivity and energy flow at all trophic levels in the River Thames, England. pp. 579-596. In Proceedings of the Symposium on Production Problems in Freshwaters, Kasimierz Dolny, Poland. IBP-UNESCO.

Paragamian, V. L. and D. W. Coble. 1975. Vital statistics of smallmouth bass in two Wisconsin rivers, and other waters. J. Wildl. Man. 39(1):201-210.

Pflieger, W. L. 1966. Reproduction of the small mouth bass (Micropterus dolomieui) in a small Ozark stream. Am. Midl. Nat. 76(2):410-419.

Serchuk, F. M., C. J. Schmitt, and B. Floyd. 1980. Rainbow trout: a population simulation based on individual responses to varying environmental and demographic parameters. Env. Biol. Fish. 5(1):15-26.

Shuck, H. A. 1945. Survival, population density, growth, and movement of the wild brown trout in Crystal Creek. Trans. Am. Fish. Soc. 73:209-230.

Simco, B. A. and F. B. Cross. 1966. Factors affecting growth and production of channel catfish, *Ictalurus punctatus*. Univ. Kans. Mus. Nat. Hist. Pub. 17(4):191-256.

Warren, C. E. and G. E. Davis. 1967. Laboratory studies on the feeding, bioenergetics, and growth of fish. pp. 175-214. *In* S. D. Gerking (ed.). The biological basis of freshwater fish production. John Wiley and Sons, New York.

Winberg, G. G. 1956. Rate of metabolism and food requirements of fish. Fish. Res. Bd. Can. Transl. Ser. 194. 253 pp.

6. WATER AND SEDIMENT IN CHANNELS

Previous chapters have stressed the importance of evaluating watershed and channel equilibrium. The evaluation of equilibrium conditions does not require quantification. However, many aspects of an application of the IFIM do require quantification, either of the hydrology or the channel forming characterisitics of the stream. Some of these determinations will be made by biologists, others will be made by consultants retained to make specialized determinations. This chapter is designed to help people untrained in hydrology or geomorphology to understand some of the statistics and physical process models used in these sciences. In this context, the chapter will be of little value to the professional hydrologist or civil engineer. We have attempted to confine the discussion to the essential aspects of stream hydrology and channel dynamics as they apply to the IFIM. The chapter necessarily falls far short of being a complete treatise on any of its subject matter. The "suggested reading" section at the end of the chapter provides sources covering each subject in greater detail. The objectives of the chapter are to describe the basic concepts of watershed science, hydrology, and channel dynamics and to provide the investigator with insights into those aspects of each science that require the experience of a professional.

6.1 RIVER HYDROLOGY

Nearly everyone can recite and describe the hydrologic cycle. When the hydrologic cycle is expressed as an equation for a specific location, it is termed a water balance and is written as:

$$R = P - E \pm \Delta S \qquad (6\text{-}1)$$

where R = runoff

P = precipitation

E = evaporation

ΔS = change in storage

all in units of length (e.g., inches, feet, or meters).

If the water balance is applied to an area, the result is in units of volume, such as acre feet or cubic meters. Application of a time step or rate results in units of volume-rate, such as acre feet per year or cubic feet per second.

Water supplies in rivers are normally measured in units of cubic feet per second. Reservoir water budgets are usually expressed in terms of acre feet per year or acre feet per month. Because water supplies are totally dependent on precipitation, the field of hydrology is primarily interested in the disposition of precipitation over time in terms of runoff, storage, and evaporation.

River hydrology is most concerned with the quantification of runoff. This consists of three essential elements of runoff: volume; timing; and certainty. Volume considerations include such things as the amount of water flowing in the channel at any time, the capacity of the channel, the capacity of lakes and reservoirs in the system, and the amount of water committed to offstream uses. Timing considerations include the periods of high and low runoff and high offstream demands. The element of certainty or risk reflects the probability of certain hydrologic events occurring during a particular time period.

Hydrologic processes can be described mathematically as deterministic, probabilistic, or stochastic. A deterministic model is one which follows a definite law of certainty, but ignores the chance of occurrence of the variables in the process. A simple water routing model, utilizing only a water balance, is one example of a deterministic model. A probabilistic model is one which incorporates the chance of occurrence, but assumes that the sequence of occurrence is independent of previous events. A stochastic process is one which includes both the chance of occurrence and time-dependence among the variables (Chow 1964).

Most hydrologic processes are stochastic, but are treated as deterministic or probabilistic processes for the sake of simplicity. There may be certain errors associated with such simplification. Hydrologic processes may exhibit time series which are not constant; the record may show a trend, such as a unidirectional decrease in summer flows or an increase in peak flows. These trends are often associated with water and land use patterns that have developed during the period of accumulation of the streamflow records. This pattern of land and water use now describes the present system. Use of very long records in areas experiencing such trends may result in higher estimates of water availability than is true from the present viewpoint. A portion of the record will incorporate virgin or near virgin flow conditions, some of which will have been legally appropriated for offstream use. The total record should not be used if such trends are apparent. This is especially true if a dam was constructed sometime during the period of record.

A problem associated with the use of a probabilistic, rather than stochastic, approach is that it misrepresents the phenomenon of persistence. Persistence means that events in a time series are linked by some nonrandom process. It has been observed that wet or dry years tend to occur in groups. Likewise, wet and dry months within a year also occur in groups, responding to seasonal shifts in weather patterns.

Discrepancies in the estimation of monthly and annual water supplies often result from the use of different kinds of flow statistics. These discrepancies can become a source of conflict among the parties involved in streamflow allocations. The time distribution of streamflow is log-normal, resulting in differences between the mean and the median flows for a time interval. A confusing aspect of these sources of variance is that the same types of flow statistics can be applied to different time steps. This practice gives the appearance of an error when, in reality, it is simply the description of different kinds of flow events. The following section describes several ways of assembling a hydrograph using different flow statistics. Some of these techniques give more accurate representations of the total water supply, but are expressed in time steps that are uninformative from a biological perspective. Techniques designed to provide the most biologically significant time step may result in poor estimates of the total water supply. The investigator must match the time step with the level of accuracy needed for either determination. Section 6.1.2 contains a discussion of appropriate time steps. However, it is necessary to discuss the various flow statistics and the synthesis of hydrographs before time steps are considered.

6.1.1 Determination of Flow Probabilities on Gaged Streams

The probability that a certain flow event will occur at a particular time of the year, or in a sequence of years, is determined from the frequency with which the event has occurred in the past. A frequency curve is used to relate the magnitude of a flow event to its frequency of occurrence. Frequency curves have many applications in hydrology. A flood frequency curve is an assemblage of each year's instantaneous peak streamflow, used to define channel capacity, roadbed elevations, and for flood plain zoning. Frequency curves of annual low flows (generally the 7 consecutive lowest flow days) are utilized to design water supply systems and waste treatment facilities.

Two types of frequency curves are commonly used to analyze hydrologic data: the flow duration curve and the recurrence interval curve. A flow duration curve is a cumulative frequency curve of flow events for the period of record. A partial flow duration curve is a cumulative frequency of events for a specific interval, such as 1 month, for the period of record. Virtually any kind of flow statistic can be used in a flow duration curve; e.g., average daily flows, average monthly flows, annual peak flows, or 7-day low flows.

The recurrence interval is the inverse of the probability that a certain flow event will occur. Recurrence intervals are normally computed in years. A 2-year recurrence interval means that the flow event is expected on an average of once every 2 years. A 4-year recurrence interval event will occur on an average of once in 4 years, and a 1.5-year recurrence interval event twice in 3 years. The recurrence interval is not the actual time interval between events of equal magnitude. It represents a mean time interval based on the distribution of flows over the period of record. Because the recurrence interval is expressed in years, it is typical to compute the recurrence interval on the basis of one flow statistic per year. Flood frequency curves use the annual maximum flows; the mean monthly flow is often used to define the distribution of the water supply during the year.

a. Hydrologic data sources. The first step in preparing either a flow duration or recurrence interval curve is to assemble all the flow records for each gaging station on the stream. These are most often found in the Water Supply Paper series of the U.S. Geological Survey (USGS). Many States also maintain their own gaging stations and may also have compilations of streamflow records. Most Water Supply Papers contain either a compilation of average monthly flows for a certain number of years or a 5-year compilation of average daily flows. Either document will probably fall several years short of the currently available data due to the lag time involved in compiling and publishing the records. However, the USGS also publishes a series of paperbacks called Water Resources Data for (State name), which contain the average daily flows by year and by State. Copies of these reports may be obtained from the Water Resources Division of the USGS in each State.

The USGS also maintains streamflow records on its computerized data storage and retrieval system, WATSTORE. The records on WATSTORE are usually current up through the previous year's measurements and often contain a partial record of the current year. A variety of different compilations of the same data may also be retrieved; e.g., average daily flows for each day of the month, mean monthly flows, and monthly or annual maxima or minima.

b. Compilation of flow records. Before assembling hydrologic data for analysis, the record should be examined to ensure that the time series to be used in the analysis can be considered time homogeneous. If a trend, such as a unidirectional decrease in mean monthly flow, can be detected, only the last 20 years of the record should be used. The entire record can be used if a harmonic oscillation (approximate sinusoidal cycles of flow events) is apparent. Partial records should overlap at least one high and low sequence in the cycle. There should be data for at least 10 years in the period of record to ensure minimal definition of extreme events. If a significant alteration to the flow regime has occurred in the middle of the period of record, such as dam construction and subsequent regulation, use only that portion of the record following the alteration.

c. Flow duration curves. A flow duration curve is a plot of the magnitude of the flow versus the cumulative frequency of that flow plus all higher flows. If the flow frequencies are determined by a computer, the frequencies can be computed at intervals of one cubic foot per second (essentially a frequency for every daily flow in the period of record). It is more convenient to increment flows in groups (e.g., ± 25 cfs) and count the occurrences of flows within each group if the frequencies are computed by hand.

To develop a flow duration curve:

(1) Develop an array of flows or flow intervals starting from the highest flows for the month and arraying at intervals to the lowest recorded flow for the month for the period of record;

(2) Tally the daily flows for the period of record in each of the arrayed flow increments;

(3) Divide the frequency within each flow increment by the total number of days in the record to determine the percent of time that increment is represented in the record;

(4) Starting at the increment representing the highest flow, sum the frequencies of each succeeding increment. This process is illustrated in Table 23; and

(5) Plot the magnitude of the flow, or the midpoint of each flow increment, versus the cumulative frequency as determined in Step 4. If this plot is made on log probability paper, an almost straight line will result (Figure 27). If plotted on arithmetic probability paper, a slightly curved (or sometimes sigmoid) line will result (Figure 28).

Table 23. Cumulative frequencies of average daily flows for the Yampa River near Maybell, CO, in August. Period of record 1959-1979.

Average daily discharge	Frequency	Percent of time	Cumulative percent
>900	16	2.5	2.5
875	2	0.3	2.8
850	3	0.5	3.3
825	3	0.5	3.8
800	3	0.5	4.3
775	6	1.0	5.3
750	5	0.76	6.06
700	7	1.0	7.67
675	6	1.0	8.67
650	4	0.61	9.28
625	17	2.6	11.88
600	7	1.0	12.88
575	16	2.5	15.38
550	12	1.8	17.18
525	15	2.3	19.48
500	12	1.8	21.28
475	32	4.9	26.18
450	25	3.8	29.98
425	22	3.4	33.38
400	19	2.9	36.28
375	26	4.0	40.28
350	26	4.0	43.38
325	36	5.5	48.88
300	25	3.8	52.68
275	37	5.7	58.38
250	27	4.1	62.48
225	39	6.0	68.48
200	42	6.5	74.98
175	25	3.8	78.78
150	19	2.9	81.68
125	39	6.0	87.68
100	23	3.5	91.18
75	22	3.4	94.58
50	35	5.4	99.98
25	0	0.0	

As plotted, the median flow for the month is at the intercept of the 50% flow exceedance line. The 90% exceedance flow is the flow that is equalled or exceeded 90% of the time. From Figures 27 and 28, the median flow of the Yampa River at Maybell, Colorado, is 315 cfs during August. The 90% exceedance flow for the same month is 105 cfs.

d. Recurrence interval curves. Recurrence intervals can be computed mathematically or graphically. The graphical approach is somewhat easier to understand and does not require the selection of a particular type of theoretical distribution of the data. Therefore, only the graphical solution will be presented below. For a full description of mathematical curve fitting, see Riggs (1968) or Chow (1964).

The development of a recurrence interval curve consists of arraying the hydrologic data in order of increasing or decreasing magnitude and computing a plotting position for each member of the array. There are many equations that can be used to compute plotting positions (Chow 1964), but the one used by the U.S. Geological Survey is the Weibull formula (Riggs 1968). The plotting position is computed by:

$$T = (N + 1)/m \qquad (6\text{-}2)$$

where T = recurrence interval in years

N = the number of items in the sample

m = the order number in the sample array

The sample data can be arrayed from the highest value to the lowest, or lowest to highest, depending on whether the curve is to describe the probability of exceedance or nonexceedance, respectively. A flood frequency curve data set would contain the maximum instantaneous flows for all years of record, arrayed with the highest value first. A mean monthly flow recurrence interval data set would contain the mean monthly flows for the period of record, arrayed from lowest to highest value, as shown in Table 24. A recurrence interval curve can also be constructed for total annual water supply in acre feet. The latter technique provides an accurate estimate of the probability that a certain annual water supply will be available.

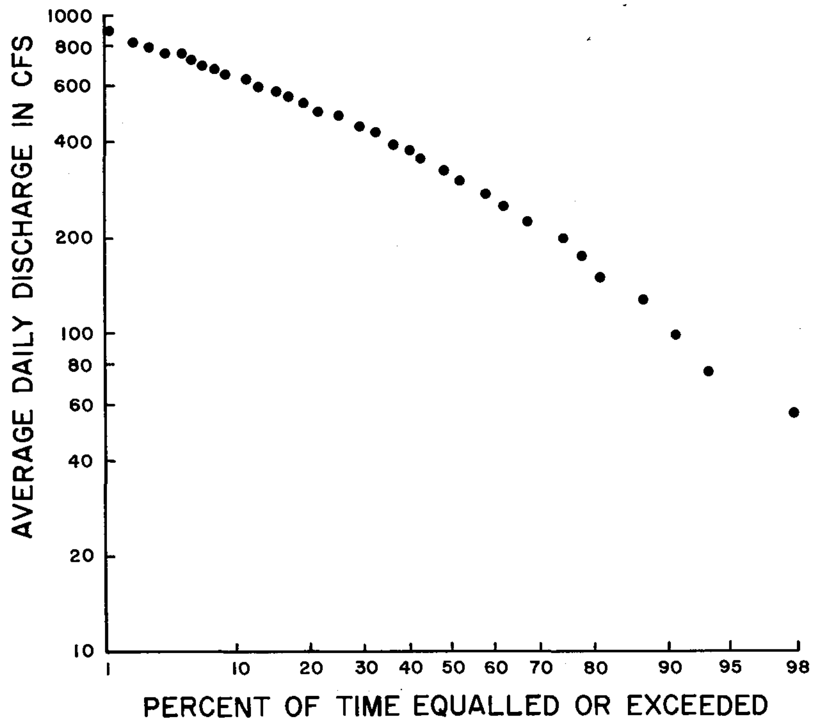


Figure 27. Flow duration curve of daily August streamflows in the Yampa River near Maybell, CO, plotted on log probability paper.

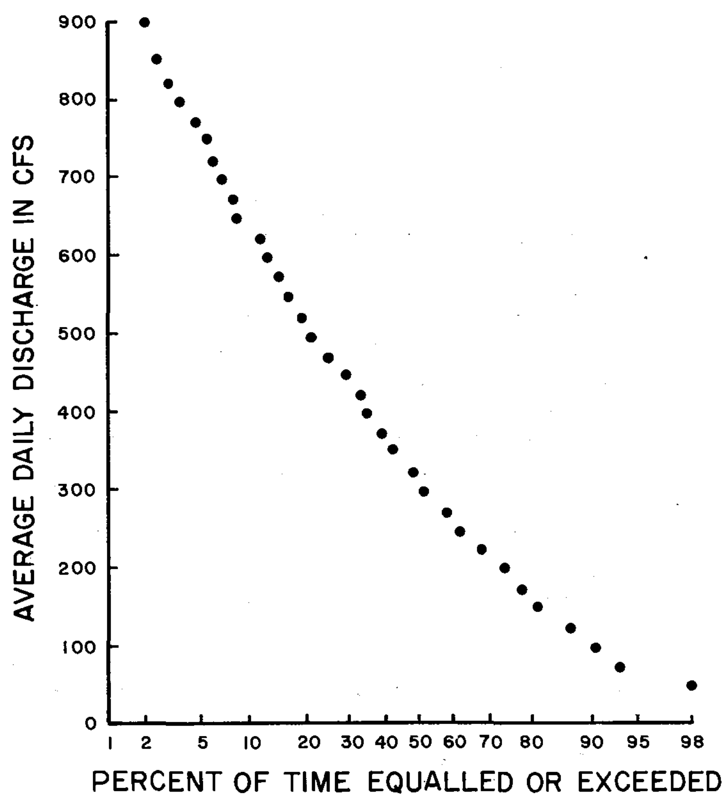


Figure 28. Flow duration curve of daily August streamflows in the Yampa River near Maybell, CO, plotted on arithmetic probability paper.

Table 24. Recurrence intervals, August mean monthly flows, for the Yampa River, CO. Period of record used, 1959-1979.

$\bar{Q}$ August	Rank (m)	Plotting position (N+1)/m
79	1	22.00
123	2	11.00
131	3	7.33
151	4	5.55
155	5	4.40
215	6	3.66
295	7	3.14
314	8	2.75
317	9	2.44
320	10	2.20
340	11	2.00
347	12	1.83
351	13	1.69
357	14	1.57
405	15	1.47
442	16	1.38
509	17	1.29
517	18	1.22
521	19	1.16
598	20	1.10
753	21	1.05

The next step is plotting the flow represented by a member in the array against the computed recurrence interval. There are several types of graph paper which can be used to plot the data. However, for most purposes, the data can be plotted on semilog or log-log paper. It may be enlightening to plot the data on both types of paper, as illustrated in Figures 29 and 30. Figure 29 is a log-log plot of a recurrence interval curve of mean August flows in the Yampa River, near Maybell, Colorado. Figure 30 is a semilog plot of the same data. Figure 30 shows two definite plateaus in the data: one centered around the 2-year recurrence interval and one extending from the 4-year to the 20-year interval. These plateaus are also apparent on Figure 29 but, because of the linearization of the log-log plot, they are not as pronounced. If one were to select a "normal" August flow, the range of 310 to about 350 cfs would correspond to the 1.5 to 3-year interval with a median flow of about 340 cfs. A drought flow would be in the range of 150 to 80 cfs and could be expected on an average of once every 4-years.

The data in Figures 27 through 30 are for the same river and time period. The median flow, as determined by the flow duration method, is 315 cfs; by the recurrence interval technique, the median is 340 cfs. The 90% exceedance flow is 105 cfs on the flow duration curve and about 125 cfs on the 10-year

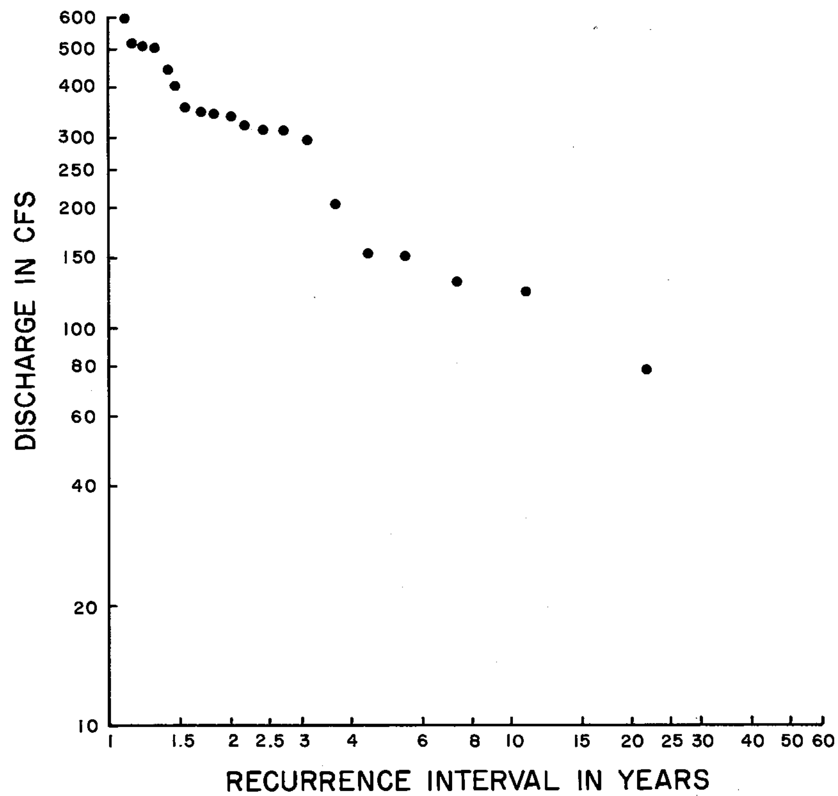


Figure 29. Recurrence interval curve for average August streamflows in the Yampa River, near Maybell, CO, plotted on full logarithmic paper.

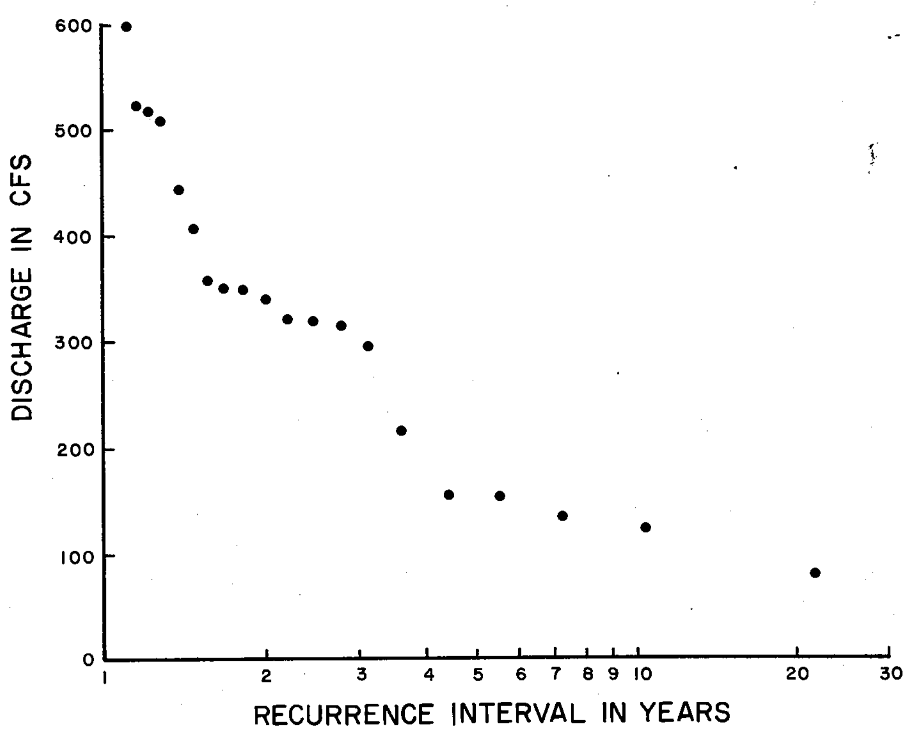


Figure 30. Recurrence interval curve for average August streamflows in the Yampa River, near Maybell, CO, plotted on semi-logarithmic paper.

recurrence interval. The reason for this discrepancy is that average daily flows were used to compute the flow duration curve, while mean monthly flows were used for the recurrence interval curve. The mean monthly flow can be affected by one or two extreme, but infrequent, events. Extreme high or low infrequent events show up as exactly that (infrequent) on the flow duration curve.

6.1.2 Hydrograph Synthesis on Gaged Streams

The objective of developing the flow statistics in Section 6.1.1 is usually to assemble an annual hydrograph representing a certain water supply probability. There are two basic approaches to assembling such a hydrograph, although there may be several variations to each approach.

The first approach utilizes some type of flow statistic for each month and simply appends one month to the next. An average monthly hydrograph uses the average flow for each month for the period of record. The flow used to represent each month can also be taken from a flow duration or recurrence interval curve. A median monthly hydrograph contains the flows equalled or exceeded 50% of the time during each month. Recall, from Section 6.1.1, that there will be a difference in the defined median flow depending on whether the flow duration curve or the recurrence interval was used. A hydrograph representing an extreme water supply condition can also be assembled using either the flow duration or recurrence interval curve. The 90% exceedence flow for each month can be used to construct a low flow hydrograph, for instance.

The second approach defines the probability of occurrence of the water supply in terms of the total annual volume. The average daily flow can be converted from cubic feet per second to acre feet by multiplying by 1.983, and all the daily volumes summed to give an annual total volume for each year. A recurrence interval curve is then constructed for total annual volume instead of mean daily or monthly flow. The distribution of flow within a water year having a certain recurrence interval is found by the following sequence:

1. The average total volume of flow for a month is divided by the average total annual volume to determine the relative contribution for each month, with respect to the total volume (Figure 31);

2. The total annual volume for a water year with a specified probability of occurrence is determined from the recurrence interval curve; and

3. The monthly hydrograph for the water year is calculated by multiplying each month's proportionality constant times the appropriate total volume. The resulting volumes are then converted back to cubic feet per second.

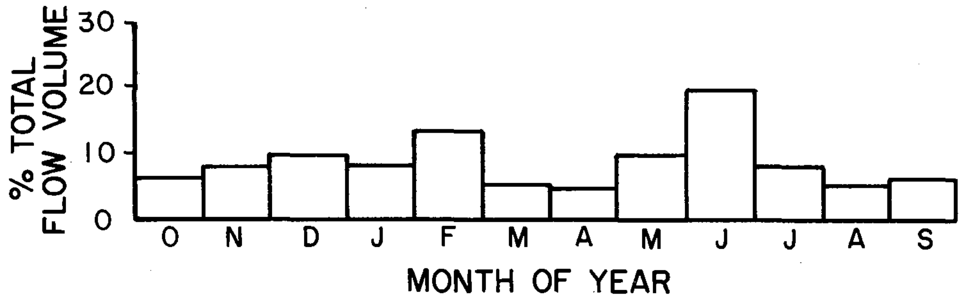


Figure 31. Determination of the total annual water supply over 12 months.

The advantage of using monthly flow statistics is that the probability of a certain flow occurring in any month can be determined with a high degree of accuracy. This makes the monthly estimate more biologically relevent because the error bounds around the estimate are small. The disadvantage of this approach is that total persistence is assumed. One 90% exceedance flow is assumed to be followed by another for 12 months in a row. The sum of all these 90% exceedance flows, converted to an annual volume, will be less than a corresponding 1-in-10 water year based on a recurrence interval of annual volumes. This happens because persistence in hydrologic events is rarely observed for more than 3 or 4 months in a row. Twelve sequential 90% exceedence months would be a fairly rare event, possibly around a 1-in-25 water year, based on the total supply. The opposite effect happens at the high flows for the same reason. A sequence of twelve 10% exceedence flows would greatly exceed the volume represented by a 1-in-10 high water year.

The advantages and disadvantages of using monthly flow statistics are reversed when the annual volume approach is used. A recurrence interval curve based on total annual water volume is naturally better for estimating the availability of water on an annual basis. However, several years may exhibit practically the same total supply with radically different delivery sequences. The time distribution of flow is computed as an average ratio between the monthly and annual flow volumes. This ratio can be fairly consistent during months when the primary source of streamflow is ground water. Surface runoff causes variations in the monthly ratio and the more random the runoff events, the greater the variation. Snow fed streams may have fairly consistent water yield ratios during the primary snowmelt month (June in Colorado). The ratio for the months on either side of the main snowmelt can be highly variable, depending on the snowpack and monthly temperatures. Streams carrying thunderstorm runoff can have even more variability. This variability in the water yield ratios causes the monthly estimate of the flow to be much less certain than the use of monthly flow statistics.

Unfortunately, there is no compromise technique that fits neatly between the two mentioned above. Use of monthly flow statistics alone will result in an underestimate of annual volume during low flow years. This may lead the investigator to believe that less water is available than is actually the case. An artificial constraint can be placed on the range of flows considered to be available during any month. Monthly flows estimated from the annual volume recurrence interval curve will not be artificially constrained, but they may not be very accurate for some months, either. Most of the error is caused by variability in surface runoff during a month. Therefore, the estimates of monthly flows when there is little surface runoff (i.e., base flow months) will have less variability and should be fairly accurate. Most of the variability occurs during high flow months, a period when the investigator may wish to trade water away. Some error in the estimate of flow is tolerable during these months.

Some months or streams may have so much flow variability that the use of monthly flow statistics are biologically meaningless. Months bracketing the snowmelt period may have 2 weeks of high flow and 2 weeks of nearly base flow. Streams in the Great Plains Region are subject to large thunderstorm events that may change the flow by an order of magnitude several times per month. Use of a monthly time step in such streams, especially for time series analysis, may average out the biologically significant flows during the month. The selection of the appropriate time step depends mostly on the monthly variability and rate of change in flow (with or without a project). For most instream flow applications, the smallest time step needed is a week. The most obvious exception is in the evaluation of hydropeaking schedules, where hourly time steps are needed. It should be noted that the primary impact associated with hydropeaking is the rate of change of flow and the migration of suitable habitat across the stream. The models used in the IFIM are steady flow models, and some modifications are needed before the real effects of hydropeaking can be quantified.

Steady flow applications with small time steps require the selection of one of the hydrograph synthesis techniques mentioned above. The proportionality constant applied to the total annual volume is highly variable when determined for a 1 week period. Therefore, the use of the total volume approach will provide a very poor estimate of average weekly flows. The best estimate will be obtained from a duration curve of the average daily flows for individual weeks. The best overall solution may be to use the annual volume recurrence interval and proportionality constants to estimate flows during steady flow months and weekly flow duration curves during highly variable flow months.

6.1.3 Hydrograph Synthesis on Ungaged Streams

An ungaged stream, in the context of this section, is any stream without a sufficient streamflow record to directly use the statistical approaches in Section 6.1.2. Some streams will be gaged, but the period of record will be too short for flow statistics to have much meaning. A 10-year period of record is recommended as the minimum record length to be used to estimate flow statistics. Some streams will have only miscellaneous streamflow measurements taken at irregular intervals. Many of the important fisheries streams will have no streamflow measurements at all. Hydrographs can be synthesized in nearly all of the cases mentioned above. The accuracy of the flow estimates depends on the amount of data available for the ungaged stream as well as for nearby streams.

The technique used to develop or extend a short period of record is to compute a regression between the daily flows of the streams with short records and related streams with long records. If the stream simply has a short record, corresponding daily flows should be sampled (e.g., at 10 day intervals) for the entire period of the shorter record. If the stream has a series of miscellaneous measurements, each measurement should be used as a data point in the regressions. It may be possible to develop regressions for several streams with long term gaging records and select the regression with the best fit. Often, there will only be one gaging station in the vicinity with a long enough record to be used in this manner. Figure 32 shows a regression of daily flows for the Terror River and the Uganik River in Alaska. The Terror River has the shorter period of record.

Once the regression has been performed to the satisfaction of the investigator, flow events of a particular frequency can be determined for the stream having the partial record. This is done by computing the recurrence interval or flow duration for the stream with the longer record and determining the corresponding flow for the other stream. Annual hydrographs of different frequencies can be assembled using either the monthly flow duration or the total annual volume method. However, time steps of less than a month are discouraged because of the errors introduced through correlation.

Despite the large network of gaged streams in the United States, many of the important fisheries streams will not be gaged. Several techniques can be used to estimate an annual hydrograph. The selection of any technique will depend more on the amount of hydrologic and meterologic data available than on the merits of the technique itself. The process of estimating an annual hydrograph can be simply stated as two steps. The first step is to determine the total annual runoff for a specified water year. The second step is to apportion the total runoff into appropriate percentages by month. The most difficult part of the process is usually the estimation of the annual runoff. In most instances, only average annual runoff can be computed so only the average annual hydrograph can be synthesized with any accuracy.

Virtually all techniques for determining average annual runoff use a water balance in one form or another. The term water balance was first introduced by Thornthwaite and Mather (1955) to refer to the balance between inflow of water from precipitation and snowmelt and the outflow from evaporation and streamflow. The difference between inflow and outflow is termed storage and may be positive (inflow > outflow) or negative (inflow < outflow).

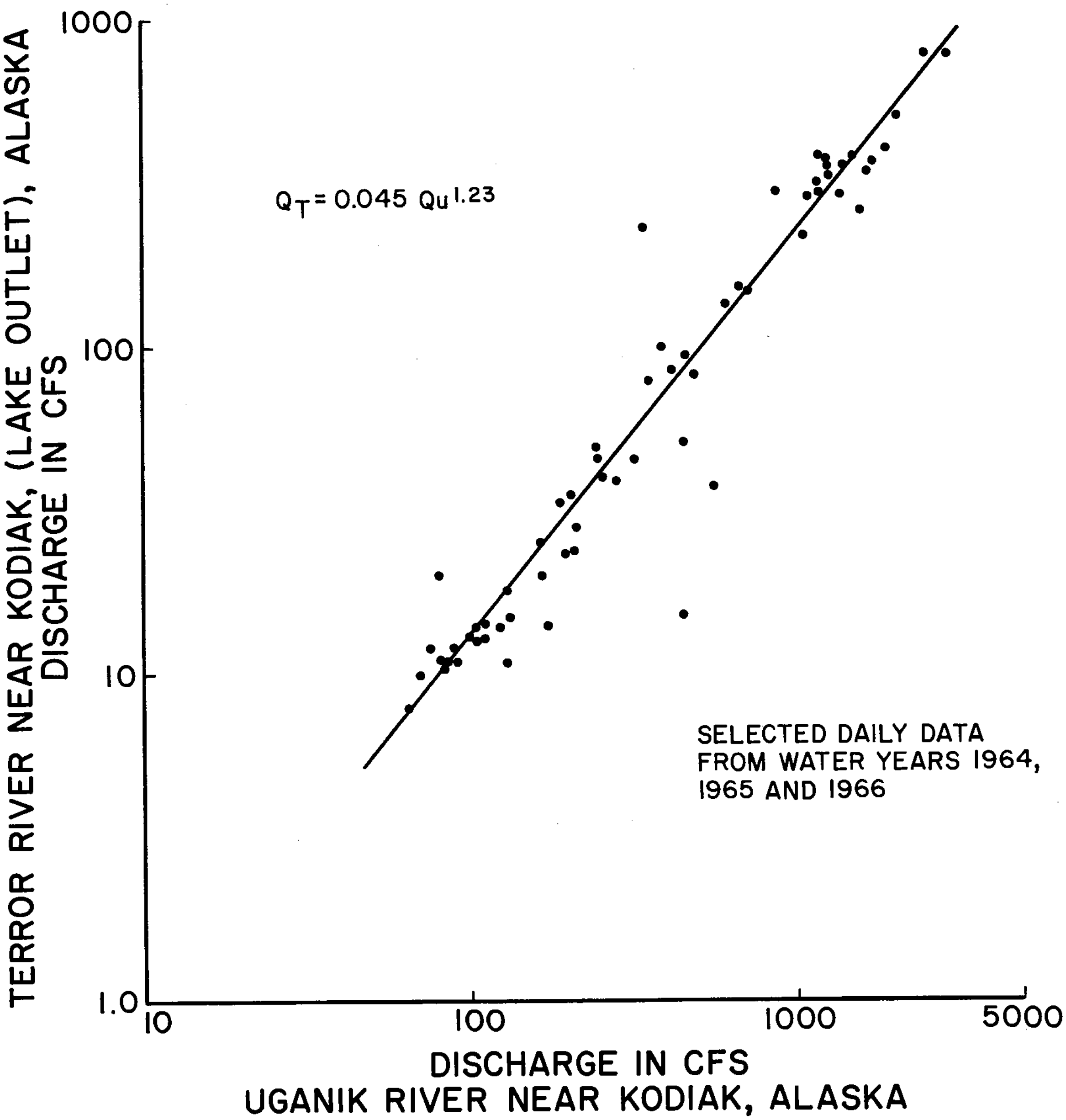


Figure 32. Correlation between mean daily flows of the Terror River and the Uganik River, both near Kodiak, Alaska.

The water balance can be expressed by the following equation (Dunne and Leopold 1978):

$$P = I + AET + OF + \Delta SM + \Delta GWS + GWR \qquad (6\text{-}3)$$

where P = precipitation

I = interception

AET = actual evapotranspiration

OF = overland flow

ΔSM = change in soil moisture

ΔGWS = change in ground water storage

GWR = ground water runoff

It is fairly obvious that the streamflow at any point in time is the sum of overland flow and ground water runoff. It is often assumed that the annual net change in storage is zero, and the right hand side of the equation has only the terms for interception, evapotranspiration, and streamflow. Unfortunately, if a stream is without gaging stations, it is likely without meterological instrumentation as well. Numerous techniques have been developed to sidestep this problem. All of these techniques involve some measure or index of precipitation applied to a catchment area and a related measure of streamflow. One such technique is the use of the area-precipitation product.

The area-precipitation product requires actual measurements of annual rainfall for a particular area, preferably in the watersheds under analysis. However, if such data are not available, it may be possible to obtain an estimate of mean annual precipitation from a rainfall map. The accuracy of rainfall estimates from an isohyetal map (a map showing contours of equal precipitation) depends on the density of rainfall stations used in the data collection for the map and the map scale. The investigator can only control the map scale and should attempt to obtain a map having the largest scale possible.

In the United States, the National Weather Service of the U.S. Department of Commerce is responsible for the gathering and compilation of precipitation data. A useful list of available data on precipitation, entitled Selective Guide to Published Climatic Data Sources, is available from the Superintendent of Documents, U.S. Government Printing Office. Other sources include the Monthly Weather Review and U.S. Weather Bureau Technical Papers (Chow 1964).

The basic technique of the area-precipitation product method is simple, perhaps deceptively so. The first step is to determine the drainage area upstream from each gaging station in the network or for gaging stations in several watersheds in the same hydrologic province. The mean annual precipitation for each area is then determined and multiplied by the appropriate drainage area. Next, a regression line is computed for the drainage area-precipitation product versus the mean annual volume for the gage at the bottom of each drainage area in the regression, as shown in Figure 33. To determine the mean annual volume for an ungaged stream in the same hydrologic province, simply determine its area-precipitation product, and read the mean annual volume from the regression line.

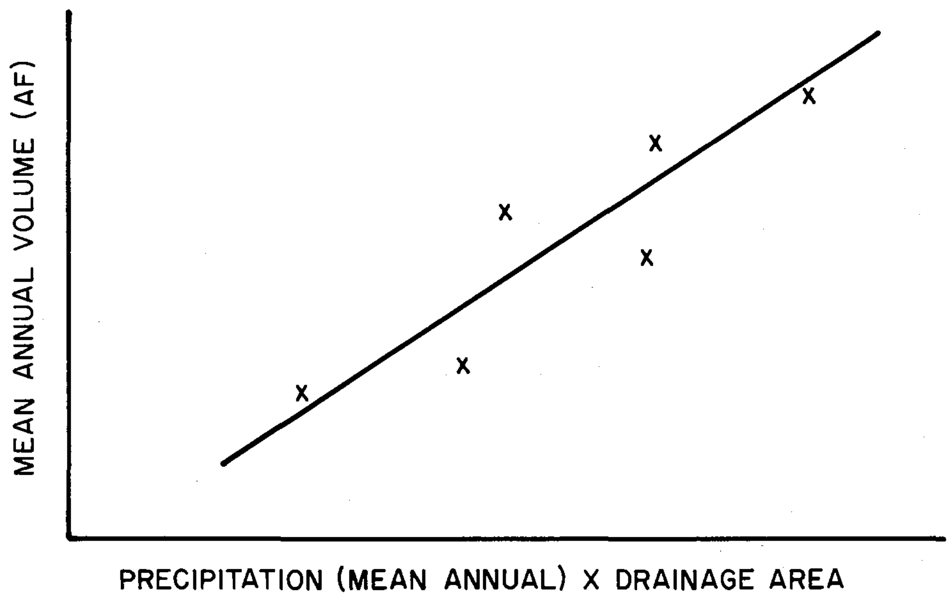


Figure 33. Regression of average annual volume versus area-precipitation products for all gaging stations in a watershed.

This technique is not so simple in watersheds having large elevation changes and corresponding precipitation gradients. In this case, certain portions of the watershed will receive proportionately more rainfall than others. An isohyetal map of each watershed can be used to integrate the effects of differential precipitation, as shown in Figure 34. An area-precipitation product can be computed for each contour interval by determining the area of the drainage lying between two rainfall contours with a planimeter and the average rainfall between the contours. The area-precipitation product for the entire drainage area would then be the sum of the individual products:

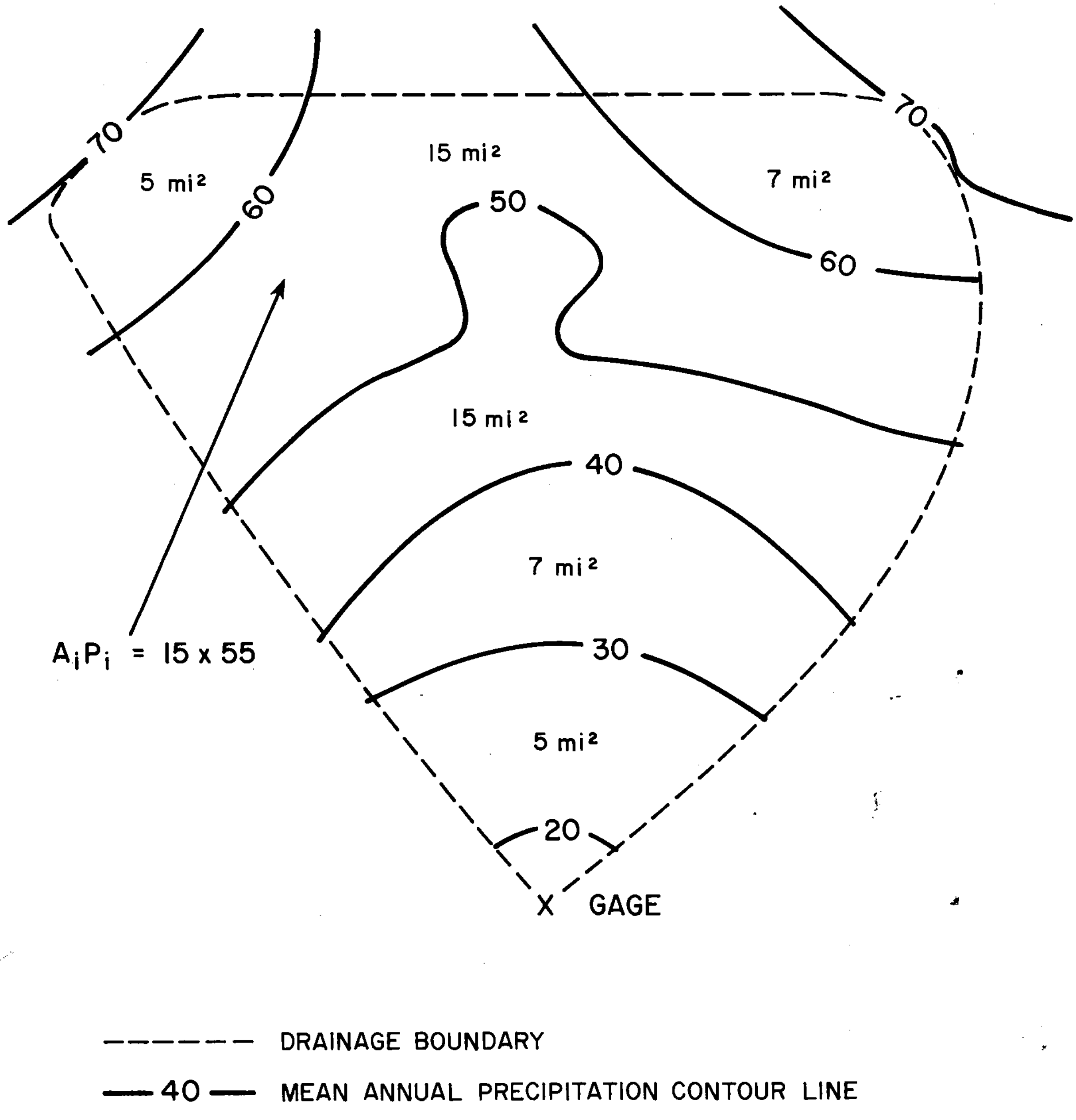


Figure 34. Numerical integration of drainage area-precipitation products, used to estimate mean annual runoff for ungaged streams.

$$AP_{(t)} = \Sigma A_i \bar{P}_i \quad (6\text{-}4)$$

where $AP_{(t)}$ = the area-precipitation product for the watershed area above a gage

A_i = the area of a portion of the total watershed lying between two adjacent rainfall contours

$\bar{P}_i$ = the average annual precipitation computed for two adjacent rainfall contours

The next step is to determine the percentage of the total annual volume contributed by each month's flow at each gaging station. This is done by exactly the same procedure illustrated in Section 6.1.2 for hydrograph synthesis from the total volume recurrence interval (Figure 31). In this case, the proportionality constant is determined for the gaged streams and assumed to be the same for the ungaged stream(s) in the same network.

A surrogate for the area-precipitation product is needed for those drainages totally lacking precipitation data. Elevation is often a good substitute for precipitation, especially in areas subject to orographic precipitation. An area-elevation product is computed and used in the same way as the area-precipitation product. When using this approach, the investigator must select the drainages used in the runoff regression according to aspect. Drainages with west and north facing slopes will have quite different runoff volumes than those facing east and south.

The accuracy of the synthesized hydrographs decreases with each method described in this section. The use of regressions to extend a short record has the greatest accuracy, allowing the synthesis of monthly flows over a wide range of frequencies. The median monthly hydrograph can be developed fairly accurately using regressions with miscellaneous measurements, but flow events of lower frequency are predicted poorly. The average annual hydrograph is about all that can be predicted using the area-precipitation product, unless there is a high density of meteorologic stations in the drainage. The estimated hydrograph using the area-precipitation product will be of fair accuracy, at best. The accuracy of the hydrograph will likely be even poorer using the area-elevation product, but it is better than no estimate at all.

6.1.4 Reservoir Operations

Storage reservoirs in a stream network present unique problems and opportunities associated with instream flow determinations. If the reservoir is an old one, the median and 1-in-10 year flows can be determined utilizing the techniques described in the previous section. The flows released from the dam may, in some cases, be insufficient to realize the potential habitat of the receiving stream, so alternative methods for operating the reservoir may be desired. However, operators of dams frequently deal with operational constraints which limit their ability to provide alternate operating schedules.

Reservoir projects are operated by their owners in numerous ways to meet their objectives, and there are no unified operation procedures applicable to all reservoirs. They may be operated for a single purpose use, multipurpose uses, or as an integral part of a system of reservoirs. Reservoir projects may store water for irrigation, rural and domestic water supply, municipal and industrial water supply, fish and wildlife conservation, water quality, navigation, recreation, flood control, hydropower, and other purposes. Designated project purposes and the priorities established for these purposes determine how a reservoir project is operated. Many of these purposes represent conflicting uses of the available water resources. The design and type of structure and the hydraulic operation of an outlet works determines operational capability and flexibility. In summary, the primary factors that determine how a reservoir project is operated are:

1. Designated project purposes;

2. Assigned priorities; and

3. Type of outlet works.

a. Project purposes and priorities. In general, most reservoir projects to date have not provided for instream flow needs as a project purpose, although many projects do provide for a minimum release. The continued improvement of cooperation between local, State, and Federal agencies and private entities should lead toward increased consideration of instream flow needs. Adequate legislative authority exists for future water resources projects to protect and maintain instream flows. In addition to the quantity of flow, the quality of the water released from reservoirs is an equally important consideration. Water temperature, dissolved oxygen, and dissolved gas saturation are water quality parameters, critical to the survival of fish populations, which may sometimes be controlled or modified by reservoir operations or design.

b. Outlet works. The outlet regulates the release of waters impounded by a dam and can be classified according to physical and structural arrangement and hydraulic operation. It can be described as either a gated or ungated, open channel or closed conduit, structure. A closed conduit can be classified by whether it flows under pressure or as a free flow waterway. A gated outlet has control devices to regulate the amount of water passed through it. An ungated outlet has no control devices, and the amount of water discharged through the structure is referred to as an uncontrolled release. Ungated structures regulate outflow by the temporary storage of that part of the flow which is greater than the capacity of the outlet: an indirect regulation of the flow. No storage occurs if the inflow is equal to the capacity of the outlet works. The release will be less than the inflow if the inflow is greater than the capacity of the outlet. The opposite is true when inflow is less than the capacity of the outlet.

Outlets can be provided with selective withdrawal capability to release the temperature and/or dissolved oxygen levels that are desired in the receiving streams by selectively withdrawing water from the appropriate levels of the reservoir. An outlet can be designed and operated to ensure that supersaturation conditions will not occur downstream from the structure.

c. Selection of reservoir storage and operating pool levels. The determination of storage requirements in a reservoir for the various project purposes normally involves the computational analyses listed below. The analyses are conducted during the preauthorization phase of project planning and usually are updated in more detail during the postauthorization period prior to construction. They include:

1. Inventory of available water supplies;

2. Inventory of existing water rights;

3. Determination of water requirements for the project purposes;

4. Determination of sediment deposition;

5. Reservoir operation studies; and

6. Selection of required storage amounts and operating reservoir pool levels.

An inventory of available water supplies in the study area requires the collection and evaluation of hydrologic and meteorologic data. Sources of streamflow information are the Water Supply Papers of the U.S. Geological Survey and other records maintained by local and State agencies, other Federal agencies, and municipalities. Precipitation data can be obtained from publications of the National Weather Service. Streamflow records are examined to determine past and current trends of streamflow variability, seasonal distribution, instream and offstream uses, diversions, and return flows and to compare streamflow conditions during low flow (droughts), normal, and above normal (flooding) periods. An examination of rainfall and snowfall records provides information for assessing snowmelt runoff and determining rainfall-runoff relationships.

An inventory of the existing surface water rights in the study area is needed. This information is usually obtained from the State agency responsible for maintaining records on applications and approvals for water rights. This information is required because only that portion of the streamflow that is surplus to senior water rights would be available for storage in a proposed reservoir.

Water requirements are determined for each designated purpose being considered for a project. For hydropower, factors to be considered are load requirements and anticipated load growth. For irrigation, consumptive use of water for each crop, irrigation efficiency, conveyance losses, and climatic conditions are considered. The projected growth of demand for water is important for municipal and rural water supply.

Loss of reservoir capacity due to siltation is also considered. An estimate of the projected amount and distribution of sediment deposits within a reservoir is needed to ensure that sufficient additional storage is allocated for the project purposes. Provisions are usually made to provide storage for sediment deposition. This is called dead storage. Dead storage is often provided to last for the life of a project. This means that, for the first decade of the project or even longer, the dead storage space is full of water, not sediment. This can sometimes be used as a potential water supply for an instream flow.

Reservoir operation studies are made to determine the storage requirements for the proposed reservoir project using information on available water supplies, water rights, and water requirements for each project purpose The dependable or safe yield of a project is usually defined as the quantity of water delivered to the user(s) on a firm basis through low flow periods. The duration of this critical low flow period may be 1 year or several years. From reservoir operation studies or an analysis of recurrence of annual volume, dependable yields are determined for given amounts of reservoir storage. A relationship between reservoir capacity and dependable yield is developed for planning and design purposes.

Reservoir operation studies are generally conducted on a daily, weekly, or monthly basis. Reservoir evaporation and seepage are accounted for. That portion of the inflow surplus to downstream water rights and, in some cases instream flow needs, is stored in the reservoir for use later on. Releases or withdrawals are made to satisfy the water requirements of all project purposes. Water shortages may be permissable during infrequent low flow periods for some of the project purposes, thus increasing the dependable yield for a given amount of reservoir capacity. A reservoir operating study is performed for the length of available streamflow records in the study area. The results of this study usually show how the reservoir would have been operated had it been in place over the existing period of record. This is the source of the "with project" flow regime used in impact analysis and mitigation planning.

The operating storage levels selected for a project are an important design consideration. For example, the recreational use of a pool for boating and water skiing may require that the pool level should not fluctuate to any great extent in order to achieve optimal recreation benefits. Another example is the desired objective of raising a pool 3 to 5 feet higher than normal in September or October to enhance waterfowl habitat development along a migratory route. A third example would be to raise or lower the pool level for mosquito control. In many cases, the desired objectives for storage levels may conflict with some of the other designated project purposes. Whenever conflicts occur between project purposes, priorities are assigned to satisfy the most pressing demands first. Depending on the number of projects in an system, it can become very complex and difficult to account for these assigned priorities in an operation study for a system of reservoirs.

6.1.5 Water Budgets

Previous sections in this chapter have introduced the concept of water balancing or budgeting. Sometimes, a water manager will also use the phrase streamflow routing or reservoir routing to describe a water budget. The basic technical difference between budgeting and routing is that the element of time is incorporated into routing but is not a factor in budgeting.

The development of a water budget for an instream flow study can be as important to implementation of the plan as determining the relationship between flow and habitat. The benefits of developing a water balance may not be immediately obvious to a fisheries manager, but they are to a water manager.

Basically, the water balance assembled by the fisheries manager can be the bridge required to establish credibility with the water manager. The water balance enters the IFIM in three ways:

1. Incorporation of existing water rights in the computation of available water supplies;

2. Development of alternative reservoir operations or water management plans to optimize water supplies among offstream and instream uses; and

3. Computation of changes in flow regime resulting from a land use change.

A water budget is an expression of the measurement of continuity of flowing water (Chow 1964). In one form, the continuity equation can be written as:

$$Q_{(1,2)} = Q_1 \pm Q_2 \qquad (6\text{-}5)$$

where $Q_{(1,2)}$ = the combined discharge of the stream below a confluence of two or more sources or the diversion of a source

Q_1 and Q_2 = the respective portions of the combined discharge

The continuity equation can be used as a water balance when transmission losses can either be quantified or assumed zero and nothing has occurred in the watershed to change the rate of runoff. An example would be the case where streamflow records are compiled for a gaging station upstream from a diversion and the investigator wishes to determine the water supply below the diversion. The resultant streamflow can be determined by obtaining measured diversion rates and subtracting them from measured streamflows. Measured return flows can be added back in further downstream. This is elementary for a single diversion, but gets quite complicated in a complex network of diversions and return flows.

Sometimes the amount of water diverted is unknown or the diversion record is poor. In this case, it may be necessary to determine the acreage of various crops and the evapotranspiration rates for each crop to compute the water consumption for each month (Dunne and Leopold 1978). The consumptive loss can then be used to estimate average monthly stream flow losses. However, many of the more complex diversion systems are organized into irrigation or water conservancy districts. If so, the district manager probably keeps very detailed records on diversion amounts and frequencies and may even maintain records on return flows.

Reservoir managers need to worry about more than inflow and outflow as expressed by equation 6-5. They also need to be concerned with storage space and storage losses. Therefore, a water budget for a reservoir uses the more extensive Thornewaite and Mather equation:

$$\Delta S = I - O - E \qquad (6\text{-}6)$$

where ΔS = change in storage in acre feet

I = inflow in acre feet/unit time

O = outflow in acre feet/unit time

E = evaporation in acre feet/unit time

Depending on the project purpose, different storage goals are established for various times of the year. Flood control reservoirs are drawn down prior to the major period of runoff to provide maximum detention of flood peaks. Irrigation reservoirs often begin filling immediately following the irrigation season. As more uses are applied to the project purpose, the storage goals become less flexible. Therefore, making water available for instream uses below multiple purpose reservoirs often requires some type of trade-off analysis in order to attempt to maintain current storage goals. Alternatively, the storage goal must be changed, a process which is often met with resistance.

The investigator should use a water balance to determine the amount of storage in the reservoir at the end of each month if an instream flow regime is recommended below a reservoir. It may be that some of the flow recommendations simply cannot be met because of physical limitations of the reservoir. Others may not be met because of the way the reservoir is operated. In the former case, the flow regime recommendation should be modified. In the latter case, it may be possible to change the operation slightly and meet both the instream flow requirement and the storage goals of the operator.

Where there is a network of reservoirs in a system, a water balance should be computed for each reservoir. Additionally, the continuity equation should be applied to all the outflows to determine various ways of providing a desired instream flow in the collector stream. In this case, the investigator should attempt to find several alternative flow release schedules for each reservoir that best meet the instream flow requirements of the tributaries and mainstem collectively, as well as meeting the storage requirements of the reservoirs. This is a fairly complex process, well suited to the use of a computer. The IFG is currently developing the software to make these computations.

By slightly rearranging the water balance, it can be used to compute changes in runoff due to a land use change. The form used here is:

$$O = I - E \pm S \qquad (6\text{-}7)$$

where all variables have been defined previously. Troendle and Leaf (1980) give a complete description of this process, so it will only be described briefly here.

If a long enough time period is considered (generally a year), it is assumed that the net change in storage will be zero. This may or may not be a valid assumption. Nonetheless, the difference between annual precipitation and evaporation defines the average annual outflow whether by surface or subsurface runoff. This outflow can be apportioned by month and converted into an average annual hydrograph in the manner described in Section 6.1.2. If a land use change occurs that changes the amount of canopy and the rooting depth of the ground cover, the term for evaporation decreases. This leaves more water available for runoff, and a new annual outflow can be developed.

Development of a new annual hydrograph is more difficult because the ratio between surface and subsurface runoff is likely to change. The assumption that the rate of storage remains constant will not be valid for many land use changes. The infiltration rate can be changed by compacting the soil, paving, altering the vegetation, or by numerous other activities. If a land use change is likely to cause changes in the storage rate, then it must be incorporated in the model. A professional hydrologist or watershed specialist should be consulted regarding the approach to be used, if this is the case.

One of the primary reasons for including a water balance in an instream flow, reservoir operation, or mitigation study is to ensure that the flow recommended during any month is available. The results and recommendations from a study will be more credible among water users and managers because the water balance will include existing uses and water rights. The instream flow regime will be based on water that is currently available after all these other uses have been accounted for, and the instream flow often will be protected by a senior downstream water right. Opposition to an instream flow allocation can sometimes be converted to support when the water user community can see that their use of the water is unaffected (or sometimes enhanced) by the instream flow.

The flow recommendations made at the end of a study should also be subjected to a water balance. The flow recommended for a segment should approximately equal the recommended flows for the next upstream segment plus those for any tributaries entering at the upstream segment boundary. Individual recommendations emerge as parts of an integrated, operational plan when the recommended flows among segments and tributaries are balanced. Alternative water delivery options can also be investigated.

The water balance also serves as a first order cross check on the consistency (if not the accuracy) of the flow recommendations within the network. If the system is in equilibrium and there is not too much difference in the sizes of the streams or the characteristics of the stream segments, the recommended flow in the largest order stream should be about the same, or slightly less than, the sum of the recommended flows of all the tributaries. Naturally, the greater the variation in slope, channel shape, or other habitat features encountered in the system, the greater the variation among the recommended flows. However, suppose that the recommended flow in the mainstem is 1,000 cfs but the sum of the recommended flows from all the tributaries is only 300 cfs. This is an indication that some factor besides streamflow is controlling habitat availability in the system. Chances are good that the controlling factor is channel structure or water quality and that this discrepancy in the water balance could be a warning that some remedial measures would be appropriate. It may also signal a change in the behavior of the fish, conditional on the size of stream from which the suitability criteria were derived. (See related discussion in Chapter 7.) If there are no obvious differences between the streams other than size, a close re-examination of the criteria is warranted.

6.2 CHANNEL DYNAMICS

The investigator in an instream flow study will ultimately be confronted with one of two problems related to channel dynamics. The first is the determination of a flow regime that will prevent the channel from changing. The second is the determination of a new channel shape in the event that a channel change is inevitable. The solution of the first problem is considerably easier than the second.

The movement of sediment past a given point on a stream is contingent on two factors: the availability of the material in the watershed and the transporting ability of the stream. Either factor may limit the rate of sediment transport. Sediment will be deposited in the channel if the supply temporarily exceeds the transport capacity. The stream will remove available sediment from the channel until the transport capacity is filled or the available supply of sediment is exhausted if the transport capacity of the stream exceeds the sediment supply. A permanent oversupply of sediment causes a change in the shape of the channel through the process of aggradation. The adjustment consists of a raising of the streambed elevation and is usually accompanied by channel widening. A permanent undersupply of sediment results in the removal of all the sediment that can be moved, leading to a degraded channel; i.e., one which is narrower and deeper than the original channel.

6.2.1 Classification of Channels

The interaction between the sediment load and the water load defines the nature of the stream. There are three basic types of streams:

1. Streams in which the channel form is defined by bedrock;

2. Streams located in sediments transported by the stream (alluvial streams); and

3. Streams that are partially controlled by bedrock.

In bedrock streams, the channel form is controlled by the resistance of the rock and does not change with flow quantity. This is in sharp contrast to an alluvial channel which can change in response to the quantity of flow. The partially controlled channel is one that is locally controlled by resistant materials but is an alluvial channel between the local control points.

Material eroded from a watershed or from a stream bank reaches the stream channel and either becomes part of the bed material or part of the wash load. The wash load is the sediment of small size that tends not to settle onto the streambed because the turbulent forces in the stream channel keep it suspended. It is "washed" through the system as soon as it reaches the stream channel. In contrast, the larger particles are soon deposited on the streambed. If the active forces on the streambed are great enough, some material will be suspended and transported some distance downstream prior to being redeposited. This material is the suspended bed material load. Some of the bed material will roll or bounce along the stream bed. This is the bed material load, or simply bed load.

Schumm and Meyer (1979) have proposed a channel classification based on the nature of the sediment load carried by the stream. They suggest that the absolute quantity of water and sediment, while important determinants of the channel dimensions, are less important than the type of load in determining the shape of the channel. The pattern and the shape of the channel are highly influenced by the proportion of the total load made up by suspended load (silt and clay) and bed load (sand and gravel). On this basis, channels are classified as predominantly suspended load, mixed load, or bed load channels. Five basic channel patterns have been identified which correspond to each of the types of load and transitions between load types. These channel patterns are illustrated in Figure 35.

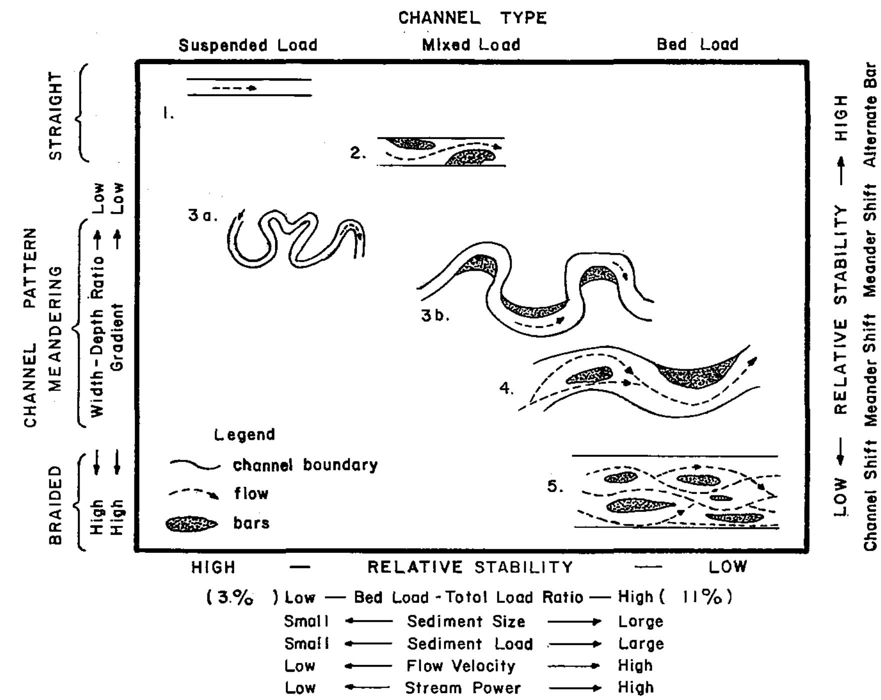


Figure 35. Classification and stability of alluvial channels (from Shen et al. 1981).

A sample of the suspended sediment load in a stream will contain the wash load and the suspended bed material load. The bed load and the suspended bed material load are complex functions of the streamflow while the wash load is a function of the land use practice, channel stability, and the rainfall intensity, to name only three of the main factors. The wash load can be very important to the quality of the bed material (substrate) from a fisheries viewpoint, but it is of lesser significance in the channel forming process.

Figure 35 is useful for estimating what type of pattern a stream might assume given a change in the predominant type of sediment. It does not provide the basis for estimating the dimensions of the channel, nor the flow needed to maintain the channel in its present pattern given no change in sediment load. For the purposes of this discussion, it is convenient to divide the topic into two problem areas: the effects of flow alone and the combined effects of flow and altered sediment yield on channel configuration.

6.2.2 Discharge as a Channel Forming Agent

Stream discharge is an important factor in the formation of a channel, affecting channel shape and size, the type of vegetation along the banks, and the particle size and percentage of fine material comprising the bed. However, not all discharges are important in the channel forming process. Wolman and Miller (1960) suggest that very large flow events occur too infrequently to have much effect on the long term channel configuration. On the other hand, low flow events occur frequently but lack the power to shape the channel. These authors concluded that the most effective channel forming flow was the bankfull discharge. It is common for the hydrologist to use the terms effective discharge and dominant discharge as synonyms for bankfull discharge. This discharge has been found to have an average recurrence interval of 1.5 years on flood frequency curves. This statistic is frequently used to find the dominant discharge for a stream.

Changes in the magnitude or frequency of the dominant discharge are likely to force changes in the channel. An extension of the dynamic equilibrium and dominant discharge concepts is the concept of regime theory. A channel is considered to be "in regime" if the net change in the channel morphology is zero over its hydrologic cycle. This means that its banks and bed are neither eroding nor aggrading over the hydrologic cycle.

The initial regime equations were developed around the turn of this century for canal systems in the Far East and later were extended to canals in other parts of the world. The hydrologic cycles of canals are very simple; they are either wet or dry. When wet, the discharge tends to be constant over time and space. It is this simplistic hydrologic cycle that limits the direct applicability of the canal regime equations to natural streams. In the early 1950's, regime theory concepts were extended to natural stream systems for the Great Plains Province. Some subsequent work has been done for limited areas elsewhere. The important additional concept permitting this extension was the recognition of the complexity of hydrologic cycles in natural streams.

Natural stream systems have individual hydrologic cycles that vary from year to year, throughout each year, and over the entire fluvial system. To use regime theory concepts, this complexity requires: (1) the recognition of frequency or return period (recurrence interval) for water discharge; and (2) the acceptance of the concept of dominant discharge. Dominant discharge becomes the surrogate for the entire hydrologic cycle and, therefore, is used as the principal architect of the stream channel geometry.

The equations used to relate the hydraulic geometry of stream channels to the dominant discharge are:

$$w = aQ^b \qquad (6\text{-}8)$$

$$d = cQ^f \qquad (6\text{-}9)$$

$$v = kQ^m \qquad (6\text{-}10)$$

where w = the channel width

d = the mean channel depth

v = the mean velocity

The coefficients a, c, and k and the exponents b, f, and m are empirical parameters obtained from case studies of similar fluvial systems (Leopold and Maddock 1953). Q is the dominant discharge (assumed to be the 1.5 year recurrence interval flow from the flood frequency curve). Table 25 contains values for the exponents based on empirical relationships for numerous streams in the United States. The coefficients vary considerably from site to site and have not been compiled.

Table 25. Values of exponents in the hydraulic geometry equations of river channels in various hydrologic provinces in the United States.

Exponent	Great Plains perennial streams	Province[a] ephemeral streams	Pennsylvania[b] Brandywine Creek	Theoretical[c]
b	0.50	0.50	0.42	0.46
f	0.40	0.30	0.45	0.46
m	0.10	0.20	0.05	0.08

[a]Leopold and Miller (1956).

[b]Mahmood and Shen (1971).

[c]Simons and Li (1980).

The utility of the hydraulic geometry equation is not to make absolute predictions of the channel morphology; the coefficients are not well enough defined. Its utility is to make relative judgments of changes in channel morphology if the hydrologic regime is changed. The relative judgments are based on ratios of new bankfull discharges to those presently occurring in the stream.

To illustrate the use of these equations, assume that a combination flood control-irrigation reservoir is planned for a perennial stream in the Great Plains Province. A hydrologic analysis shows that the bankfull discharge return period is 1.5 years, and the reservoir will reduce the 1.5-year discharge by 50%. What will be the ultimate impact of this water development project on the stream channel morphology?

Using the subscripts p and a to denote present and altered conditions, respectively, the following relationships can be derived for the new width (W_a), the new depth (D_a), and the new velocity (V_a):

1. $\frac{Wa}{Wp} = (Qa/Qp)^b = (1/2)^{0.50} = 0.71$

   $Wa = 0.71\ Wp$

2. $\frac{Da}{Dp} = (Qa/Qp)^f = (1/2)^{0.40} = 0.76$

   $Da = 0.76\ Dp$

3. $\frac{Va}{Vp} = (Qa/Qp)^m = (1/2)^{0.10} = 0.93$

   $Va = 0.93\ Vp$

Thus, the width of the new channel will only be 71% of the width of the old one, the mean depth will be reduced by 24%, and the velocity will be reduced by 7%. These represent the changes to the geometry of the channel. Changes in channel pattern, periodicity, and alignment may be estimated in a similar manner. The periodicity of riffles and pools or meander bends is highly correlated to channel width. Leopold et al. (1964) present two equations relating meander length to channel width:

$$\lambda = 6.6\ w^{0.99} \qquad (6\text{-}11)$$

$$\lambda = 10.9\ w^{1.01} \qquad (2\text{-}12)$$

where λ = meander wavelength

w = channel width

It is likely that the difference between the equations is a result of differences in bank cohesion. Schumm (1960) found that channels having greater percentages of silt and clay in the banks generally had smaller width to depth ratios and higher sinuosity (shorter meander wavelenths) than streams with less cohesive banks. Therefore, the equation $\lambda = 6.6\ w^{.99}$ is recommended for suspended load channels. Because the exponents of both equations are nearly 1.0, it can be shown that the decrease in meander length is proportional to the change in width. Therefore, because width would be reduced 29%, the same reduction in meander length could be expected. A new sinuosity could be computed from this value.

The change in channel morphology does not occur instantaneously, and the hydraulic geometry equations do not predict any time spans. They only suggest steady state or ultimate dynamic equilibrium tendencies. Much more research is necessary for time and absolute quantitative predictions.

6.2.3 Combined Effects of Sediment Load and Discharge

Modification of the sediment load, with or without a change in discharge, will force channel change processes that cannot be addressed by regime theory alone. Channel width, depth, and meander wavelength are direct functions of discharge, while channel slope is an inverse function. Width, meander wavelength, and channel slope are direct functions of the sediment load, while depth and sinuosity are inverse functions. Therefore, the change in any hydraulic geometry characteristic depends on the proportional change in sediment load with respect to discharge.

Based on these relationships, the removal of water from a stream without changing the sediment load will reduce both the width and depth, but increase the width to depth ratio. Removal of sediment with no change in water discharge reduces the width to depth ratio, increases the depth, and reduces the width. An increase in sediment yield increases the width to depth ratio, increases the width, and reduces the depth. Removal of water and an increase in sediment load results in a decrease in depth, increase in width to depth ratio, and an uncertain change in width. The direction of change that can result from alterations of both streamflow and sediment yield is given in Figure 36. The actual magnitude of the change is difficult to determine.

Kellerhals (1981) suggests that the best way to estimate new channel shape and dimensions following a modification of the sediment load and discharge is to look at a similar stream that has already experienced the same type of impact. This is good advice for the expert in channel change modeling and the uninitiated alike. In essence, the modified stream can be treated as a large physical model without the sediment scaling problems of small physical models. (Very small sediment particles behave differently than larger ones so, while it is possible to develop a scale model of the stream, it is impossible to load it with similar behaving sediment of the same scale).

In addition to the evaluation of channel change by comparison of altered systems, there are numerous analytical procedures which can be used to predict channel changes. Most of these techniques have been developed for use in sand bed streams, and their accuracy in coarse bedded streams is not very high. A great deal of present sedimentation research is directed toward gravel bedded rivers, so a solution to this problem may be forthcoming. At present, the prediction of channel changes requires a combination of complex analytical tools, comparison with other systems, and a large amount of experience.

A channel change model utilizes an iterative approach of defining a channel shape and computing a theoretical sediment transport rate associated with that shape. A mass balance is then made, comparing the transport rate with the supply. If the rates do not balance, the channel shape and slope are changed to reflect either aggradation or degradation and a new transport rate computed. This process is repeated until a mass balance is achieved. The main difference between different models is the technique used to determine the theoretical sediment transport rate. It is beyond the scope of this discussion to describe sediment transport models. Their complete derivations can be found in the references for additional reading listed below.

Independent Variable		Dependent Variable					
Stream Discharge	Sediment Load	Channel Width	Average Channel Depth	Meander Wave Length	Channel Scope	Ratio of Valley Slope to Channel Slope	Width/ Depth Ratio
+	No change	+	+	+	-	-	-
-	No change	-	-	-	+	+	+
No change	+	+	-	+	+	-	+
No change	-	-	+	-	-	+	-
+	+	+	±	+	±	+	-
-	-	-	±	-	±	+	-
+	-	±	+	±	-	+	-
-	+	±	-	±	+	-	+

+ = direction of change is an increase

- = direction of change is a decrease

± = direction of change is indeterminate

Figure 36. Changes in channel morphology resulting from streamflow alterations and segment yield alterations. Modified from Schumm (1977).

6.3 SUGGESTED ADDITIONAL READING

Chow, V. T. 1964. Handbook of applied hydrology. McGraw - Hill Book Co., New York. 1418 pp.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman Co., San Francisco. 522 pp.

Riggs, H. C. 1968. Frequency curves. Techniques of Water - Resources Investigations of the U.S. Geological Survey. Book 4, Chapter A2. Superintendant of Documents, Washington, D.C. 15 pp.

Simons, D. B., and F. Senturk. 1977. Sediment transport technology. Water Resources Publications, Littleton, Co. 807 pp.

Simons, D. B., R. M. Li, N. Duong, N. Kouwen, V. M. Ponce, E. V. Richardson, K. Schneider, S. A. Shumm, and R. K. Simons. 1980. Watershed and stream mechanics. U.S. Dept. of Agriculture, Soil Conservation Service, Washington, D.C.

U.S. Forest Service. 1980. An approach to water resources evaluation of non-point silvicultural sources (a procedural handbook). U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Ga. EPA-60018-80-012. 861 pp.

7. PHYSICAL HABITAT SIMULATION

The physical habitat simulation (PHABSIM) system is a collection of computer programs used to relate changes in discharge or channel structure to changes in physical habitat availability. The output from the PHABSIM system, and its uses, are described in Chapter 5. The underlying principles of PHABSIM are that: (1) each species exhibits preferences within a range of habitat conditions that it can tolerate; (2) these ranges can be defined for each species; and (3) the area of stream providing these conditions can be quantified as a function of discharge and channel structure.

7.1 GENERAL CONCEPTS OF PHABSIM

A natural stream contains a complex mosaic of physical features in different combinations. One area may be deep, fast, and have a cobble bed with no cover. Another area may be deep and slow, with a sand bed and abundant cover. One species might find the first condition desirable, while another would prefer the latter condition. A third species might find neither condition satisfactory. The quantification of physical habitat requires the determination of the area associated with each combination of features and an evaluation of that combination in terms of its utility as habitat. When the flow is changed, all the combinations are redefined and the process must be repeated for the new condition.

The PHABSIM system describes this mosaic on the basis of strategically placed transects used to describe the longitudinal distribution of different habitat types within the stream. Measurements of physical microhabitat parameters, such as depth, velocity, substrate type, and cover, are made at intervals along each transect to describe the lateral distributions and gradations of these parameters. The point on each transect where a measurement is made is called a vertical (the measurement is perpendicular to the plane defined by the water surface). Each vertical marks the edge of a stream "cell", the length of which is established by the investigator in the field, as illustrated in Figure 37. Each stream cell is unique and characterized by a surface area (defined by the distances between transects and verticals), a substrate type, a cover type ("no cover" is also a cover type), and an average depth and velocity, both of which are functions of streamflow.

The utility of each cell for a life stage of a species is then evaluated by the application of habitat related criteria. The surface area of each cell is weighted by a suitability index, $C_{i,s}$, which reflects the relative preference of the species for the combination of structural and hydraulic characteristics found in the cell at a given discharge. Various derivations of $C_{i,s}$ are detailed in the next section. This produces an index of the habitat potential for the cell called the weighted usable area (WUA). For a cell, the WUA is equal to:

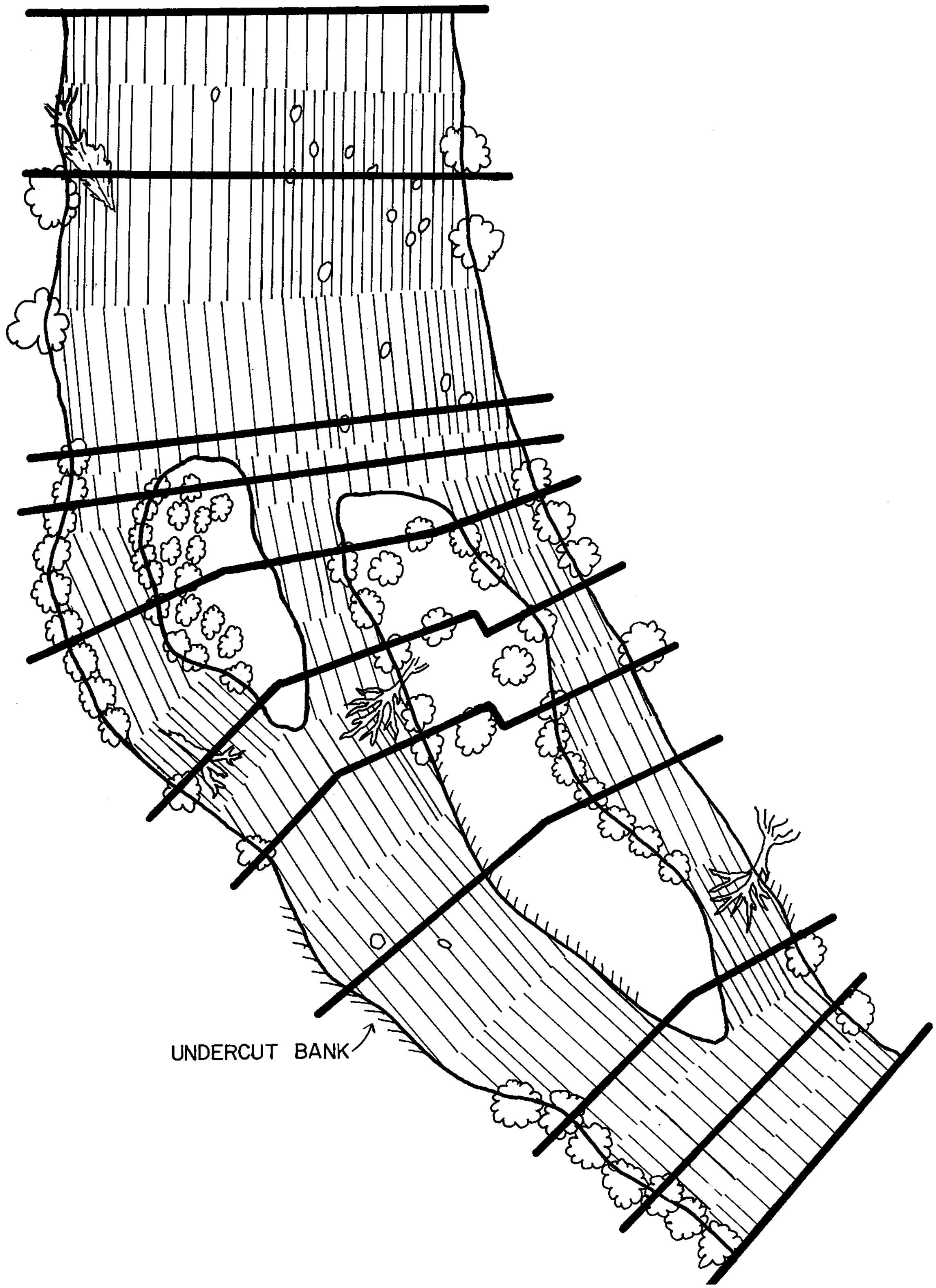


Figure 37. Placement of transects and measurement verticals to define stream cells, used to describe microhabitat distribution in a stream reach.

$$WUA = C_{i,s} \times A_i \qquad (7\text{-}1)$$

where $C_{i,s}$ = the suitability index for the combined characteristics of the cell (i), by the target species(s). These suitability indices are unique for each life stage of each species. The same life stage may have different indices depending on activity (e.g., spawning or resting adults) or season

A_i = the surface area of the cell

This computation procedure is applied to each cell for each life stage, for each discharge. The WUA for the reach is then determined by the equation:

$$WUA_{Q,S} = \sum_{i=1}^{n} C_{i,s} \times A_i \qquad (7\text{-}2)$$

where the weighted usable area for the reach is unique to the flow, the life stage of the species, and the reach to which it applies.

The same stream reach could be measured at each discharge for which a quantification of available habitat was desired. In fact, prior to 1977, this was the technique used. However, this method was very labor intensive, enough so that its use was confined to only the smallest and most important streams. The PHABSIM system uses the concepts of open channel hydraulics to predict changes in depth and velocity in each cell as a function of discharge. The use of hydraulic simulation has greatly reduced the time required to conduct an intensive microhabitat study, both in terms of actual manhours worked and the total time to study completion. Studies that used to take a year can now be completed in several weeks.

7.2 DETERMINATION OF MICROHABITAT PREFERENCES

The field measurements and hydraulic simulations determine the relative amounts of different habitat conditions in the channel at a particular discharge. In essence, this represents the universe of habitats available for different organisms at that discharge. Some of these habitats will be perfect for some species, others will be of marginal value, and still others will be totally unusable. In order to evaluate the quality of the habitat, as well as its quantity, it is necessary to describe the conditions of depth, velocity, cover, and substrate which define usable microhabitat for the species.

Each stream cell generated within PHABSIM has a discrete combination of depth, velocity, substrate, and cover. This exact combination occurs in the cell at only one discharge. In order to evaluate the utility of that combination of conditions, it is necessary to approximate a function which quantifies the species' preferences or tolerances for the combination. This is defined as a <u>combined</u> or <u>joint preference function</u>, $C_{i,s}$.

There are several techniques for approximating a joint preference function for a species. Four methods can be used in the PHABSIM system: binary criteria; preference curves; multivariate suitability functions; and multivariate functions in association with preference curves. Each technique has certain strengths, weaknesses, and limiting assumptions.

7.2.1 Binary Criteria

The concept of binary criteria was first used in an instream flow methodology by Collings et al. (1972) and was later refined by Smith (1973) and Hunter (1973). The concept is quite simple. Suppose that spawning chinook salmon are most often found utilizing a gravel substrate having a depth greater than 1.5 ft and a velocity between 1.5 and 3.0 ft/sec. An area of stream having all these conditions is considered usable habitat for that life stage. However, when any of these conditions are not met, the area is considered unusable. In equation form, the joint preference factor is computed by:

$$JPF = f(v) \times f(d) \times f(s) \qquad (7\text{-}3)$$

where JPF = the joint or combined preference factor

f(v) = a preference factor for velocity having a value of either 0 or 1

f(d) = a preference factor for depth having a value of either 0 or 1

f(s) = a preference factor for substrate having a value of either 0 or 1

When any of the preference factors for an individual variable is unusable (outside the criteria bounds), that variable and, therefore, the joint preference factor for that area, takes on a value of zero.

In his development of binary criteria for several Pacific Northwest salmonid species, Smith (1973) conducted a frequency analysis of observed fish and included 80% of the observations within the criteria bounds. One of the advantages of binary criteria is that it does not imply selective behavior of the fish within the conditions specified by the criteria. This type of criteria can be developed where no data on the fish are available. That is, because they are criteria and not functions describing species behavior, they do not imply any particular statistical rules, nor do they require more than professional judgment as to sufficiency of conditions.

These advantages, to some extent, also describe the disadvantages. The frequency distributions of many species often indicate rather narrow ranges of conditions that the species actually select, yet wide ranges of conditions that they will tolerate. Binary criteria make no distinction among optimal, suboptimal, and barely tolerable conditions.

7.2.2 Preference Curves

Waters (1976) was one of the first practitioners of instream flow methodologies to suggest the use of weighting factors other than 0 and 1 to define habitat preferences for fish. He argued that, within the range of conditions considered suitable, there is a narrower range of conditions that fish select as a preferred or optimal range of that parameter. Furthermore, the tails of the distribution represent true unsuitability rather than an arbitrary cutoff point. In short, the behavioral characteristics of a species can be defined by a curve. The peak of the curve represents the optimal range of a parameter and is given a weighting factor of 1. The tails of the curve represent 0 usability. Values between 0 and 1 can be determined empirically from a frequency analysis of observed fish over the range of the parameter. The computation of the joint preference function (JPF) uses the same equation as binary criteria:

$$JPF = f(v) \times f(d) \times f(s), \qquad (7\text{-}4)$$

except the variables f(v), f(d), and f(s) have values equal to, or between, 0 and 1.

Bovee and Cochnauer (1977) developed a series of techniques for deriving such preference curves with varying amounts of data. When actual measurements of sites utilized by fish are available, a frequency curve is fit by eye to a histogram and then normalized so that the peak of the curve receives a weighting factor of 1. In many cases, data are not available to construct histograms for a species. Then, a range of preferred and tolerated conditions is obtained from the literature or inferred from site descriptions of the collection area. Preference curves in these cases consist of four points connected by an idealized curve. Such curves are developed for as many life stages of fish as the available information allows. Using similar techniques, and more advanced curve fitting procedures, Gore and Judy (1981) developed preference curves for several species of midwestern macroinvertebrates.

Preference curves have several advantages. Like binary criteria, they can be constructed in the absence of hard data. Professional judgment can be incorporated into the model simply by modifying existing curves or developing new ones. The use of preference curves also allows the use of extremely complex mathematical functions with relative ease.

The use of preference curves has been criticized from two perspectives. First, because the preference curves represent relative probabilities (actually ratios of probabilities), the multiplication of the preference factors implies independence among the variables. In a limited sensitivity analysis conducted by the IFG, and independently conducted by Orth and Maughan (1980), the error caused by this assumption was small. Second, in developing preference factors from fish capture data, a bias is introduced by the physical conditions available to the fish at the time the data are collected.

7.2.3 Multivariate Suitability Functions

As a result of the criticism of the preference curve concept, a model for computing the joint preference, or suitability, was designed and tested by personnel of the IFG and Utah State University (Voos et al. 1981). Several models were tested and rejected before settling on the concept of the multivariate suitability function. For the most part, models were rejected because the methods and limitations of gathering species-related data were incompatible with the requirements of the model.

a. Concepts of joint suitability functions. A reasonable suggestion for a joint suitability function is the probability, P[N|E]. This is the probability of finding one or more fish (N), given a certain set of environmental conditions (E). This function has two attributes which make it a good suitability function. The first is that it is environment independent. That is, once the function is properly defined, it is theoretically transferable to any environment where the fish occurs. The second attribute is that a good, intuitive measure of the usability of a stream results when the function is integrated with the environmental conditions of the stream.

Using P[N|E] as the suitability function requires systematic random sampling of the stream from which the fish were collected. Representative unit areas of a stream must be sampled, the number of fish of a particular type occurring there recorded, and all the environmental attributes measured, regardless of whether fish are caught or not. Additionally, the function P[N|E] implies that the entire population has been sampled. These assumptions can seldom be met adequately by conventional fish sampling or observation techniques. Random sampling is more applicable to plants and inanimate objects than to fish.

Typically, the way that data on fish and their habitats are collected is by first observing the location of the fish and then measuring the stream attributes where the fish was observed. This allows the investigator more flexibility in the sampling procedures and places the emphasis on good, unbiased (by interference) observations on the fish. However, this type of data leads to the development of a different kind of probability function, P[E|F], the probability of observing a combination of stream attributes given the presence of a fish.

Although the function P[E|F] is much easier to derive than P[N|E] it, too, has several disadvantages. The most serious is that P[E|F] is environment dependent. That is, the function is valid only in the stream(s) from which the data are obtained. Extrapolation to other streams becomes weaker the more dissimilar the streams are. Furthermore, the fish in the streams from which the data are taken may be distributed in the stream in the same proportions as the environmental attributes of the stream. This function approximates a suitability function, but it does not distinguish tolerances from preferences.

The advantages of collecting the data in the form leading to the function P[E|F] are considerable. The data are likely to be of higher quality. Fish can be sighted from a position where the fish cannot see, or will not react to, the observer. Specific areas in the stream can be targeted for sampling and the data collected in such a manner that the fish will not be disturbed. Additionally, the entire population does not need to be sampled. Only a representative proportion needs to be observed. One requirement of this technique is that areas must be sampled in roughly the same proportion that they occur in the stream, even though a species is known to occupy specific areas. For example, if a stream has 25% pools and 75% riffles, most of the sampling (i.e., 75%) should be done in the riffles.

A third function, combining the advantages of the above two functions without the encumbrances of either, is defined as:

$$S = \frac{P[E|F]}{P[E]} \qquad (7\text{-}5)$$

where S is the joint suitability function describing the suitability and P[E|F] is the probability of finding a certain combination of environmental conditions given the presence of a fish.

The term P[E] is a probability function describing the relative abundance of various combinations of environmental attributes available to the population. Data for this function are collected the same way that the channel and hydraulic data are collected for PHABSIM, although more transects are used. Often, these data are collected regardless of whether or not criteria development is contemplated.

The suitability index function, S, has the advantage of being <u>essentially</u> environment independent. It is not totally independent of the environment, but if care is taken in the selection of the collection area, it can be developed as environment independent. Section 7.2.5 discusses the types of situations to avoid to prevent environment dependence. Another advantage of this formulation is that the function S is essentially biomass independent; the total biomass of the stream from which S is developed does not enter into subsequent calculations of stream usability. However, S cannot be totally biomass independent unless the stream from which S is developed is at carrying capacity at the time it is sampled. The function may also be dependent on the presence of sympatric species. This dependency relates to the "fundamental niche" and the "realized niche" concepts of Hutchinson (1957). In an allopatric population which is significantly under carrying capacity, only the most preferred sites will be utilized, which does not indicate the range of conditions the species would use if the population were at carrying capacity. Conversely, the portion of the realized niche used by a species may be conditioned by the presence of other species competing for the same sites. It must be emphasized that this problem is inherent to any type of criteria and is not unique to this approach.

The definition of S, from Equation 7-5, does not result in the most meaningful measure of stream usability. A meaningful suitability index must have a maximum value of 1.0 when a cell provides optimal habitat. This allows the model to "count" the entire surface area of the cell as 100% suitable habitat. As a function of environmental attributes, S provides a measure of the relative suitability of environmental conditions in providing habitat for species. The optimal mix of environmental conditions occurs where S reaches its maximum probability value. Therefore, the term $C_{(i,s)}$ in the WUA equation can be found by:

$$C_{(i,s)} = \frac{S_{(i)}}{S_{max}} = \frac{1}{S_{max}} \frac{P[E|F]}{P[E]} \qquad (7\text{-}6)$$

The preceeding discussion has been simplified considerably from the mathematics actually involved. For a complete discussion of the theory, the reader is referred to Voos (1981).

The principle advantages of the multivariate suitability functions are the inclusion of interactions among variables and the removal of the bias caused by physical habitat availablity. The functions represent a rigorous mathematical fitting of the data, a vastly superior technique than fitting a curve to a histogram by eye. This technique also has some disadvantages. First, a multivariate suitability function cannot be derived without data, and the data requirements can be appreciable. Second, it is difficult, if not impossible, to inject professional judgment into the function. Modifications of the function require considerable experience and expertise; it is not a matter of drawing a new line on a curve. The third, and perhaps most serious limitation, is that complex mathematical functions are difficult to simulate in the model. Cover and substrate, discussed in Section 7.3, can sometimes represent extremely complex functions depending on the amount of information incorporated in the cover description. This means that some substrate and cover descriptions cannot be used with this approach.

7.2.4 Combined Use of Joint Suitability Functions and Preference Curves

The most important concept for fitting data to a joint suitability function is that the function must be continuous and described by an exponential polynomial equation. There are numerous examples of substrate and cover descriptions in Section 7.3 that are either discontinuous functions or cannot be described by an equation. This problem leaves the investigator with two choices. Either the substrate/cover description must be simplified so that is a simple continuous function or the complex description retained and its use in a joint suitability function abandoned. Most investigators choose the latter option.

One approach to this problem is to describe the simple continuous variables, such as depth and velocity, as a joint suitability function and the complex variables, such as substrate and cover, as preference curves. In this case, the joint preference factor would be computed as:

$$JPF = f(v,d) \times f(s) \qquad (7\text{-}9)$$

or

$$JPF = f(v,d) \times f(c) \qquad (7\text{-}10)$$

where JPF = the joint preference factor

f(v,d) = a joint suitability function for depth and velocity

f(s) = a preference curve for substrate

f(c) = a preference curve for cover

Interactions between depth and velocity would be accounted for by this computation of the JPF, but independence between these two variables and substrate or cover are assumed. There does not appear to be a good solution to this problem with respect to substrate. However, cover can be treated as a discrete variable and a joint suitability function for depth and velocity derived for each cover type. This approach is discussed in Section 7.3.3.

b. Development of equations describing the joint suitability function. The IFG has developed a computer program called GOSTAT which is capable of fitting data describing either P[E|F] or P[E] to an exponential polynomial equation (Voos et al. 1981). The joint probability density function (joint pdf) is given as:

$$P[E|F] \text{ or } P[E] = \frac{1}{N} \exp^{-(p(x))} \qquad (7\text{-}7)$$

where p(x) is a polynomial equation and N is a normalizing term. The joint suitability function is the ratio between the joint pdf's for P[E|F] and P[E]. The polynomial describing the depth-velocity joint suitablity functions in Figures 38 and 39 would take the form:

$$p = a_1 d + a_2 v + a_3 d^2 + a_4 dv \qquad (7\text{-}8)$$

Figures 38 and 39 are read like contour maps, with the higher suitability values corresponding to elevation. In two dimensions, a curve expressing the depth preference is bell shaped with its peak at 2.4 ft and its tails at 0.6 and 4.4 ft. The velocity curve, in two dimensions, is simply a concave curve with a peak at 0.0 ft/sec and a single tail at about 3.0 ft/sec. The depth term in equation 7-8 is second order and the velocity term is first order in order to fit both types of curves. Some fish species show bimodal distributions for a variable, resulting in a curve with two peaks. Higher order terms must be substituted into equation 7-8 to fit these complex functions. The term $a_4 dv$ in equation 7-8 is called the cross-product. This term determines the amount of intervariable dependence within the joint suitability function. If there were no interdependence between depth and velocity, the axis of the contour map shown in Figure 38 would be parallel to the x-axis. Figure 39 is typical of a joint suitablility function with little dependence among variables.

7.2.5 Guidelines for Data Collection

The problem of dependence on the environment from which the data are collected is mentioned in Section 7.2.3. The following example shows what the problem is and how it can be avoided. For this example, assume that a "universal" suitability function applies to a species no matter where it is found and that the function shown in Figure 38 is such a universal function for adult brown trout between 10 and 14 inches in length.

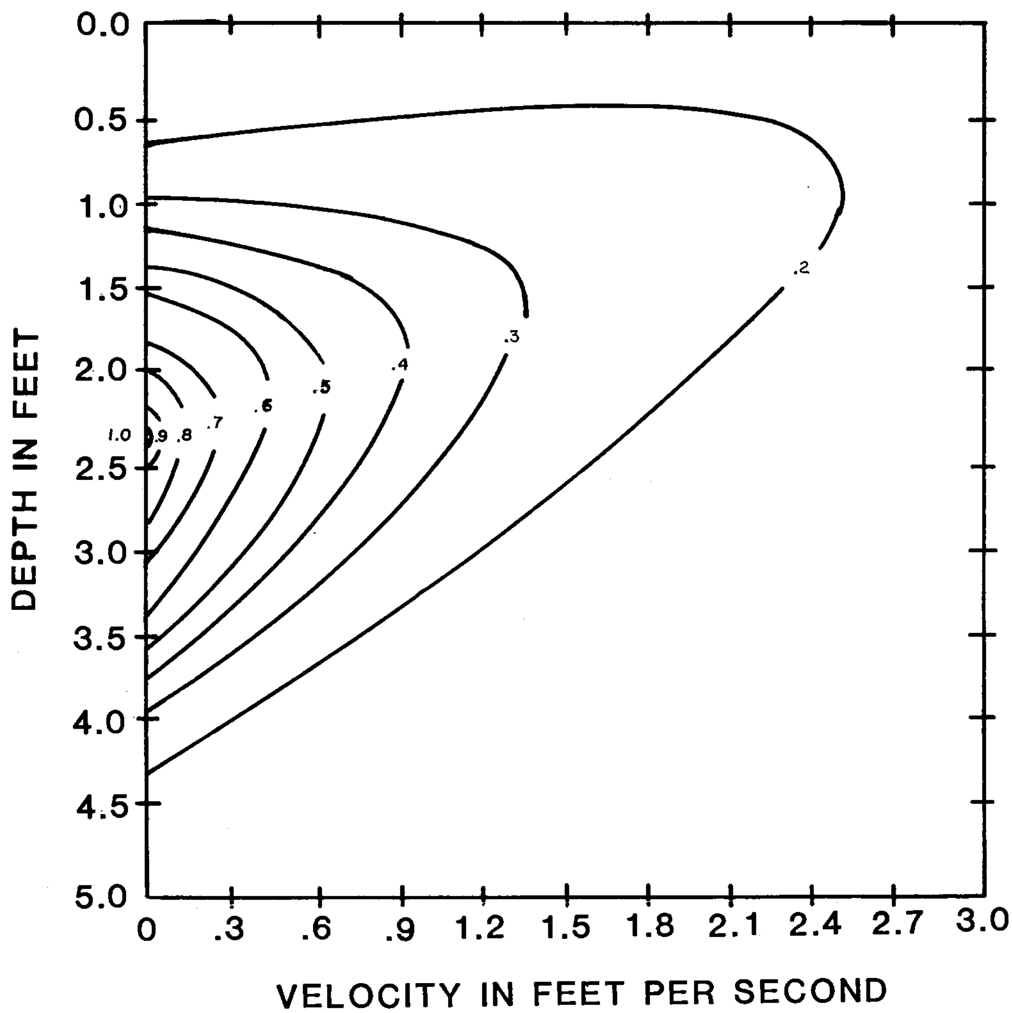


Figure 38. Joint suitability function for depth and velocity preferences of adult brown trout in southeastern Wyoming.

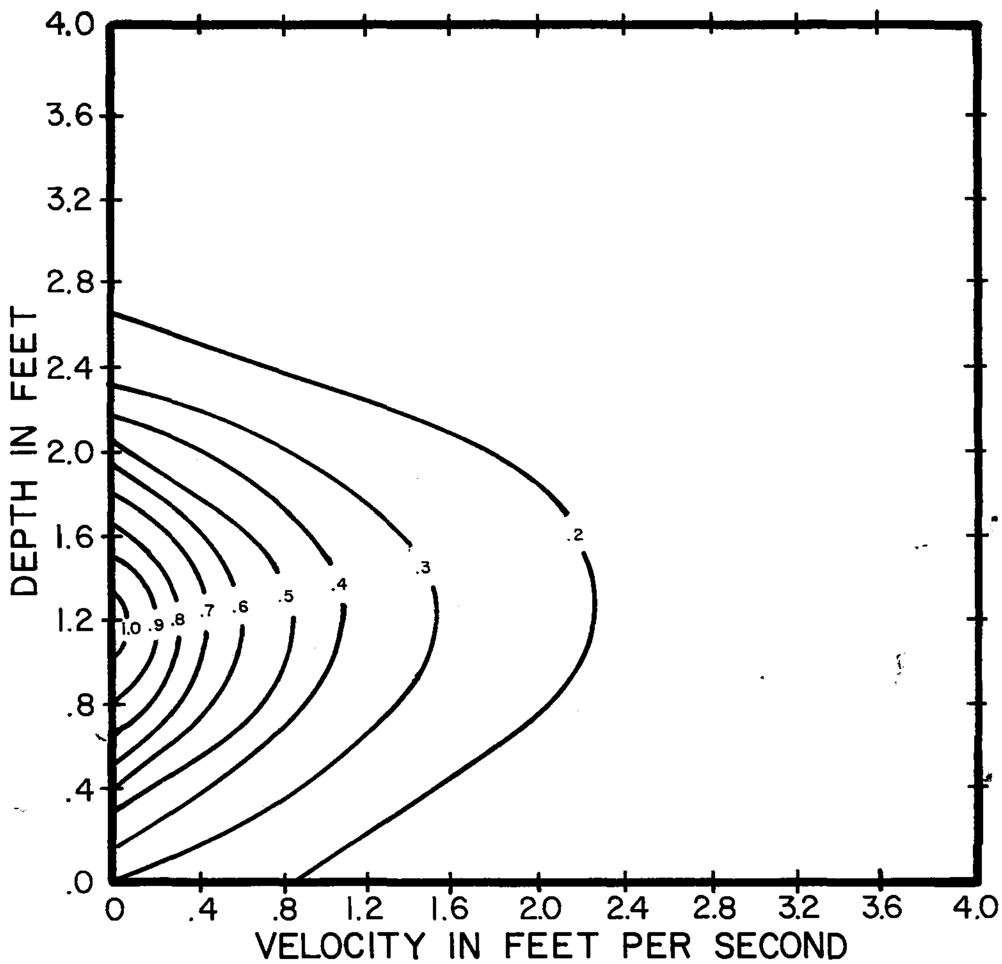


Figure 39. Joint suitability function for depth and velocity preferences of juvenile chinook salmon in northern British Columbia.

Compare this function with those shown in Figures 40, 41, and 42. Figure 40 is a joint suitability function developed for South Fork Hog Park Creek. This stream, at the time of sampling, has little in the way of optimal or preferred brown trout habitat. Lake Creek, illustrated in Figure 41, has some optimal habitat but much less than the Laramie River, illustrated in Figure 42. Of the three, the function for the Laramie River most nearly matches the "universal" function. In the other two streams, the optimal condition must be estimated by extrapolation. It is not likely that the universal function could be replicated in South Fork Hog Park Creek, no matter how many fish were sampled. Therefore, the investigator should have some a priori knowledge about the habitat preferences of the species being investigated. Efforts should be made to select study streams with the entire range of conditions that the species might occupy, including a considerable amount of preferred or optimal habitat.

A second consideration is the effect of biomass and the presence of sympatric species in the community on the range of conditions actually used by the species under study. The study area selected should be at or near carrying capacity when sampled. Otherwise, it is likely that only the optimal or near optimal habitat will be included in the joint pdf. Those streams with an abundance of optimal habitat very often attract large numbers of fishermen. Criteria should not be derived from heavily fished streams regardless of how good the habitat is.

The third consideration is the number of observations needed to adequately define the joint pdf. Voos (1981) found that the equation describing the joint function for brown trout, using two variables, tended to converge at around 150 samples (i.e., the equation did not change significantly when there were more than 150 observations). It is conceivable that species utilizing a wider range of conditions (such as white suckers or carp) might require a larger sample size. Species occupying a narrower range of habitats (such as dace or darters) might require fewer observations. When more variables are included in the equations, the data requirements increase exponentially.

A final consideration is the introduction of error through sampling bias, a source of error that is virtually undetectable by statistical analysis. The first indication of such error is a curve or joint suitability function that does not "look right" to an experienced biologist. Criteria development relies heavily on the experience and judgement of the biologist, even when using multivariate statistics and a large data base. There is often a tendency to let the statistics speak for themselves. When statistics alone are applied to the available data base, biased data passes through as though nothing were wrong. The two most common sources of sampling bias are gear bias and disproportionate sampling effort. A third bias, misidentification, has not been a problem but could become one as more nonbiologists participate in the data collection.

Many of the guidelines regarding sampling bias presented by Bovee and Cochnauer (1977) are still applicable. Precautions must be made to avoid sampling a fish from an area not originally occupied by the fish. The fish must not be attracted to the gear, sampled in transit from one area to another, or be frightened into another area and then sampled. The first type of gear bias can be avoided by abstaining from the use of traps of any kind, angling (especially with bait or lures), and direct current electrofishing. The

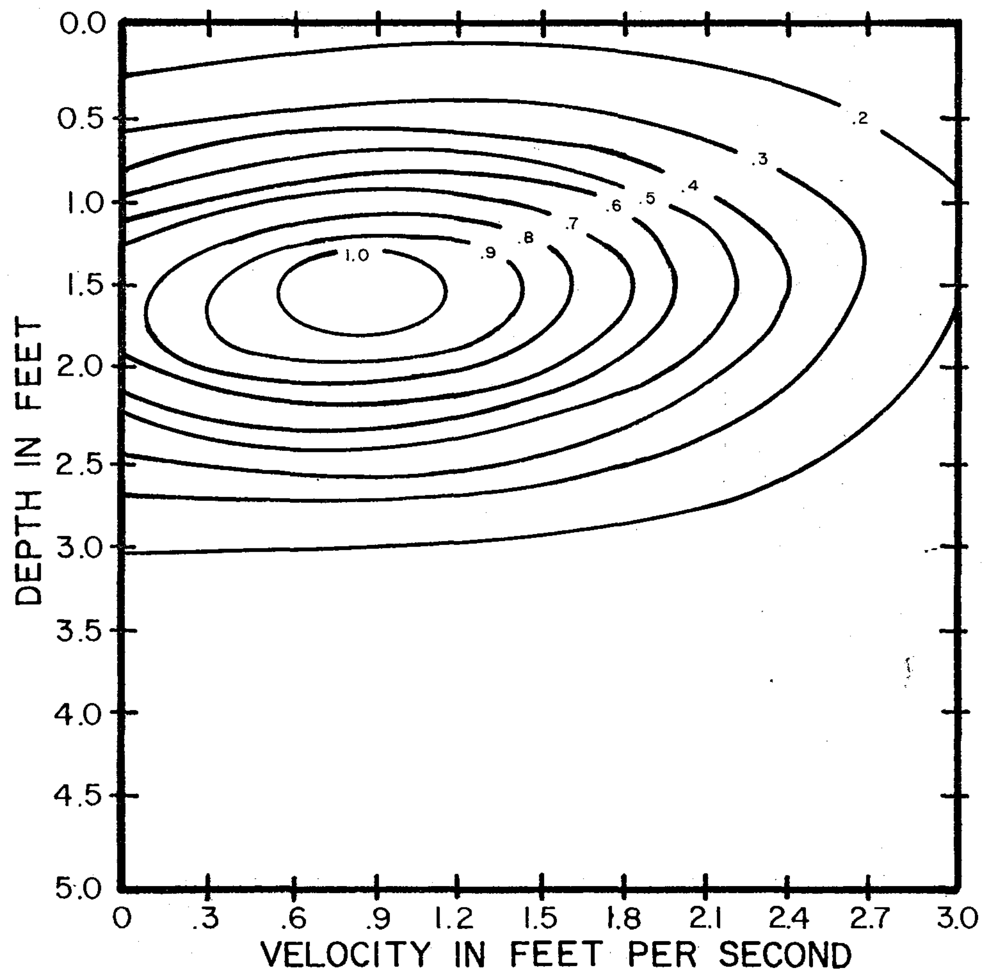


Figure 40. Joint suitability function for depth and velocity preferences of brown trout observed in South Fork Hog Park Creek in southeastern Wyoming.

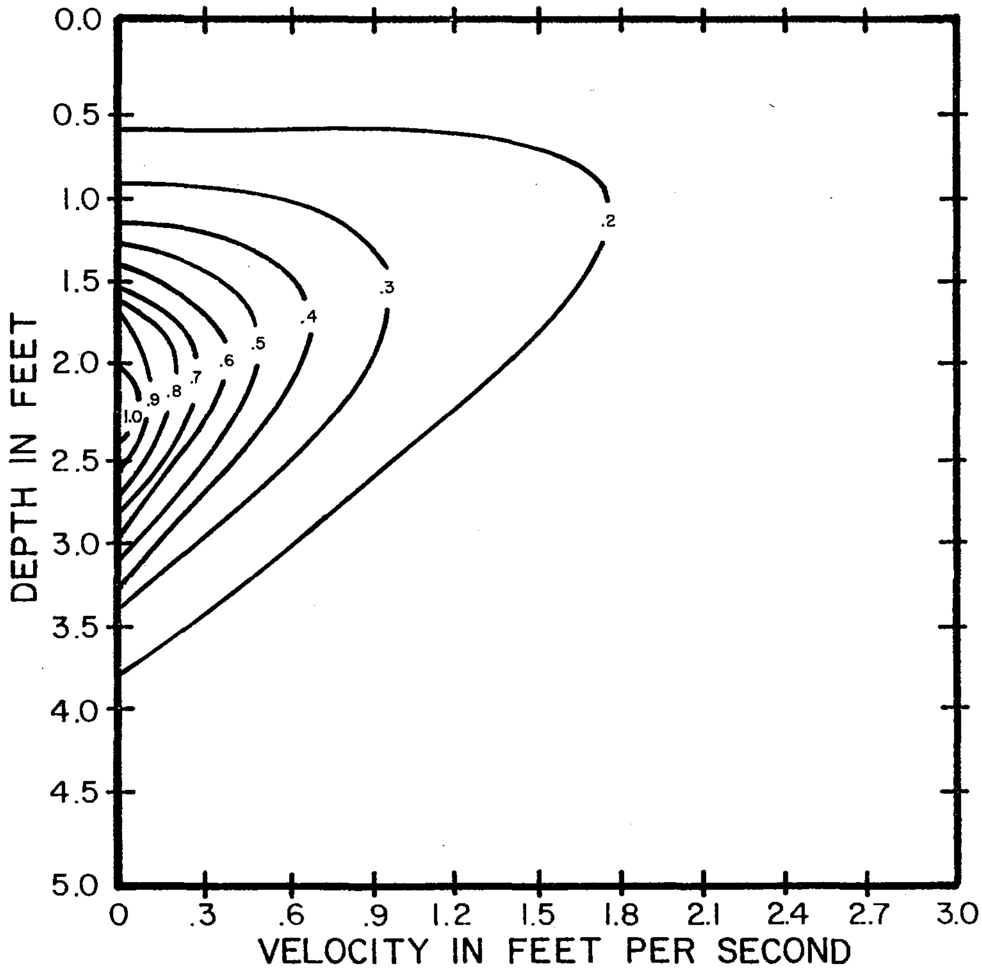


Figure 41. Joint suitability function for depth and velocity preferences of brown trout observed in Lake Creek in southeastern Wyoming.

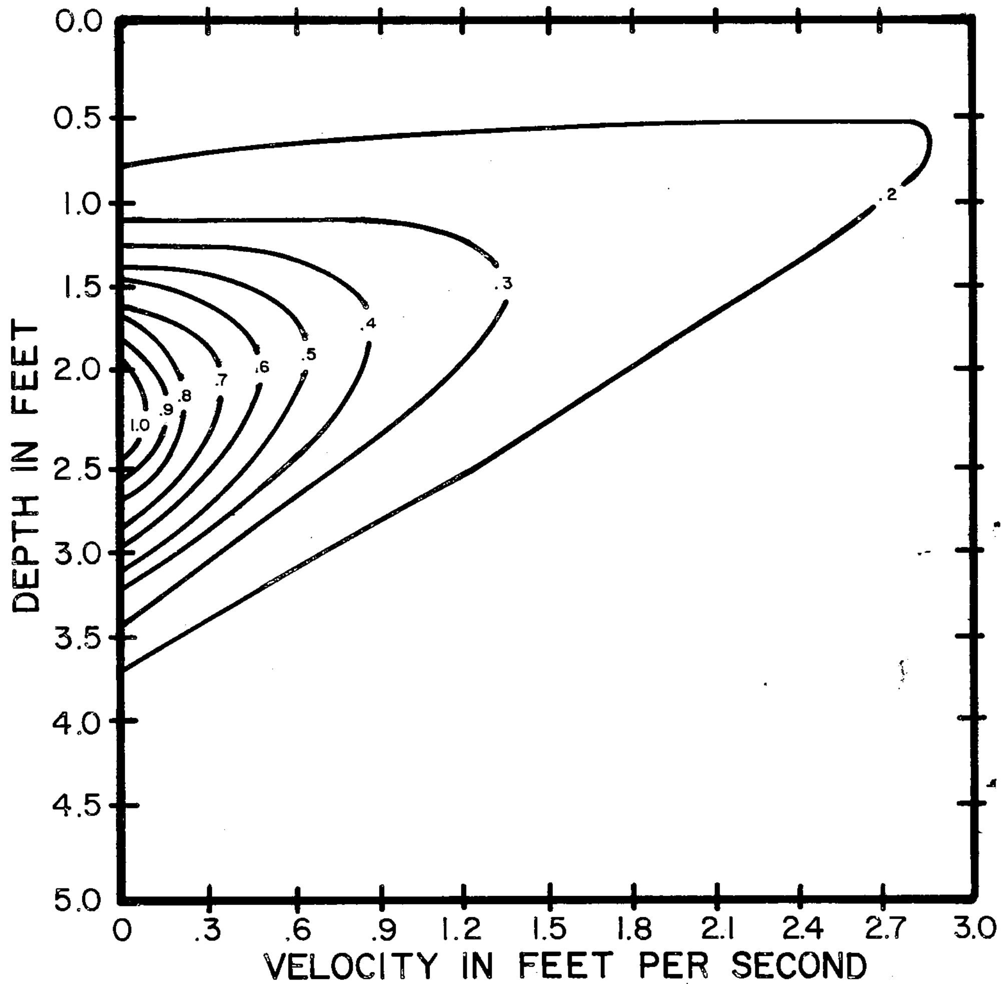


Figure 42. Joint suitability function for depth and velocity preferences of brown trout observed in Laramie River in southeastern Wyoming.

second type of bias is usually associated with gill nets and hoop nets with leads. It can also occur in sampling turbid streams by any means because it is impossible to distinguish between a fish in transit and one at rest. A potential solution for turbid streams is to develop criteria from radio tagged fish. Otherwise, it is important to avoid sampling when fish are likely to be moving around, such as dusk and dawn, unless they can be seen. Any sampling technique can cause "fright bias" if the investigator is not extremely careful. This problem can be avoided by sampling or observing in an upstream direction. Fish orient themselves into the current and sampling upstream allows the observer to approach from behind. However, fish often behave like herd animals and one frightened fish may touch off an aquatic stampede. The best approaches to avoid this problem are quiet observation from the bank and snorkel or scuba diving. Bank observations may lead to misidentification unless the fish are big and readily identifiable.

Finally, if a nonrandom sampling or observational technique is used, the investigator should normalize or equalize the effort. This can be accomplished by noting the time taken while sampling a particular habitat area. Sampling should never be confined to those areas that are more likely to contain the fish under study. Another imperative is that measurements to define P[E] must be made at the same flow, and preferably the same time, as the fish observations. These environmental measurements may be obtained by random sampling or by the same techniques used to describe a reach in PHABSIM.

7.3 SUBSTRATE AND COVER

The methods of describing and analyzing cover and substrate data have probably undergone more evolution than any other aspect of PHABSIM. The hydraulic models used in the system have a long history in engineering and hydrology, so a fairly standardized procedure had developed prior to their adaptation to instream flow analysis. The situation is reversed when the subject matter is cover and substrate. Although biologists have known that these two variables are very important to fish and invertebrates, a standard procedure of description and analysis has not yet been developed. The reader is advised that the methods presented in this text are not the only ones that can be used to describe and analyze cover or substrate. The methods described below really have only one advantage. They have been tested in the model and are compatible with the system.

The term substrate is used to describe the mixture of particles comprising the streambed. Cover is defined as something that fish can hide under or behind. Cover and substrate perform essentially the same function, but differ in scale. While cover applies mainly to fish, substrate provides the same function to benthic macroinvertebrates and fish eggs. The critical feature of many forms of cover, and certainly of substrate, is the size of the interstitial spaces between particles. This space can be measured in cubic meters among boulders and in cubic millimeters among substrate particles.

The analysis of either substrate or cover in PHABSIM requires the use of a numerical coding system to translate a description of the substrate or cover into a number that can be read by the computer. A preference curve must then be constructed to illustrate the relative suitability of each coded value for a species or a life stage. The development of the coees and their subsequent use in PHABSIM is discussed below.

7.3.1 Substrate Codes

The first substrate code used in PHABSIM consisted of a series of integers describing size classes of substrate particles. This code is shown in Table 26.

Table 26. Original IFG substrate code used to describe size classes of bed materials.

Code	Substrate description
1	Plant detritus
2	Clay
3	Silt
4	Sand
5	Gravel
6	Cobble
7	Boulder
8	Bedrock

The code shown in Table 26 was designed to show mixtures of adjacent size classes. A code of 5.2 designated gravel with 20% cobble. There were several problems with this code that diminished its utility, the most serious of which was that the code could not be used to describe mixtures of very different size classes, such as boulders and sand. The second problem was that the code did not contain enough biologically important information.

Brusven (1977) developed an improved substrate index that was completely compatible with PHABSIM. The Brusven index is composed of a three-digit number. The integer in the ten's place represented the larger materials in the matrix, called the dominant particle size. The one's place denoted the size of the material surrounding the dominant size, called the subdominant size. The decimal place was used to describe the percent embeddedness of the dominant size in the subdominant material. The IFG has made a minor revision to the Brusven index. The integers still refer to dominant and subdominant sizes, but the decimal is used to describe the percentage of fine material (sand and smaller) in the matrix. This was done to allow a finer distrinction among the larger particle sizes. Table 27 shows one suggested expansion of the basic substrate code from Table 26, for use with the Brusven index. The codes shown in either table are not the only one's that could be used. Table 27 does not contain codes for clay, silt, or bedrock, any of which may need to be described. These can be added only by making room for them by collapsing the internal gradations (e.g., eliminating medium gravel and covering the range with small and large gravel). A code of 0.00 is not permitted because of a default mechanism in the HABTAT program. Zero can be used as a code for one of the size classes as long as the complete index is greater than zero. It is better to avoid the use of zero entirely, if possible. Using the Brusven index and the codes shown in Table 27, a mixture of small cobble, medium gravel, and 50% fines is represented by 53.5. A large boulder completely surrounded by sand has an index of 91.9.

Table 27. Expanded substrate code for use with the Brusven substrate index.

Code	Substrate description
1	Fines (sand and smaller)
2	Small gravel (4-25 mm)
3	Medium gravel (25-50 mm)
4	Large gravel (50-75) mm)
5	Small cobble (75-150) mm)
6	Medium cobble (150-225) mm)
7	Large cobble (225-300) mm)
8	Small boulder (300-600) mm)
9	Large boulder (> 600) mm)

7.3.2 Substrate Curves

The next step in incorporating substrate data into a physical habitat simulation is the development of a curve showing the relative suitability of each coded value for each organism of interest. Up to 99 points can be used to describe such a curve, but not all code values need to be entered. The computer interpolates between the entered codes and connects the points by linear segments. Therefore, the only points that need to be entered are the tails of the curve and intermediate inflection points. An example of a substrate curve based on Brusven's index is shown for trout embryos in Figure 43.

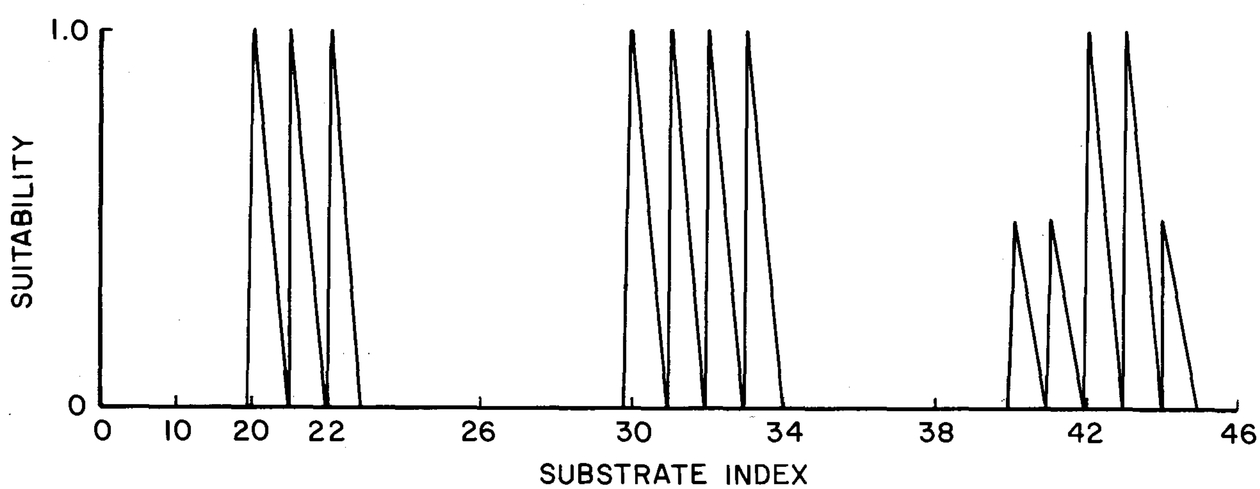


Figure 43. Portion of a substrate curve for trout embryos using the Brusven substrate index.

Figure 43 covers only a part of the total range of substrates described by the Brusven index. Zero suitability has been given to codes 22.9 through 29.9 and 33.9 through 39.9 because these are undefined or unused codes under this system. For example, a code of 29.9 would be nonsense because the first integer in the code is reserved for the dominant particle size and gravel is obviously smaller than a boulder. The combination of boulder and gravel would be expressed as 92.0 (with no fines). Rather than waste space and time on a substrate code that should never be entered, the curve skips to the next size of usable gravel. The curve can be interpreted as follows. The survival of embryos in gravel is primarily determined by the percentage of fines in the gravel. A code of 21.0 has a suitability of 1.0 because the code implies a clean, uniform small gravel with <10% fines. A code of 21.9 has a suitability of 0.0, because it represents small gravel completely embedded in fines. This example assumes a linear decline in survival between 0% and 90% fines, but there is no reason that the survival estimate cannot be shifted. For example, a 1.0 suitability can be applied between 21.0-21.3 and 0.0 between 21.7-21.9, implying that up to 30% fines will not affect survival, but anything above 70% fines causes complete mortality.

7.3.3 Cover Codes and Curves

There are two different approaches that can be taken to analyze the utility of cover as a function of flow in PHABSIM. The first is to treat cover as a continuous variable in the same manner as substrate. The second approach is to treat cover as a discrete variable that conditions the types of hydraulic characteristics a species will tolerate. Both approaches are presented below, although we believe that the second approach is easier to use and much more realistic.

Cover can simply be described as any feature of the stream which provides reduced lighting, reduced velocity, or increased visual isolation, singly or in some combination. Even more simply, cover is something the fish can either get under (overhead cover) or behind (object cover). Thus, the simplest of cover codes is:

Code	Cover type
1	No cover
2	Object cover
3	Overhead cover
4	Overhead and object cover combined

Several questions regarding this code should immediately come to mind. First, how big is an object? Obviously the size of object used as cover depends on the size of the fish. Secondly, are all forms of overhead cover equally desirable? Is the shadow cast by canopy cover as good as overhanging vegetation that hangs in the water? Is overhanging vegetation as good as an undercut bank or a root wad or a debris jam? If not, then perhaps the code should be expanded:

Code	Cover type
1	No cover
2	Objects less than 150 mm in diameter
3	Objects between 150 mm and 300 mm in diameter
4	Objects larger than 300 mm in diameter
5	Overhanging vegetation
6	Root wads or undercut banks
7	Objects less than 150 mm with overhanging vegetation
8	Objects less than 150 mm with root wads or undercut banks
9	Objects between 150 mm and 300 mm with overhanging vegetation
10	Objects between 150 mm and 300 mm with root wads or undercut banks
11	Objects larger than 300 mm with overhanging vegetation
12	Objects larger than 300 mm with root wads or undercut banks

The next layer of complexity occurs when cover is considered in association with substrate. For some species and life stages, one or the other will dominate. Brown trout, while rearing, may key on overhead cover regardless of the substrate; while spawning, brown trout key on the substrate regardless of the cover. However, some species will exhibit a tendency to select both conditions. Smallmouth bass, for example, tend to spawn near a cover object in association with a gravel substrate. A code can be devised such that the first number in the code refers to the cover type and the second to the substrate type. Building on the previous code, the following example shows the incorporation of substrate with cover as both an integer and real number code:

Code		Cover/substrate type
Integer	Real	
10	1.0	No cover/silt or mud
11	1.1	No cover/sand
12	1.2	No cover/pea sized gravel (4-10 mm)
13	1.3	No cover/10-25 mm gravel
14	1.4	No cover/25-50 mm gravel
15	1.5	No cover/50-75 mm gravel
16	1.6	No cover/75-150 mm cobble
17	1.7	No cover/150-300 mm cobble
18	1.8	No cover/boulder (> 300 mm)
19	1.9	No cover/bedrock
20	2.0	Object < 150 mm/silt or mud
•	•	
•	•	
•	•	
60	6.0	Root wad, undercut/silt or mud
61	6.1	Root wad, undercut/sand
62	6.2	Root wad, undercut/pea sized gravel

The substrate portion of the code can also be expanded to reflect dominant size and percent fines.

Code	Cover/dominant substrate/percent fines
5.30	overhanging vegetation/10-25 mm gravel/< 10% fines
5.31	overhanging vegetation/10-25 mm gravel/10-20% fines
•	
•	
•	
5.39	overhanging vegetation/10-25 mm gravel/90-100% fines
5.40	overhanging vegetation/25-50 mm gravel/< 10% fines

The cover codes developed to this point indicate only the type of cover contained in each cell. None of the codes contain any information regarding the amount of cover contained in the cell. Depth and velocity, and to some extent substrate, are all continuous variables. That is, there is a continuum of these variables within the stream, which allows their description from transect lines. However, cover is a discrete function; it is either present or absent. Therefore, a transect which adequately describes the distribution of depths and velocities might not cross any areas having cover, even though cover features are present in varying amounts within the cell.

This factor presents a bit of a dilemma for personnel conducting the field work. It is much easier to describe cover on a presence or absence basis, and this description is more reproducible than estimates of the amount of the cell having cover. On the other hand, it is logical to say that a cell having 100% overhead cover should be four times "better" than one having 25% of the same cover type if the fish prefer overhead cover. The estimation of cover amounts does not add appreciably to the field time. However, actual quantification of cover will double or triple the time that it takes to complete measurement of a site. In either case, codification of this information is relatively easy. Another integer is added to the code to describe the percentage of a cover type in the cell. For example:

Code	% of cell/cover type/substrate/% fines
16.19	10%/undercut/silt/100% fines
56.19	50%/undercut/silt/100% fines
96.65	90%/undercut/mded. gravel/50% fines

A code with precision to the nearest 10% of a particular cover type requires quantification. However, if an estimation technique is used, a code can be devised using a quartile approach:

Code	% of cell/cover type
16.19	< 25%/undercut/sand/100% fines
26.19	25-50%/undercut/sand/100% fines
36.19	50-75%/undercut/sand/100% fines
46.19	75-100%/undercut/sand/100% fines

In summary, the amount of information on cover and substrate capable of being incorporated in a physical habitat simulation can range from a simple single digit code to a very complex four-digit real number. This procedure has been left as flexible as possible, so that the user can decide how much information and complexity to incorporate in the model. However, a very complex code will undoubtedly exceed the 99 point limit in PHABSIM. The codes shown above serve only to illustrate the kinds of information that can be incorporated.

The cover codes described above require an estimate of the preference of a species by life stage for various cover types. Presently, the lack of data forces the user to construct cover preference curves based predominantly on experience and judgment. The logic and assumptions used to build these curves should be documented as thoroughly as possible. It is usually easiest to identify the cover type or combination that is most preferred by the species and then rate all others relative to the preferred type. A table of preference by species vs. cover code can then be constructed. Not all intermediate values need to be recorded; these will be interpolated by the computer. The points used in the table are entered as substrate data. Figures 44 and 45 are hypothetical cover preference curves for adult brown trout, corresponding to the first and last (quartile) cover codes, respectively, and illustrating the differences in complexity of the curve as a function of the information contained therein.

The cell-by-cell determination of cover type in the reach requires accurate cover mapping. One problem is the increased field time; even without a time constraint, cover mapping can be difficult. For example, the ground elevation of an undercut bank determines, to a large extent, its usefulness as cover. However, it is often difficult to measure this elevation. Undercuts can also be discontinuous and their value as cover over- or underestimated depending on transect placement. Instream objects also present a problem because it is not the area occupied by the object, but the low velocity area behind it, that is utilized by a fish. Therefore, the investigator must attempt to quantify the cover available between rocks rather than the number of rocks. Spacing of rocks becomes especially important because individual small rocks may have no cover value singly, while a cluster of the same small rocks could have great cover value. All of these problems can be dealt with, although a great deal of forethought is needed.

The use of the cover curve allows the description of a detailed and complex array of cover types. The biggest drawback to this approach is that it requires the assumption that fish have the same depth and velocity preferences with all cover types. It is easy to see the fallacy of this assumption. A fish hiding under a log might not care if the water is only a few inches deep. In the absence of overhead cover, the depth might need to exceed 3 or 4 ft to be as acceptable. However, if it is sufficiently deep, an area with no cover can be equally acceptable as an area with overhead cover.

Similarly, a fish hiding behind a boulder can tolerate (and may actually prefer) mean column velocities that would be untolerable without the object. This relationship may be partially resolved by simulating bottom velocities instead of mean column velocities. However, many fish species select sites in the stream having low bottom velocities and fast water overhead. This type of three-dimensional velocity distribution is extremely hard to model, but the

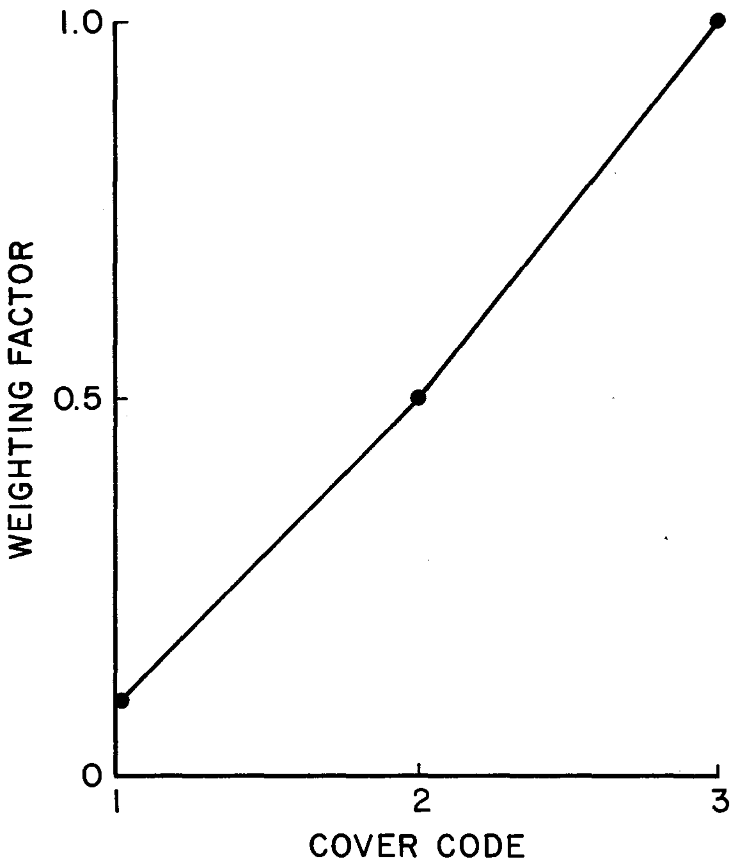


Figure 44. Simple cover curve for adult brown trout.

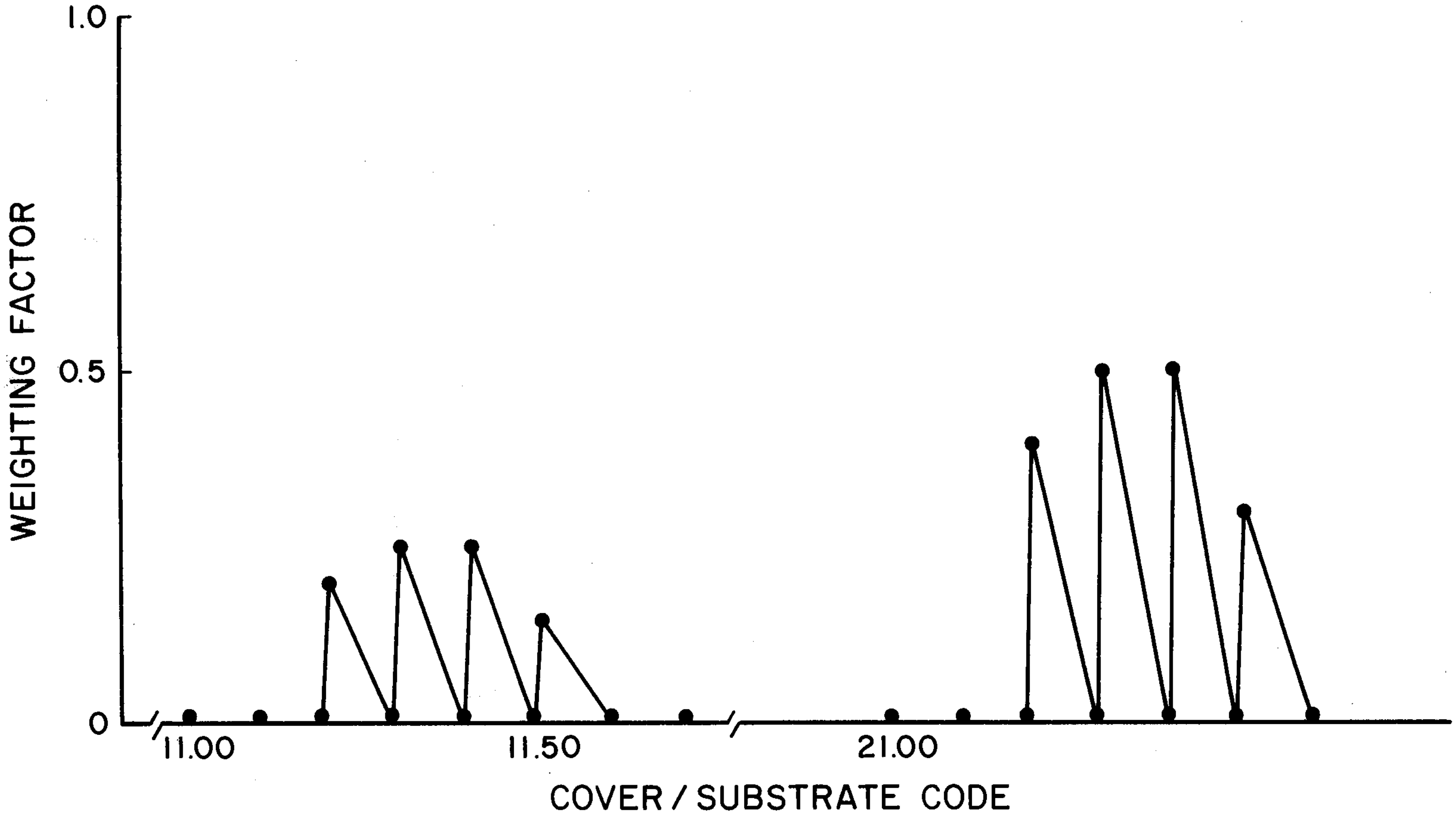


Figure 45. Partial, complex cover/substrate curve incorporating percent of cell with cover/substrate type, cover type, dominant particle size, and percent fines.

phenomenon can be reproduced simply by stating that a fish will tolerate high mean column velocities if it can hide behind a rock.

The second advantage of using cover as a conditional factor for depth and velocity preferences is that no judgements regarding the relative value of different kinds of cover are needed. Separate depth and velocity functions for each cover type are required, however. This requirement means that cover codes must be kept simple. This approach is entirely compatible with the multivariate suitability function, whereas complex cover curves are not. Finally, this approach may actually be easier to use than the cover curve.

The concept of introducing cover as a variable in PHABSIM involves substituting a cover code for a substrate code. Treating cover as a discrete variable involves treating each cover type as a life stage of a species. Figure 46 illustrates this substitution. The first curve set represents the hydraulic conditions used by adult brown trout in association with overhead cover. Shallow depths, around 0.5 ft, are acceptable with overhead cover, but, because there is nothing to hide behind, velocities above 1.5 fps are avoided. The velocity constraint is often minor because the additional roughness adjacent to the banks tends to slow the water. A cover code of 1.0 refers to overhead cover and, with the curve shown, the depth and velocity curves for that curve set will be applied only in those cells designated by a cover code of 1.0. The weighting factors for all other cover types are set to 0.0. The format in the user's library of curves identifies each cover type as though it were a different life stage by searching the curve identification number and the life stage identifier. Construction of a curve file library is discussed in Chapter VI of the PHABSIM manual. (See suggested additional reading). The resulting output for the HABTAT program is shown in Table 28. The table now contains weighted usable areas printed out by cover type instead of by life stage; one full table is printed for each life stage. A separate program, TOTHAB, is used to obtain the total habitat column shown in Table 28.

Table 28. Example HABTAT output using cover as a discrete variable.

Brown Trout Adults

	Discharge	Nocover	Object	Overhead	Combined	Total
* 1	10.00	278.69	191.39	22.54	0.00	492.62
* 2	15.00	454.36	498.37	68.29	2.04	1023.06
* 3	20.00	641.29	675.75	63.93	55.71	1436.68
* 4	25.00	814.49	802.10	52.38	111.59	1780.56
* 5	30.00	943.54	860.49	56.71	135.23	1995.97
* 6	40.00	1052.36	900.48	63.17	162.16	2178.17
* 7	50.00	1081.43	894.07	87.35	173.29	2236.14
*******						

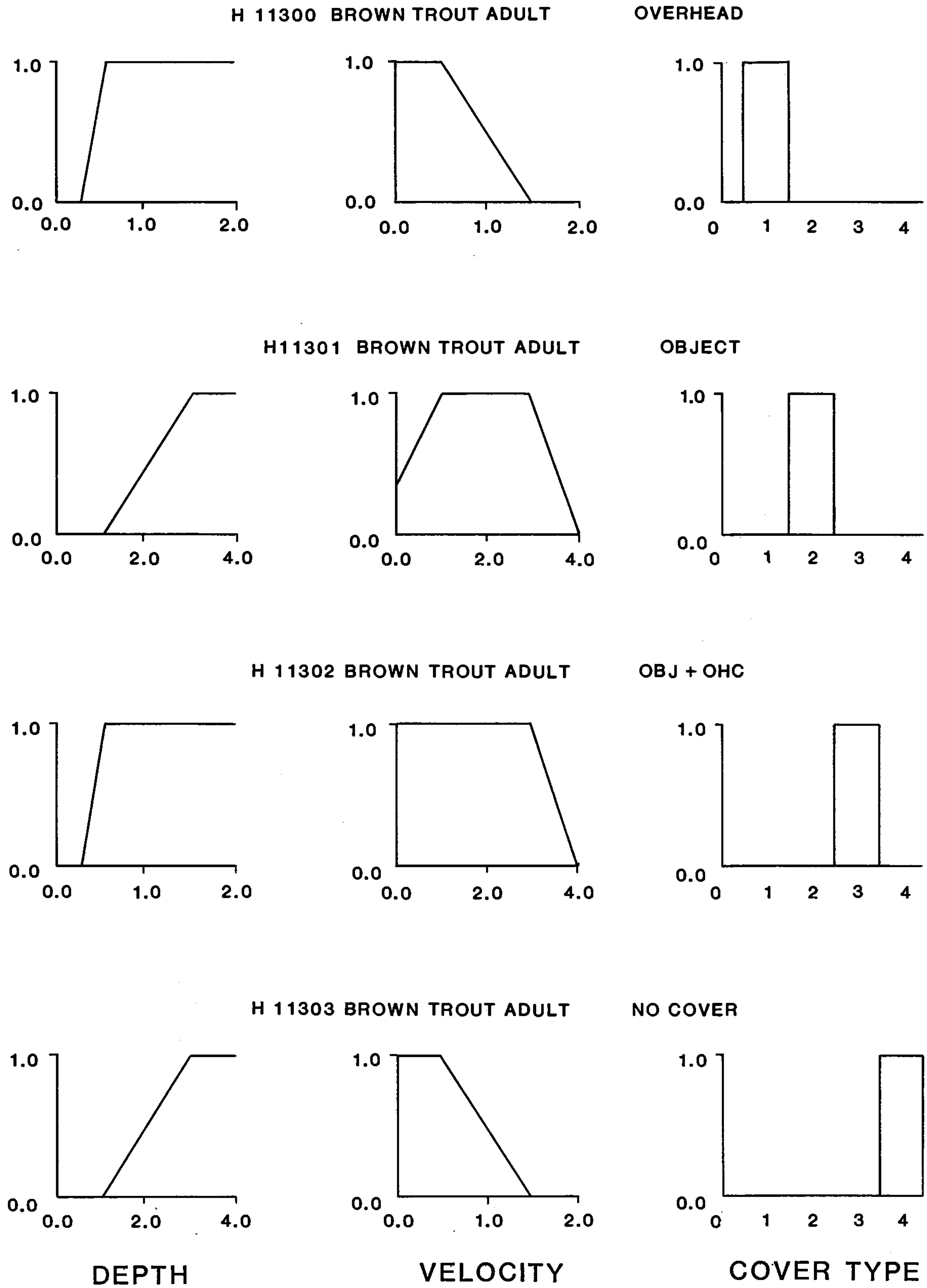


Figure 46. Example development of conditional depths and velocities as functions of cover.

7.4 PASSAGE

7.4.1 Natural Barriers

The analysis of flows for passage requires a different approach to microhabitat analysis. The main difference is that only one or two transects are needed to determine passage flows. Another difference is that the only factors of real importance are depth and velocity. Depth is frequently the only variable considered. Furthermore, flows must be provided for microhabitat year-round while passage flows may apply for only a month or two.

The hydraulic models used with PHABSIM have the option of producing a table specifying the width of stream having a certain depth at each simulated discharge. The specified depth is usually entered as some type of minimum or average clearance requirement for the size of migrating fish. Table 29 summarizes several passage criteria recommended for migratory salmonids by Thompson (1972) and for white sturgeon by White (1976).

Table 29. Reported depth and velocity passage criteria for selected species of fish.

Species	Minimum depth (ft)	Maximum velocity (ft/sec)	Source
Chinook salmon	0.8	8.0	Thompson (1972)
Coho salmon	0.6	8.0	Thompson (1972)
Chum salmon	0.6	8.0	Thompson (1972)
Steelhead trout	0.6	8.0	Thompson (1972)
Large trout	0.6	8.0	Thompson (1972)
Other trout	0.4	4.0	Thompson (1972)
White Sturgeon	5.0	-	White (1976)

The minimum recommended clearance requirement should probably be no less than two-thirds of the body thickness of the fish. The investigator should temper this criterion by the number and length of crossings the fish must make. Fish that encounter very few passage barriers can probably negotiate some fairly shallow water. The same species moving up a stream with many passage bars may arrive at the spawning area in poor condition if the passage depths are minimal. Another consideration in establishment of passage criteria is the vulnerability of the fish to predation while making the crossings. The depth (or rise in stage) required to initiate migration may also need to be considered a form of passage criteria. This may be one reason, in addition to the size difference between the species, that White's depth criteria for white sturgeon is so much larger than Thompson's criteria for salmon.

Passage flows can be determined from the information contained in the hydraulic output. The clearance depth is specified in the input, and the computer calculates both the total width and largest contiguous width of stream equalling or exceeding that depth. If these values are plotted against discharge, a graph like Figure 47 is generated.

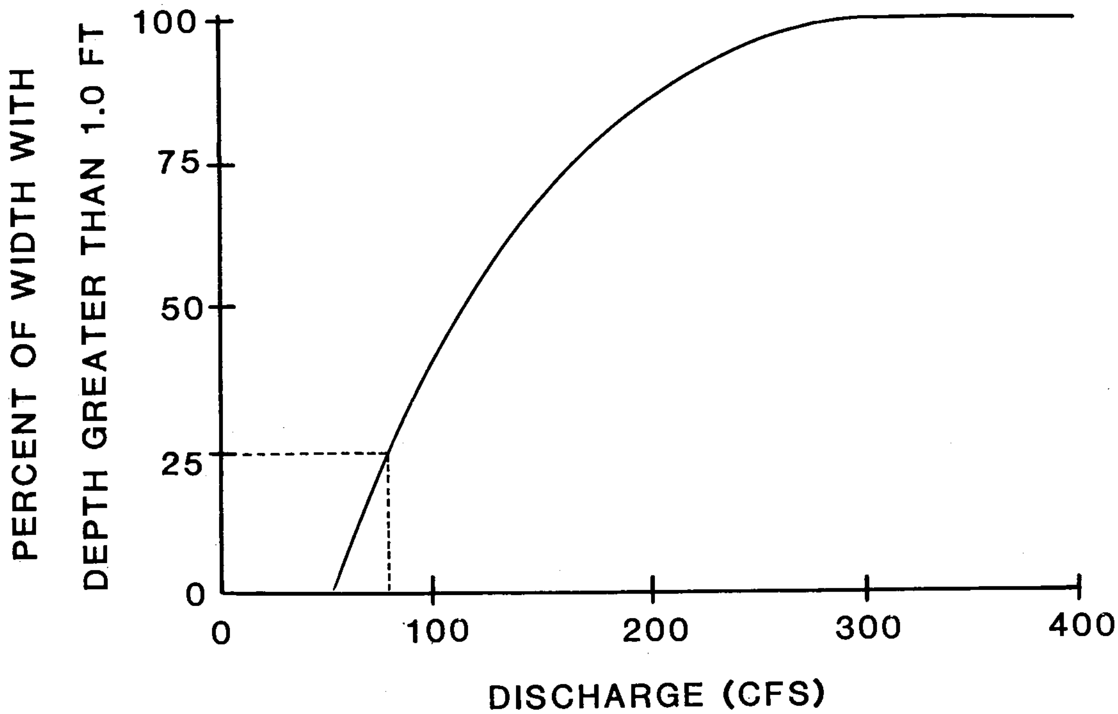


Figure 47. Width of specified depth plot used to determine passage flow.

The Oregon State Game Commission (Thompson 1972) suggests that the total width of stream having the specified passage depth should be at least 25% of the top width or that the longest continuous portion be at least 10% of the top width. These recommendations may be somewhat arbitrary but have been widely used and accepted by many fisheries agencies.

The above procedure needs to be applied only to the shallowest cross sections if passage flows are to be determined routinely in the representative reaches. However, only one or two transects are needed at critical passage barriers, depending more on the hydraulic model used than on the nature of the barrier.

7.4.2 <u>Culverts</u>

Whereas the primary factor in passage over natural barriers is usually depth, the primary factor for passage through culverts is often velocity. Depth may be a factor at low flow and can be analyzed using the previously described procedure. Three factors related to velocity are important in determining the passage of fish through a culvert. These are:

1. Sustained swimming speed of the fish;

2. Velocity through the culvert; and

3. Length of the culvert.

Swimming speeds of fish are classified as the burst speed, sustained speed, and cruising speed (Anonymous 1980). The burst speed is defined as the speed that a fish can maintain for a very short period of time, generally less than 10 seconds. The sustained speed represents above-normal activity less severe than the burst speed, but still capable of inducing fatigue. The sustained speed can be maintained for 300 to 500 minutes by some salmonid species. The cruising speed can be maintained for extended periods without fatigue. Swimming speeds for various species are summarized by the Stream Enhancement Research Committee (Anonymous 1980), and illustrated in Table 30.

Table 30. Swimming speeds for average sized adult fish of various species (ft/sec) (Anonymous 1980).

Species	Cruising speed	Sustained speed	Burst speed
Brown trout	0-2.3	2.3- 6.2	6.2-12.8
Carp	0-1.3	1.3- 3.9	3.9- 8.5
Chinook	0-8.8	8.8-10.8	10.8-22.3
Coho	0-8.8	8.8-10.5	10.5-21.6
Grayling	0-2.6	2.6- 6.9	6.9-14.1
Lamprey	0-1.0	1.0- 3.0	3.0- 6.2
Shad	0-2.3	2.3- 7.2	7.2-15.1
Sockeye	0-3.3	3.3-10.2	10.2-20.7
Steelhead	0-4.6	4.6-13.8	13.8-26.5
Suckers	0-1.3	1.3- 5.2	5.2-10.2
Whitefish	0-1.3	1.3- 4.3	4.3- 8.9

Passage is analyzed by computing the time that it would take the fish to travel the length of the culvert. There is a large difference in the time that a fish can swim at its sustained and burst speeds (i.e., 5 hours vs. 10 seconds), so the investigator must decide which criterion will be used. The time requirement is computed by dividing the length of the culvert by the resultant velocity of the fish:

$$T = \frac{L}{(V_f - V_c)} \qquad (7\text{-}11)$$

where T = the time of passage through the culvert

L = the length of the culvert

V_c = the velocity through the culvert

V_f = the swimming speed of the fish

The preferred flow would be one which would produce a velocity sufficiently smaller than the sustained swimming speed, so that most of the fish can pass the culvert in less than 5 minutes. This approach should also be taken in the design of new culvert crossings. If the mean velocity in the culvert cannot be sufficiently reduced, consideration should be given to using a larger culvert or placing baffles in the culvert to provide intermediate resting areas for the fish. Flow through culverts can be analyzed by virtually any hydraulic simulation model, up to the stage where the culvert is half full. Because it may safely be assumed that a culvert represents a length of uniform flow, Manning's equation (Equation 7-14) can be used. Once the culvert is over half filled, the relationship between the wetted perimeter and cross sectional area changes, and the programmed version of Manning's equation cannot be used. Manning's equation can be used with hand calculations, however. The wetted perimeter and area must first be determined and the hydraulic radius calculated. Figure 48 shows how to compute area and wetted perimeter for a partially filled, round conduit (from Chow 1959).

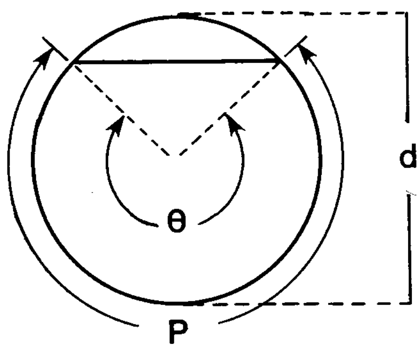


Figure 48. Computation of area and wetted perimeter for a partially filled, round culvert.

The wetted perimeter is computed by:

$$P = 1/2\ \theta d \tag{7-12}$$

and the cross section area by:

$$A = 1/8\ (\theta - \sin\theta)d^2 \tag{7-13}$$

where θ = the exterior angle defined from the center to the edges of the free surface, in radians (one radian = 57.3 degrees)

d = the diameter of the culvert

These parameters are then used to compute the hydraulic radius (R = A/P) and substituted into the Manning equations:

$$V = \frac{1.49}{N} R^{2/3} S^{1/2} \qquad (7\text{-}14)$$

$$Q = \frac{1.49}{N} R^{2/3} S^{1/2} A \qquad (7\text{-}15)$$

The process described above will work as long as neither end of the culvert is submerged. A pressure head is developed when the culvert is submerged, and the hydraulics are more like a pipe. The simulation of flow in submerged culverts is discussed in Linsley and Frazini (1964).

In all equations for submerged culverts, the slope of the culvert has no bearing on the velocity of the water. The only factor influencing the flow rate is the head difference (water surface elevation differential) between entrance and outlet. This factor becomes even more important for fish passage when the outlet is suspended above the streambed. Fish must leap from the stream into the culvert and then, swim through it. The techniques described in this section address the latter problem but not the former. The jumping ability of the fish must be considered on a case-by-case basis for each suspended culvert. The Stream Enhancement Research Committee (Anonymous 1980) suggests the construction of a series of weirs below suspended culverts to submerge the outlet. Normally, design of instream flows through existing culverts will be a minor portion of an instream flow study, although it may be very important in some streams. The inverse situation, designing culverts to accommodate the existing flow regime and permit fish passage, may be a major activity for some agencies, especially the U.S. Forest Service, U.S. Soil Conservation Service, and U.S. Bureau of Land Management.

7.5 SUGGESTED ADDITIONAL READING

Bovee, K. D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: fisheries. Instream Flow Information Paper 3. USDI Fish and Wildl. Serv., Washington, D.C. FWS/OBS-77/63. 39 pp.

Bovee, K. D., and R. T. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and techniques. Instream Flow Information Paper 5. USDI Fish and Wildl. Serv., Washington, D.C. FWS/OBS-78/33. 130 pp.

Linsley, R. K. and J. B. Franzini. 1964. Water-resources engineering. McGraw-Hill, New York. 654 pp.

Milhous, R. T., D. L. Wegner, and T. Waddle. 1981. User's guide to the physical habitat simulation system. Instream Flow Information Paper 11. USDI Fish and Wildl. Serv., Washington, D.C. FWS/OBS-81/43. 254 pp.

Prewitt, C. 1982. The effect of depth-velocity correlations on aquatic physical habitat usability estimates. Ph.D. dissertation, Colorado State University, Fort Collins, CO. 83 pp.

Trihey, E., and D. L. Wegner. 1981. Field data collection procedures for use with the physical habitat simulation system of the Instream Flow Group. U.S. Fish and Wildl. Serv., Cooperative Instream Flow Service Group, Fort Collins, CO. 151 pp.

Voos, K. A. 1981. Simulated use of the exponential polynomial/maximum likelihood technique in developing suitability of use functions for fish habitat. Ph.D. dissertation, Utah State University, Logan, UT. 85 pp.

8. CHANNEL MODIFICATION TO INCREASE HABITAT POTENTIAL

Physical habitat in rivers is defined by two equally important factors: channel characteristics and streamflow. A stream with poor channel characteristics will not support many fish, no matter how much water it carries. Likewise, a stream with good channel characteristics will not support many fish if adequate streamflow is not present. Channel modification to increase habitat potential can be considered any time that changes in flow have little appreciable effect on habitat availability, as computed by PHABSIM. However, there are two situations where channel modification for habitat improvement is practically the last viable alternative capable of maintaining or restoring stream habitat. The first of these is when the stream has already been "improved." Channel improvement in the engineering sense means improved water conveyance ability and reduced flood hazard in the vicinity of the alteration. The result is usually a biological desert through the channelized section. The second situation is when competition over a limited water source is so intense that, for all intents and purposes, negotiation for an adequate instream flow is unlikely to succeed. When neither side is able (as opposed to willing) to reduce its demand in the negotiation, three things can happen:

1. One side will win and the other side will lose;

2. An arbitrary decision will be made which probably won't do either side much good; or

3. Both sides can examine the possibilities of modifying the channel so that a lower instream flow does not result in a loss of habitat.

Channel modifications have been attempted in the past for the expressed purpose of improving habitat. The record for these modifications has been mixed; some were successes and some were failures. The failures are usually due to an ineffective biological or engineering design; either the fish do not use the modified area or it washes out during the spring flood. PHABSIM can be used effectively for evaluating alternative channel designs, cover features, and alignments. The major advantage of trial and error on a computer is that, when a design fails, the only loss is a little computer time and some paper. The goal of computerized analysis is to identify two or three promising channel designs that are most likely to succeed in a particular area. To be considered potentially successful, a channel design must be evaluated according to four criteria: effectiveness as fish habitat; longevity; installation and maintenance costs; and increase in flood hazard.

8.1 EFFECTIVENESS OF VARIOUS CHANNEL DESIGNS

The procedural pathway to evaluate the effectiveness of a particular channel design is essentially the same as that used for impact analysis. The river is measured in its present state and the habitat available for each target species computed for the existing flow regime. If an alternative flow regime is proposed, it too is evaluated for habitat potential in the existing channel.

Next, various alternative channel designs are entered into the hydraulic simulation portion of PHABSIM and the habitat potential reevaluated for either the existing or proposed flow regime. The investigator can narrow the range of alternatives considerably by examining the preference functions of the evaluation species and incorporating design changes which generally reflect the preferences of the species. Channel modifications can be structural, non-structural, or mixed. The most effective modification depends on the initial condition of the stream, the range of streamflows, and the species.

Effectiveness must be evaluated not only in terms of the management species, but also its food supply. Life stages other than adult may or may not be evaluated, depending on the type of fisheries management envisioned for the channel. For example, adults only would be evaluated for a put-and-take fishery, fry and juveniles evaluated in streams stocked with fingerlings, and spawning evaluated in streams where natural reproduction is desired.

8.1.1 Structural Modifications

Structural modifications include deflectors, revetments, weirs, headgates, and artificial cover devices. Structures are commonly used to fulfill one of three roles: to provide cover; to create channel diversity; or to control the flow. Obviously, artificial cover objects are used to provide cover. Deflectors, also known as spurs, wing dams, and jetties, are used to direct the flow in such a way that the force of the water creates habitat by scouring and filling places in the channel. Revetment is used to protect areas where erosion is not wanted. Weirs and headgates are used both to direct and control the flow.

a. Artificial cover devices. Some cover objects are cheap and easily installed and maintained, but others can be very expensive. One popular option is the placement of large boulders at strategic places in the channel (PHABSIM can be used to determine which places provide the greatest benefits). The feasibility of installing boulders depends largely on a ready supply of them. For example, this option might be fairly cheap in Colorado, but expensive in Illinois. Another option is the use of old car bodies, refrigerators, and tires. While these objects are often highly utilized by fish, they are aesthetic disasters and are not recommended. A satisfactory substitute for a boulder may be a log that is fastened to the bed or bank with a cable or partially buried in the bed. If boulders are not available, but large cobbles are, many cobbles can be held in a gabion (a woven wire or chain link container) to create the effect of a boulder. Gabions are usually asthetically unpleasing in a sport fishing environment and become hazardous when the wire disintegrates, so their use is discouraged, except as a last resort.

Overhead cover in natural streams can be provided by several conditions. Low hanging vegetation creates an area of reduced lighting and, if it drags in the water, it may also create surface turbulence. This type of overhead cover provides little slowing of the water and virtually no tactual stimulus. Submerged overhead cover, such as undercut banks, snags, and root wads, provides all three benefits and is the type of cover most artifical cover objects are designed to simulate.

In nature, these forms of cover are created by erosion. Snags are created when banks are undercut to the point that trees near the edge of the stream topple in. Undercut banks are created where part of the bank erodes, but part is held in place by the roots of plants (or occasionally, where a shelf of resistant bedrock extends into the stream). This should give the investigator an idea about where artificial covers should be placed: in the erosional parts of the channel; near the thalweg; and on the outsides of meander bends. Placement of such objects in depositional areas will result in their loss to siltation over a relatively short time span.

White and Brynildson (1967) present a design for a combined deflector and artificial overhead cover structure for use in low gradient streams. The design of this structure is shown in plan and cut-away views in Figure 49. The pilings shown in the cut-away view are not to scale. White (personal communication 1982) recommends that the pilings be at least 6 ft long. This construction appears to be very good and should last for a long time, provided it is not installed in too steep a stream or one subject to extremely high flows. The actual construction specifications for this structure can be found in White and Brynildson (1967).

Another type of artificial overhead cover is the "half log" structure. This structure consists of one or more logs, split in half, and supported under each end by a block of wood somewhat narrower than the half log. The entire apparatus is held together and anchored to the bed by long pieces of concrete reinforcement bar (rebar). The principal advantages of the half log are economy and flexibility. Because they are inexpensive, placement for durability is not the concern that it is for artificial undercuts. Furthermore, the design provides an area of reduced velocity as well as overhead shelter. The principal disadvantage of half logs is their lack of durability; if the streambed moves during high flow, the anchors are exposed, and the apparatus will simply float away.

b. Deflection devices. The purpose of installing deflection devices in a stream is to direct the flow in such a way that local scour and fill occurs in the channel, creating a more diverse bed profile. This is frequently a more economical means of developing pools, point bars, and riffles in a stream than mechanical excavation. If the structures are properly placed in the stream, the channel features created can often be self cleaning.

Numerous types of devices can be used as flow deflectors. In many cases, the material and deflector type is a matter of stability and availability of materials. More significantly, the placement and alignment of the structures must be compatible with the channel and the channel materials. Section 6.2.1 illustrated a number of channel patterns associated with different sediment characteristics. Thalweg sinuousity in straight channels can be increased by offset deflectors, as illustrated in Figure 50. Logs can be used instead of rock or concrete structures if the flood forces are not too powerful and the stream is not too large. Sedimentation generally occurs at the downstream edge of the deflector, creating a straight channel with point bars. Therefore, this type of structure is most compatible with a mixed load stream and would be essentially worthless in a bed load stream.

Deflectors should be constructed to do their work at high flows. Low flows do not have enough power to scour much sediment with or without a deflector. Any sediment removed at the point of the deflector would be deposited a short distance downstream anyway. Deflectors designed to redirect

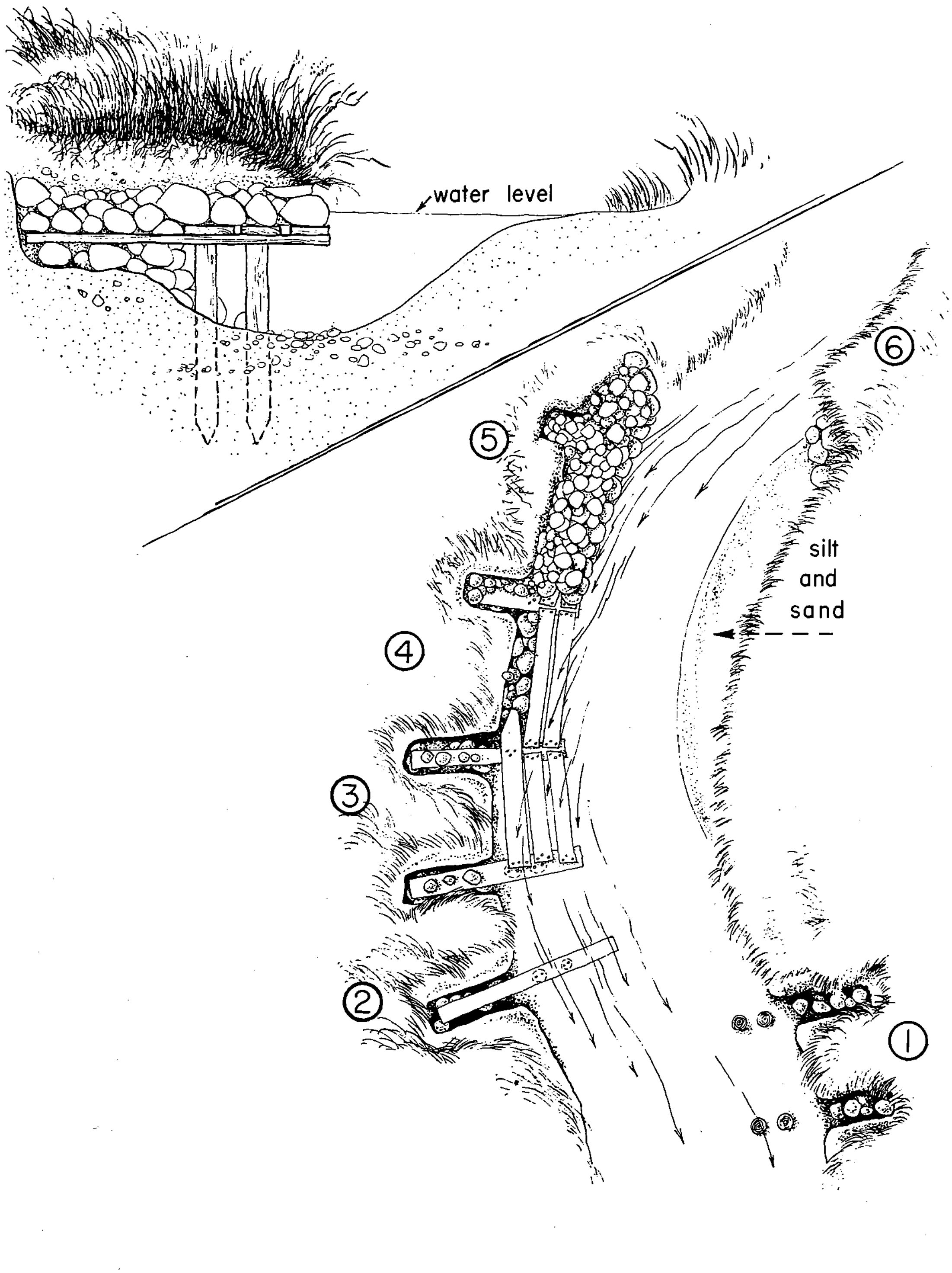


Figure 49. Construction schematics for artificial overhead cover structures (from White and Brynildson 1967).

low flows are severe channel constrictions at high flows. Constriction may cause flooding in itself, but debris is likely to collect on the deflector, almost guaranteeing that flooding will occur. The Federal Highway Administration (Anonymous 1979) recommmends that deflectors should extend no more than halfway across the channel and be no taller than 1.5 ft. Peninsular deflectors cause problems with erosion and sedimentation where neither is desirable. White and Brynildson (1967) provide a very efficient deflector design, illustrated in Figure 50. The design prevents the formation of eddies that can cause bank erosion immediately downstream from the deflector and encourages point bar formation, thereby extending the effect of the deflector.

The purpose of placing deflectors in the stream is to create habitat areas through the process of erosion. This may mean that certain places in the stream will erode where erosion is not wanted. Points of inpingement on the bank opposite the deflector will be susceptible to erosion and should be protected if meandering is not wanted. A scour pool develops along the leading edge of the deflector and, unless the base of the deflector is below the depth of scour, the structure may be undermined and fall into the pool.

Weirs behave similarly to riffles and, therefore, are most appropriate in streams normally having a riffle-pool sequence. The spacing of weirs should follow the general guidelines outlined by Leopold et al. (1964), with the average spacing of riffles five to seven times the bankfull width. Weirs are very susceptible to undermining and should be protected by hard surfacing on the downstream side of the weir. Undermining may be desired, in some cases, because it provides overhead cover as well as a plunge pool. A special kind of weir, called a Hewitt ramp, has been designed to permit limited undermining without causing structural failure. Construction details for the Hewitt ramp are given in White and Brynildson (1967).

c. <u>Headgates and flow control devices.</u> Flow control devices have a limited, but potentially useful, role in terms of channel modifications to increase habitat potential. Braided and realigned rivers are often characterized by a main channel, which carries most of the flow, and intermittently dewatered or stagnant side channels, backwaters, and oxbows that are isolated from the main channel. It is sometimes possible to direct a part of the flow through these side channels and derive great benefits in terms of habitat availability. This may require cutting an opening into the side channel. During the low flow season, the headgate is opened to allow proportionately greater flow through the side channel. The headgate can be closed down so that high flows do not damage the channel.

8.1.2 Nonstructural Modifications

Nonstructural channel modifications are used to enhance existing habitat conditions or create new ones. They are defined as nonstructural because they do not utilize a physical structure, such as a deflector or headgate. Nonstructural modifications have several advantages over structural modifications. The first is that the design of the habitat feature can be established with more certainty. For example, if a pool is excavated with a backhoe or bulldozer, it can be built to tighter specifications than building a deflector and allowing the stream to scour a pool. Second, a nonstructural approach usually produces immediate results. That is, the habitat is created quickly, and the only time lag for utilization by fish is the colonization time for the

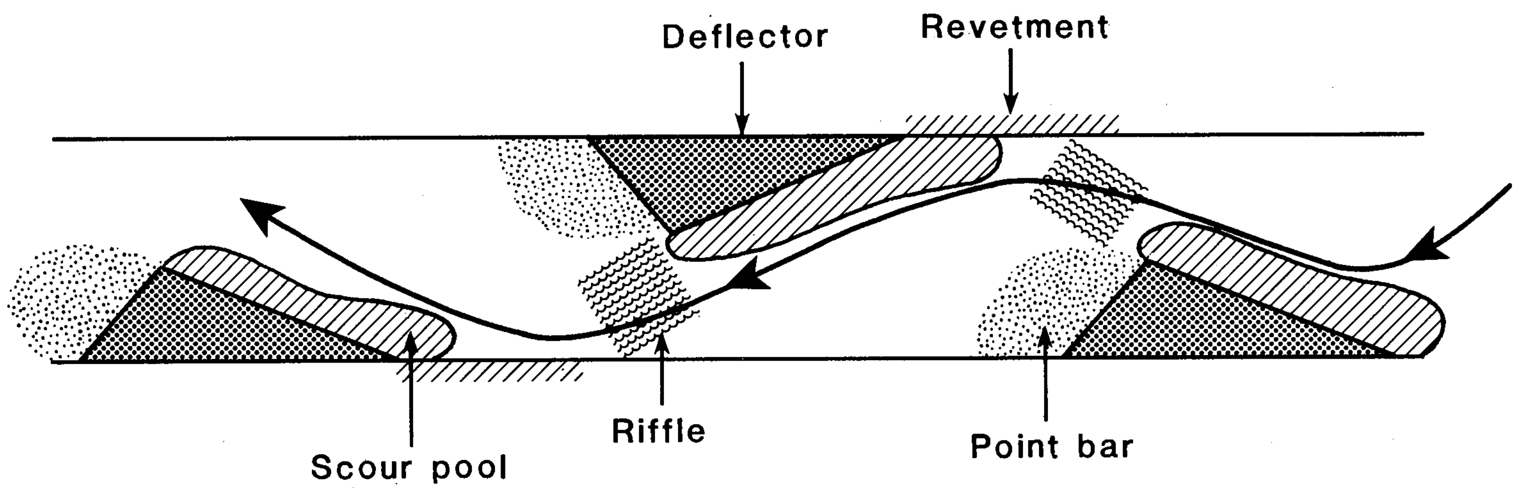


Figure 50. Straight channel with offset rock spurs to impose a meander pattern and bed profile diversity.

fish and its food base. It does not include a lag time for the habitat to be created through the hydraulic process. A third advantage of nonstructural modification is that it will probably look more natural than a structural alternative. The major disadvantage of nonstructural alternatives is that they tend to be less stable than many structural modifications. However, maintenance costs can be minimized with a design consistent with the channel type.

One example of nonstructural channel modification is the excavation or enlargement of pools. This may take three forms: the excavation of the pool only; raising the elevation of the hydraulic control (usually a riffle); or both. Deepening a pool will increase its cross section area, resulting in a reduction in velocity. Increasing the elevation of a riffle reduces the hydraulic gradient in the pool, thereby reducing the pool velocity and increasing its depth by an increment roughly equal to the raise in elevation of the riffle. It is often most effective to excavate the pools and use the excavated material to build up the riffles. This has the advantage of eliminating the need for a disposal area for materials removed from the pool or for obtaining fill materials for building up the riffles. However, there are two important considerations regarding this type of modification. First, any modification which raises the elevation of a hydraulic control feature, such as a riffle, increases the possibility of flooding. The second consideration is that the material placed on the riffle may not be suitable for riffle-living species, such as macroinvertebrates. Therefore, it may be necessary to dispose of materials dredged from the pools and import materials to build up the riffles. Both processes will add to the cost of the project. Care must also be taken not to deepen the pools too much, because this may cause instability along the walls or at the ends. This subject will be discussed in the section on longevity.

Another nonstructural alternative is the construction of floodways or bypass channels. Floodways are used primarily to alleviate flooding by dredging or realigning the original channel. To be truly effective, this alternative must be considered prior to channelization of the existing channel. A bypass channel is essentially a canal used to carry excess water through or around a flood prone area, thereby reducing (but not eliminating) the incidence of overbank flooding of the natural channel. Besides reducing flooding, reduction of the high flows may also improve habitat in the natural channel. The feasibility of using a bypass channel is often determined by the availability of a place to put it. Flow into the bypass can be controlled either by a headgate or by elevating the entrance so that only flows above a certain stage are diverted.

A floodway might be envisioned as a channel within a channel. Low flows are concentrated in the inner (lower) channels. High flows are accomodated by the outer channels, as illustrated in Figure 51. A floodway acts much the same way a natural floodplain does, except that it may be kept devoid of vegetation. Floodways typically lack two desirable features of good fish habitat: cover and bed profile diversity. Example A of Figure 51 is a typical configuration for a floodway. Example B of Figure 51 shows some habitat modifications that can be made without seriously affecting the performance of the floodway. The floodway can be planted with short to medium length species of grasses or low shrubs to provide overhead vegetation cover for the fish. Tall grasses or shrubs provide better cover, but also increase the roughness of the floodway and may defeat the purpose of the floodway. Ledges and undercuts can be constructed along the sides of the inner channel, but must be very sturdy as flood flows will concentrate their force along the bottom and sides of the inner channel.

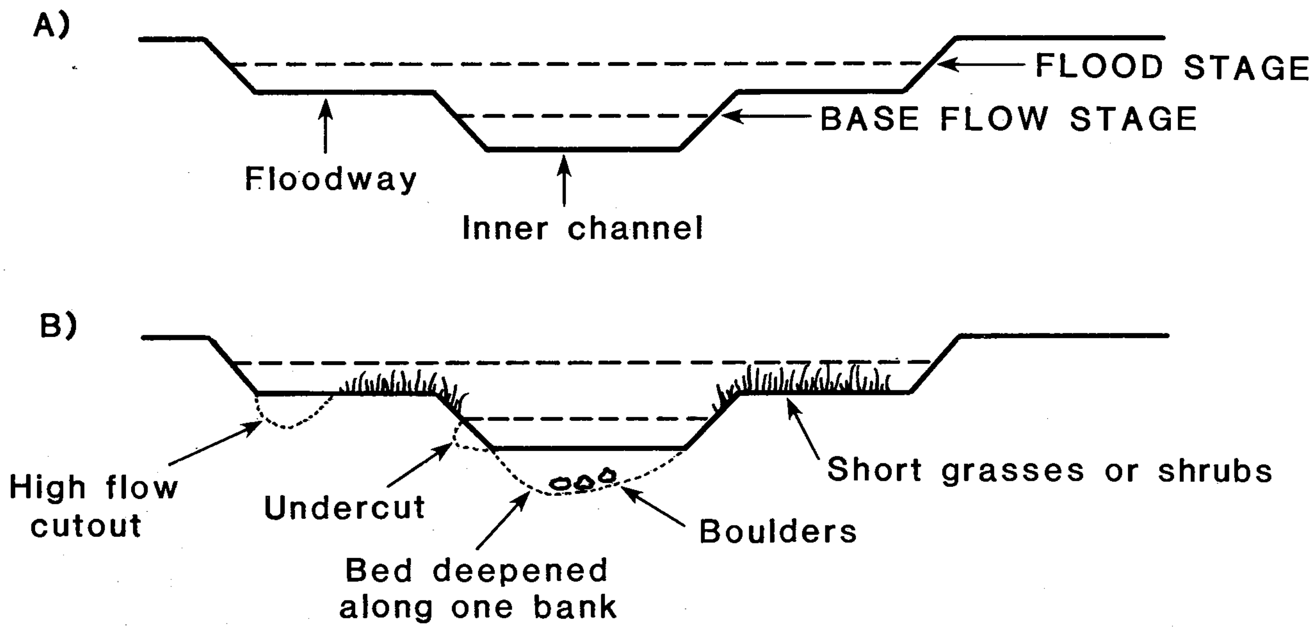


Figure 51. Channel improvements that can be made on a floodway without affecting its performance.

Flood flows can generate very high velocities in a floodway and inner channel, so it is important to provide refuges for the fish. Boulders placed in the inner channel serve this purpose and will be used as cover during low flow. Boulders can also be placed in the outer channel and may, in fact, provide better refuge from high velocities than those placed in the inner channel. Care must be used not to place so many boulders in the channel and floodway that the roughness is increased.

The bed of the inner channel can be modified to form a triangular, rather than trapezoidal, cross section without modifying the conveyance of water. The increase in cross section area will provide reduced velocities at high flows and create lateral bed profile diversity. It is important to leave parts of the channel as trapezoidal sections when this modification is made. The trapezoidal sections act as hydraulic controls and will maintain the same relationship between stage and discharge as the original trapezoidal channel. If these control sections are removed or altered, the stage-discharge relationship will change, with the possibility that some of the habitat improvement structures will be dewatered at low flow.

d. Mixed modification alternatives. Many combinations of structural and nonstructural modifications can be used in concert to enhance habitat potential. A few examples follow, but will are not intended to be a comprehensive list. Excavation of a pool, with adjacent construction of artificial undercuts (bank hides), may increase the effectiveness of both modifications. Often, the diversion of water into a side channel, and either nonstructural or structural improvement of the side channel, is more practical and effective than modifying the main channel (Wegner 1980). This is particularly true if flow into the side channel can be controlled by a headgate or other means. Another combination is the use of boulders to protect pockets of spawning gravel from being flushed away.

8.2 LONGEVITY

No structure or channel modification will last forever. If modifications are very well designed regularly inspected and maintained, and no major floods occur, they may last 100 years. Most habitat improving structures and modifications in active streams (those with other than a flat hydrograph) rarely remain intact for 10 years. Replacement costs may be greater than the original installation when the total cost of a design is computed. A structure may be designed to withstand a 100-year flood event, but the cost of installing it will be very high. Conversely, a structure designed to withstand a 2-year flood event may have to be replaced two or three times in a 10-year period. In some cases, it may be desirable to design a structure or channel shape which is guaranteed to fail at a particular flow. This may be needed to reduce a flood hazard created by the modification. Many channel modifications are not designed to withstand any flood event and must be replaced every year.

Much of what is known about designing stable channels comes from the design of irrigation canals. While this constitutes a fairly extensive body of knowledge, it is appropriate for uniform flow hydraulics. Few rivers naturally exhibit uniform flow characteristics. If they do, that is probably the one characteristic that will be changed in order to develop habitat. There are three primary considerations governing the longevity of a particular design: siltation; erosion of bed and banks; and scour associated with structures. The essential difference between design of a stable canal and a "stable" river is the frequency of scour and fill. A canal is designed in such a way that it neither scours nor fills. However, the discharge in a canal does not vary over time like that of a river. Therefore, river channel modifications must be designed not only to accomodate, but to take advantage of, the features resulting from inevitable scour and fill.

8.2.1 Siltation

Siltation is a more general problem than the obvious effects of filling pools with sediment and changing the cross section shape. Even small amounts of fine sediments can fill the pore spaces in cobble or gravel beds, seriously reducing the suitability of such substrates for invertebrate production or egg incubation. These changes can occur without significantly affecting the cross section shape.

Sedimentation is affected by both the size and the amount of sediment in transport. Accordingly, there are two approaches which can be used to evaluate the potential for siltation. The first is the use of transport models. These models address both components of size and amount, but require specialized training in their use. A simpler approach, using a threshold concept, can also be applied to this type of problem. There are several threshold concepts, but the most common type utilizes the tractive force. The tractive force is a measure of the drag or shear created by moving water in contact with the bed. The average value of the tractive force per unit wetted area is called the unit tractive force and is defined as:

$$\tau_o = WRS \qquad (8\text{-}1)$$

where τ_o = the unit tractive force in pounds per square foot

W = the unit weight of water (about 62 pounds per cubic foot)

R = the hydraulic radius in feet

S = the energy slope, dimensionless

The critical tractive force, τ_c, is the value of the unit tractive force at which the movement of a particular size of sediment ceases. The U.S. Bureau of Reclamation has developed the concept of a permissible tractive force. This value is the maximum unit tractive force which will not erode the bed, but likewise will not result in siltation by various sizes of sediment (Chow 1959, 1964). These values are summarized in Table 31.

Table 31. Summary of critical and permissible tractive forces for channels transporting various sizes of sediment (from Chow 1959, 1964).

Particle size (mm)	Critical tractive force (lbs/ft²)	Permissible tractive force	
		Clear water (lbs/ft²)	High silt content (lbs/ft²)
0.125	0.016	0.026	0.080
0.25	0.017	0.028	0.081
0.50	0.022	0.031	0.088
1.0	0.032	0.038	0.094
2.0	0.051	0.059	0.110
4.0	0.089	0.105	0.116

A size fraction of sediment will cease movement when the unit tractive force is less than the critical value. Because the slope and hydraulic radius changes throughout the length of the river (the slope may approach zero in a pool), there will be some places with sufficient tractive force to move certain sized particles and other places lacking sufficient tractive force. Thus, the tractive force technique can be used to determine whether or not a particle of a certain size will be deposited in various parts of the stream.

The tractive force method will not quantify how much sediment will be deposited. Its principle value is in designing a channel which will not silt at all. Unfortunately, if this is the only criterion applied, it is unlikely that a totally nonsilting channel can be constructed that has very much effectiveness in terms of fish habitat. Silting in some areas, such as pools, may need to be considered inevitable. As long as the silt can be removed during a flushing or high runoff streamflow, there may be no problem. However, if the potential exists for a large accumulation of sediment, a more rigorous technique than the tractive force method must be employed.

8.2.2 Erosion

Several types of erosive processes must be considered in the design of a channel modification: erosion of the streambed; erosion of the banks; and erosion in association with structures placed in the stream. In some cases, as in those mentioned in the previous section, some erosion is desirable. Erosion is not desirable in other cases, such as bank erosion along private property.

Bed erosion is often an insignificant consideration. In fact, it may be beneficial in terms of fish habitat. Too much bed erosion may result in oversteepening of the banks or riffles entering the pools. This may induce instability in the system, resulting in bank failure, degradation of riffles, or both. This factor should also be considered with mechanical excavation. The tractive force equations and maximum permissible tractive force method can be used to determine whether or not bed erosion will occur. However, if it is determined that erosion will occur, the size distribution of underlying sediments must be known in order to determine how far the stream will degrade.

Unchecked bank erosion, particularly when it occurs along privately owned land, is an undesirable consequence of channel modification. One obvious reason is that bank erosion may substantially undo previous habitat improvements. This is probably the most common cause of failure of artificial undercuts (bank hides). The eroded bank also becomes a sediment source for the filling of pools. However, perhaps the single best argument for preventing bank erosion along private property is that once it occurs, it may encourage realignment of the channel and bank stabilization.

Several types of forces act on the banks, any of which are capable of moving sediment. The tractive forces along the edge of a channel are smaller than they are in the center, but particles along the edge are subject to gravity forces which tend to cause the particle to roll toward the center. If we define the tractive force parallel to the channel as F1 and the gravity force perpendicular to the channel as F2, the resultant of the two forces acting on a particle is:

$$R = (F_1^2 + F_2^2)^{1/2} \qquad (8\text{-}2)$$

The magnitude of the gravity force acting on the particle is determined by the steepness of the bank and the size and shape of the particle. The latter two items define the angle of repose for an object. This concept is similar to the concept of the coefficient of friction in mechanics. The larger and more angular the object, the larger its angle of repose. Chow (1959) presents angles of repose for a number of objects of different sizes and shapes.

Once a nonscouring tractive force has been determined for the bed, a noneroding tractive force for the banks can also be determined (Chow 1959). The permissible tractive force along the banks can be found by:

$$\tau_S = \tau_B \cos\phi \left(1 - \frac{\sin^2\phi}{\sin^2\theta}\right)^{1/2} \tag{8-3}$$

where τ_S = the permissible tractive force along the sides

τ_B = the permissible tractive force along the bed

ϕ = the angle of the side slope to the horizontal

θ = the angle of repose for the bank material

These tractive forces refer to straight channels in course, noncohesive materials. Cohesive materials in the banks allow an increase in the permissible tractive force. Banks with large quantities of silt and clay have such cohesive forces that the gravity component can safely be ignored. Tree roots also provide a large amount of cohesion, but it is spotty, allowing erosion and cavitation of noncohesive materials not protected by the roots. At some point, the cavities may become extensive enough to allow a rotational failure of the bank. For sinuous channels, the permissible tractive force along the bank should be reduced. Approximate percentages of reduction are 10% for slightly sinuous channels, 25% for moderately sinuous channels, and 40% for very sinuous channels (Lane 1955b).

While silt-clay banks are fairly resistant to erosional forces; however, they can fail through another process, rotational or slump failure. This occurs when the bank becomes saturated, and the water level in the stream is reduced rapidly. The pore pressure in the banks exceeds the cohesive forces, and the toe of the bank slips out toward the stream. This results in an approximately semicircular failure of the bank. In this case, layering the bank with riprap will not prevent failure; the riprap will fail right along with the rest of the bank. Likewise, bank vegetation is little protection against this type of failure. About the only way to prevent it is to reduce the bank side slope or to avoid rapid fluctuations in the streamflow. This problem is primarily confined to banks with fine cohesive materials. Coarse, noncohesive banks drain quickly so that pore pressures do not remain high for long, and the side slopes are usually lower for these banks.

The third type of erosion occurs at very sharp bends in a river and around objects which obstruct the flow. In either case, the flow accelerates, creating a vortex. The creation of a vortex, and associated erosional processes, are extremely difficult to quantify. The computational procedures alone are enough to dissuade most people from attempting to quantify this type of scour. Most of our knowledge of vortex erosion has been developed in association with scour around bridge pilings. Empirical relationships have been developed for certain types of vortex erosion. One commonly used relationship is that the depth of scour below a boulder or weir is equal to 1.25 times the height of the object. This relationship was developed for gravel beds and would probably change according to bed particle size.

Vortex erosion is not something that can be ignored. Even the simple habitat improvement practice of placing boulders in the channel can be undone by vortex erosion. A scour pool may develop behind the boulder, and the first thing that happens is that the boulder rolls into the hole. There are two pieces of advice that should be heeded by the fisheries biologist contemplating channel improvement. First, if a structure or object is to be placed in a stream, a competent hydraulic engineer should be consulted. Second, if a structure of similar design has been placed elsewhere, it should be examined to determine the resulting channel changes.

8.3 FLOOD HAZARD

Some modifications to a channel can increase the potential for overbank flooding. Naturally, any modification which decreases the size of the channel can result in increased flood potential. Modifications which fall under this category include raising the elevation of a riffle and the placement of weirs and deflectors in the channel.

The second type of modification which can increase flood potential is anything which radically increases channel roughness. For example, one boulder placed in a channel will probably have a negligible effect on flood stage. The placement of numerous boulders in the channel may effectively double or triple the resistance to flow, creating the potential for increased flooding. Large aggregations of boulders also act as debris traps and may create debris dams.

The last consideration with respect to flooding is the consequence of failure of a structure. This is primarily a concern associated with artificial cover structures, especially artificial undercuts and half log structures. When these devices fail, they become part of the debris load. Furthermore, they tend to fail as a unit, creating a raft of floating debris. If this debris load collects in the throat of a culvert or on bridge pilings, or even on a riffle or gravel bar, it can create a serious flood problem. This debris alone would not normally create much difficulty. However, when it is joined by all the other debris in the river and flooding results, a disproportionate part of the blame may be placed on the failed structure. The most desirable preventative measure would be to design such structures to be failure proof. However, this is unlikely, and the investigator should evaluate areas downstream of the modification to determine potential lodgement points. It may be necessary to change the dimensions or the materials used in the structure so that they either pass the lodgement point (downsizing) or never get there (upsizing). White and Brynildson (1967) have compiled a collection of channel modifications that either do not work or create more problems than they solve. These devices have been illustrated in Figure 52, with comments regarding the problems associated with the structures.

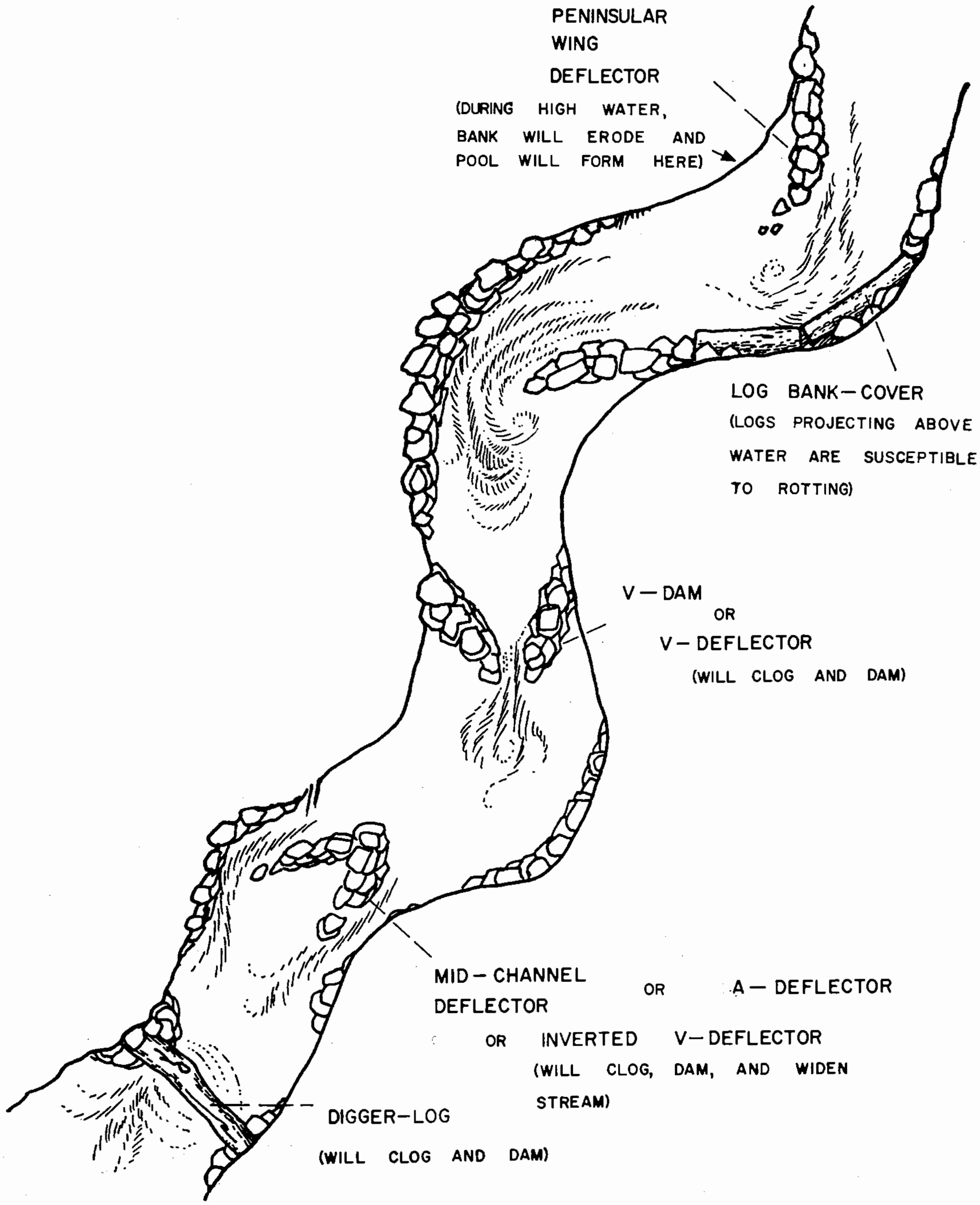


Figure 52. Channel improvement structures that cause more problems than they solve (from White and Brynildson 1967).

8.4 SUGGESTED ADDITIONAL READING

Anonymous. 1979. Restoration of fish habitat in relocated streams. U.S. Department of Transportation, Federal Highway Administration. FHWA-IP-79-3. 63 pp.

Chow, V. T. 1959. Open-channel hydraulics. McGraw-Hill Book Company, NY. 680 pp.

Chow, V. T. 1964. Handbook of applied hydrology. McGraw-Hill Book Company, NY. 1418 pp.

Wegner, D. L. 1980. Uinta River habitat development study. U.S. Bureau of Reclamation, Utah Projects Office, Provo, UT. 170 pp.

White, R. J., and O. M. Brynildson. 1967. Guidelines for management of trout stream habitat in Wisconsin. Wis. Dept. Nat. Res. Tech. Bull. 39. 65 pp.

Wydoski, R. S., and D. A. Duff. 1978. Indexed bibliography on stream habitat improvement. U.S. Bureau of Land Management, Denver, CO. 35 pp.

REFERENCES

Allen, K. R. 1951. The Horokiwi Stream: a study of a trout population. Fisheries Bulletin of New Zealand 10:1-238.

Alley, D. W., Jr., and H. W. Li. 1978. Microhabitat segregation and seasonal movements by fishes in a Sierra foothill stream. Manuscript submitted to Trans. Am. Fish. Soc. 37 pp.

Anonymous. 1979. Restoration of fish habitat in relocated streams. U.S. Dept. Trans., Fed. Highway Admin. FHWA-IP-79-3. 63 pp.

Anonymous. 1980. Stream Enhancement Research Committee. Can. Dept. Fish and Oceans, Vancouver, B.C. 82 pp + app.

Anonymous. 1981. Glen Canyon peaking power study: planning aid memorandum. Unpub. mimeo. USDI Fish. Wild. Serv. Phoenix, AZ. 22 pp.

Bayha, K. D. 1980. Instream flow studies and the Instream Flow Incremental Methodology in water resources planning. Instream Flow Information Paper 13. USDI Fish. Wildl. Serv., Instream Flow Group, Fort Collins, CO. mimeo rept. 44 pp. + attachments.

Bormann, F. H., and G. E. Likens. 1967. Nutrient cycling. Science 155:424-429.

Bovee, K. D. 1974. The determination, assessment, and design of "Instream Value" studies for the Northern Great Plains Region. Northern Great Plains Resources Program. 204 pp.

Bovee, K. D., and T. Cochnauer. 1977. Development and evaluation of weighted criteria, probability-of-use curves for instream flow assessments: fisheries. Instream Flow Information Paper 3. USDI Fish. Wildl. Serv. FWS/OBS-77/63. 38 pp.

Bovee, K. D., and R. T. Milhous. 1978. Hydraulic simulation in instream flow studies: theory and techniques. Instream Flow Information Paper 5. USDI Fish. Wildl. Serv. FWS/OBS-78/33. 130 pp.

Brusven, M. A. 1977. Effects of sediments on insects. Page 43 in D. L. Kibbee (ed.). Transport of granitic sediments in streams and its effects on insects and fish. USDA Forest Service. Forest, Wild., and Range Expt. Sta. Bull. 17. Univ. Idaho, Moscow, ID.

Burton, G. W., and E. P. Odum. 1945. The distribution of stream fish in the vicinity of Mountain Lake, Virginia. Ecology 26:182-194.

Chow, V. T. 1959. Open-channel hydraulics. McGraw-Hill, NY. 680 pp.

Chow, V. T. 1964. Handbook of applied hydrology. McGraw-Hill, NY. 1418 pp.

Collings, M. R., R. W. Smith, and G. T. Higgins. 1972. The hydrology of four streams in western Washington as related to several Pacific salmon species. U.S. Geological Survey Water Supply Paper 1968. 109 pp.

Dettman, D. H. 1977. Habitat selection, daytime behavior, and factors influencing distribution and abundance of rainbow trout (Salmo gairdneri) and Sacramento squawfish (Ptychocheilus grandis) in Deer Creek, California. M.S. Thesis, University of California, Davis, CA. 47 pp.

Doerksen, H. R., and B. L. Lamb. 1979. Managing the rippling stream: a model in decision-making in natural resource administration. Water Res. Bull. 15(6):1707-1715.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman and Co., San Francisco. 818 pp.

Everest, F. H., and D. W. Chapman. 1972. Habitat selection and spatial inter-action by juvenile chinook salmon and steelhead trout in two Idaho streams. J. Fish. Res. Bd. Can. 29:91-100.

Gore, J. A. 1978. A technique for predicting instream flow requirements for benthic macroinvertebrates. Freshwater Biology 8:141-151.

Gore, J. A., and R. D. Judy, Jr. 1981. Predictive models of benthic macroinvertebrate density for use in instream flow studies and regulated flow management. Can. J. Fish. Aq. Sci. 38(11):1363-1370.

Grenney, W. J., and A. K. Kraszewski. 1981. Description and application of the stream simulation and assessment model: version IV (SSAM IV). Instream Flow Information Paper 17. USDI Fish. Wildl. Serv. FWS/OBS-81/46. 199 pp.

Huet, M. 1959. Profiles and biology of western European streams as related to fish management. Trans. Am. Fish. Soc. 88(3):155-163.

Hunter, J. W. 1973. A discussion of game fish in the state of Washington as related to water requirements. Washington State Dept. of Game, Olympia, WA. Unpub. ms. 66 pp.

Hutchinson, G. E. 1957. Concluding remarks. Cold Spring Harbor Symp. Quant. Biol. 22:415-427.

Hynes, H. B. N. 1971. The biology of polluted waters. University of Toronto Press. 202 pp.

Kellerhals, R. 1981. Yampa River. Pages 46-53 in D. B. Simons and R. M. Li (eds.). Proc. symp. on downstream river channel changes from diversions or reservoir construction. Res. Inst. Colo., Fort Collins, CO.

Keup, L. E., W. M. Ingram, and K. M. MacKenthun. 1966. The role of bottom-dwelling macrofauna in water pollution investigations. Pub. Health Serv. Pub. 999-WP-38. 23 pp.

Lamb, B. L. 1976. Instream flow decision-making in the Pacific Northwest. Ph. D. dissertation. Washington State University, Pullman, WA. 328 pp.

Lane, E. W. 1955. The importance of fluvial morphology in hydraulic engineering. Proc. Am. Soc. Civ. Eng. 21(745). 17 pp.

Lane, E. W. 1955b. Design of stable channels. Trans. Am. Soc. Civ. Eng. 120:1234-1260.

Lee, G. F., and R. A. Jones. 1981. An approach for evaluating the potential significance of chemical contaminants in aquatic habitat assessment. Presented at American Fish. Soc. Symposium, "Acquisition and utilization of aquatic habitat inventory information," Portland, OR. Oct. 1981. 25 pp.

Leopold, L. B., and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Professional Paper 252. 57 pp.

Leopold, L. B., and J. P. Miller. 1956. Ephemeral streams: hydraulic factors and their relation to the drainage net. U.S. Geological Survey Professional Paper 282-A. 37 pp.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W. H. Freeman Co., San Francisco. 522 pp.

Lindblom, C. E. 1959. The science of muddling through. Public Admin. Rev. 14:79-88.

Linsley, R. K., and J. B. Franzini. 1964. Water-resources engineering. McGraw-Hill, NY. 654 pp.

Mahmood, K., and H. W. Shen. 1971. Regime concept of sediment transporting canals and rivers. Pages 30-1 to 30-39 in D. B. Simons (ed.). River mechanics, Vol. 2. Water Resources Publication, Littleton, CO.

Mann, K. H. 1967. The cropping of the food supply. Pages 243-257 in The biological basis of freshwater fish production. S. D. Gerking (ed.). John Wiley & Sons, Inc., NY. 495 pp.

Megahan, W. F., W. S. Platts, and B. Kuleza. 1980. Riverbed improves over time: South Fork Salmon. Pages 380-395 in Symposium on Watershed Management, Vol. 1. Am. Soc. Civ. Eng.

Needham, P. R., and R. L. Usinger. 1956. Variability in the macrofauna of a single riffle in Prosser Creek, California, as indicated by the Surber sampler. Hilgardia 24(4):383-409.

Odum, H. T. 1957. Trophic structure and productivity of Silver Springs. Ecol. Monogr. 27:55-112.

Orth, D. J., and O. E. Maughan. 1980. Instream flow methodology evaluation and flow quantification for Oklahoma streams. Completion Report. Okla. Co-op. Fish. Unit. Stillwater, OK. 292 pp.

Prescott, G. W. 1968. The algae: a review. Houghton Mifflin Co., Boston. 436 pp.

Prewitt, C. G. 1982. The effect of depth-velocity correlations on aquatic physical habitat usability estimates. Ph. D. dissertation, Colorado State University, Fort Collins, CO. 83 pp.

Riggs, H. C. 1968. Frequency curves. Techniques of water resources investigations of the U.S. Geological Survey. Book 4, Chapter A-2. 15 pp.

Ruthven, P. M. 1971. The dispersion of a decaying effluent discharged continuously into a uniformly flowing stream. Water Research 5(6):343-352.

Schumm, S. A. 1960. The shape of alluvial channels in relation to sediment type. U.S. Geological Survey Prof. Paper 352-B:17-30.

Schumm, S. A. 1977. The fluvial system. John Wiley & Sons, NY. 333 pp.

Schumm, S. A., and D. F. Meyer. 1979. Morphology of alluvial rivers of the Great Plains. Pages 9-14 in Great Plains Ag. Council Publ. 91. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. Fort Collins, CO.

Sheldon, A. L. 1968. Species diversity and longitudinal succession in stream fishes. Ecology 49(2):193-198.

Shelford, V. E. 1911. Ecological succession: I. stream fishes and the method of physiographic analysis. Biol. Bull. 21:9-34.

Shen, H. W., S. A. Schumm, J. D. Nelson, D. O. Doehring, M. M. Skinner, and G. L. Smith. 1981. Assessment of stream related hazards to highways and bridges. Federal Highway Admin., Washington, D.C. 241 pp.

Simons, D. B., and R. M. Li. 1980. Downstream river channel changes from diversions or reservoir construction. Proc. of symposium held at Colorado State University, Aug 27-29, 1980. Research Institute of Colorado, Fort Collins, CO. 252 pp. + app.

Smith, A. K. 1973. Development and application of spawning depth and velocity criteria for Oregon salmonids. Trans. Am. Fish. Soc. 102(2):312-316.

Theurer, F. D. 1982. Instream water temperature model. Instream Flow Information Paper 16 (in preparation). USDI Fish Wildl. Serv., Fort Collins, CO. 131 pp.

Thompson, K. 1972. Determining streamflows for fish life. Pages 31-46 in Proc. Instream Flow Req. Wkshp., Portland, OR., March 15-16, 1972.

Thornthwaite, C. W., and J. R. Mather. 1955. The water balance. Laboratory of Climatology, Publication 8. Centerton, NJ.

Thurston, R. V., R. C. Russo, C. M. Fetterolf, T. A. Edsall, and Y. M. Barber (eds.). 1979. A review of the EPA Red Book: Quality criteria for water. Water Quality Section, American Fisheries Society, Bethesda, MD. 313 pp.

Trihey, E. W., and D. L. Wegner. 1981. Field data collection procedures for use with the physical habitat simulation system of the Instream Flow Group. USDI Fish. Wildl. Serv., Cooperative Instream Flow Service Group, Fort Collins, CO. 151 pp.

Troendle, C. A., and C. F. Leaf. 1980. Hydrology. Pages III.1-III.173 in An approach to water resources evaluation of non-point silvicultural sources (A procedural handbook). U.S. Environmental Protection Agency. EPA-600/8-80-012.

U.S. Environmental Protection Agency. 1976. Quality criteria for water. U.S. Environmental Protection Agency. Washington, D.C. 256 pp.

U.S. Fish and Wildlife Service. 1980. Habitat Evaluation Procedures. USDI Fish Wildl. Serv. ESM 102. Unpaged.

Velz, C. J. 1970. Applied stream sanitation. Wiley Interscience, New York. 619 pp.

Voos, K. A. 1981. Simulated use of the exponential polynomial/maximum likelihood technique in developing suitability of use functions for fish habitat. Ph. D. Dissertation, Utah State University, Logan, UT. 85 pp.

Voos, K. A., W. J. Grenney, and K. P. Burnham. 1981. A model for fish habitat usability. (Submitted to The American Naturalist.) 23 pp.

Warren, C. E., and G. E. Davis. 1967. Laboratory studies on the feeding, bioenergetics, and growth of fish. Pages 175-214 in S. D. Gerking (ed.). The biological basis of freshwater fish production. John Wiley and Sons, NY.

Wassenberg, P. S., S. Olive, J. L. DeMott, and C. B. Stalnaker. 1979. Elements in negotiating stream flows associated with Federal projects. Instream Flow Information Paper 9. USDI Fish. Wildl. Serv. FWS/OBS-79/03. 41 pp.

Water Resources Council. 1970. Water and related resources planning: a policy statement. U.S. Water Resources Council, Washington, D.C. 5 pp.

Waters, B. F. 1976. A methodology for evaluting the effects of different streamflows on salmonid habitat. Pages 254-266 in J. F. Orsborn and C. H. Allman (eds.). Instream flow needs. Am. Fish. Soc., Bethesda, MD.

Waters, T. F. 1981. Seasonal patterns in production and drift of *Gammarus pseudolimnaes* in Valley Creek, Minnesota. Ecology 62(6):1458-1466.

Weatherley, A. H. 1972. Growth and ecology of fish populations. Academic Press, NY. 293 pp.

Wegner, D. L. 1980. Uinta River habitat improvement study. Utah Projects Office, U.S. Bureau of Reclamation, Provo, UT. 170 pp.

White, M. R., F. D. Valdez, and M. D. White. 1980. Instream flow negotiation: review of practices. USDI Fish. Wildl. Serv. FWS/OBS-80/53. 50 pp.

White, R. G. 1976. A methodology for recommending stream resource maintenance flows for large rivers. Pages 376-399 in J. F. Orsborn and C. H. Allman (eds.). Instream flow needs (Vol. 2). Am. Fish. Soc., Bethesda, MD.

White, R. J., and O. M. Brynildson. 1967. Guidelines for management of trout stream habitat in Wisconsin. Wisconsin Dept. Nat. Res. Tech. Bull. 39. 65 pp.

Winberg, G. G. 1956. Rate of metabolism and food requirements of fish. Fish. Res. Bd. Can. Transl. Ser. 194. 254 pp.

Wolman, M. G., and J. P. Miller. 1960. Magnitude and frequence of forces in geomorphic processes. J. Geology 68(1):54-74.

APPENDIX A. BLANK FORMS FOR USE WITH IFIM

This appendix contains blank forms that can be used at various stages in the preparation of output data from the IFIM. These forms are provided for the convenience of the user and are not intended to constrain data preparation to any specified format. The user should copy as many of the forms as needed for an analysis prior to compiling and analyzing the data.

The first two sets of forms are the checklists of project scoping and site selection activities illustrated in Chapters 2 and 3, respectively. These checklists should be copied and filled out prior to the initiation of any field work.

Form A is a general description of the geography, location, and hydrologic characteristics of each segment used in an analysis. If more than one study site describes the microhabitat of a segment, the length of the segment represented by each site should be entered on Form A. All computations and graphs used to determine the water supply characteristics of the segment should be attached to this form.

Form B is used to compute the total segment habitat for a single life stage of an evaluation species over a range of streamflows. Several copies of Form B will be needed if:

1. The length of stream having suitable water quality and temperature changes by month or season; or

2. The evaluation species utilizes different microhabitats by month or season.

The month or season to which the total segment habitat applies should be specified at the top of Form B. The time period should also be specified if the habitat computations apply to the entire year. Form B should be filled out in the following manner:

1. Record the first discharge to be analyzed under Column A. Normally, discharges are recorded from lowest to highest;

2. Record the identification code(s) for each study site used to represent the segment under Column B;

3. Record, in Column C, the unit WUA in square feet per mile for each study site, corresponding to the discharge recorded under Column A;

4. Determine the length of stream represented by each study site that has suitable water quality and temperature at the discharge recorded under Column A. Note that this distance applies to each study site individually. (See Section 5.1 for sample preparation of this data.) Record the length of stream having suitable water quality and temperature for each sutdy site under Column D;

5. Check all downstream segments for critical passage barriers. If any downstream barrier is impassable at the flow recorded in Column A, enter 0 under Column D, and note passage problem on form. Note that this restriction applies only to those life stages which must migrate to complete their life cycle (such as spawning) or to maintain their productivity (such as moving into a feeding area);

6. Compute the habitat subtotal for each study site in the segment by multiplying corresponding values in Columns C and D. Record the subtotal for each site under Column E;

7. Compute the segment total habitat by adding all subtotals for the discharge under Column A, and record the total under Column F; and

8. Enter a new discharge under Column A and repeat steps 2-8 until the range of discharges has been covered.

It is strongly suggested that the user organize a filing system for handling all the data produced by this methodology. Each file should contain, at a minimum, one Form A and all Forms B pertaining to a segment. It is also advisable to include field books, summary sheets, final computer calibration runs, photographs, and maps pertaining to the segment in the file. A separate file or a subsection of this master file should be reserved for data interpretation and display materials and all computations and decisions made leading to a recommendation or conclusion.

Form C is a copy of the optimization table illustrated in Section 5.2.3. This form is sometimes used to arrive at instream flow recommendations and is included solely for the convenience of the user. Section 5.2.3 should be reviewed thoroughly so that the assumptions and implications associated with Form C are fully understood.

CHECKLIST OF SCOPING ACTIVITIES

- ______ Study objectives have been identified and stated.
- ______ Project area has been reconnoitered.
- ______ Length of mainstem to be included in study has been determined.
- ______ Environmental conditions affected by proposed action have been identified (check those which apply):
  - ______ Watershed
  - ______ Channel structure
  - ______ Water quality
  - ______ Temperature
  - ______ Flow regime
- ______ Initial contacts with professional personnel have been made.
- ______ Tributaries to be included in study have been identified, if applicable.
- ______ Topographic maps of area have been obtained.
- ______ Geologic maps of area have been obtained, if available.
- ______ Streamflow records for area have been obtained.
- ______ Arrangements have been made to develop synthetic hydrographs for ungaged streams.
- ______ Equilibrium conditions of watershed and channel have been evaluated.
- ______ Arrangements have been made to model future channel structure, if necessary.
- ______ Existing water quality characteristics have been evaluated and screening equations applied to determine future water quality status.
- ______ Arrangements have been made to model future water quality, if necessary.
- ______ Longitudinal distribution of species has been determined.

CHECKLIST (Concluded)

__________ Evaluation species have been selected.

__________ Pertinent details of target species have been compiled (life history, food habits, water quality tolerances, and microhabitat usage).

__________ Periodicity charts for target species have been prepared and referenced to stream segments (see Chapter 3).

__________ Display and interpretation requirements have been determined and acquisition of biological data, if required, has been included in study design (see Chapter 5).

CHECKLIST FOR ESTABLISHING STUDY AREAS

- ________ Topographic maps or suitable substitutes (e.g., aerial photos or other maps) of the study area have been assembled so that entire area is shown on one map.
- ________ Tributaries accreting more than 10% to the average base flow below the confluences have been identified and marked on the map.
- ________ Diversions removing more than 10% of the total flow of the river above the diversion have been identified and marked on the map.
- ________ Ground water sources or diffuse small tributaries, which in aggregate add 10% to the average base flow or add 10% to the drainage area-precipitation product, have been isolated and marked on the map.
- ________ Longitudinal profile of stream(s) has (have) been constructed.
- ________ Segment boundaries, based on relief, have been determined and marked on the map.
- ________ Significant sediment sources, such as moraines, landslides, and areas of sediment-generating land use, have been identified and marked on the map (if applicable).
- ________ Locations where channel sinuosity or width to depth ratio changes appreciably (more than 25%) have been identified and marked on the map (if applicable).
- ________ Locations where channel shape, channel pattern, bed particle size, or bank vegetation change appreciably have been identified and marked on the map (if applicable).
- ________ Stream reaches containing populations of coldwater species and warmwater species, as well as transitional reaches, have been identified and marked on the map (if applicable).
- ________ Point sources of pollution or thermal effluent have been located and marked on the map (if applicable).
- ________ Areas of land use affecting nonpoint pollution have been identified and marked on the map (if applicable).
- ________ If water quality is suspected to be a problem, or may be a problem under a proposed action, an expert has been consulted and water quality monitoring or modeling stations have been identified and marked on the map.

CHECKLIST (Continued)

__________ If watershed or channel change problems are anticipated, an expert in sediment transport and channel change has been consulted and appropriate actions recommended.

__________ Segment boundaries isolating lengths of stream of less than 10% of the total stream length have been consolidated (remember well defined segment boundaries take precedence over poorly defined boundaries).

__________ Average width of stream within each segment has been determined.

__________ Length of candidate representative reaches has been calculated.

__________ Candidate representative reaches have been marked on the map at appropriate spacing and numbered sequentially from the bottom of the segment to the top.

__________ Candidate reaches having bridge crossings have been eliminated.

__________ Three to five representative reaches have been chosen at random for each segment.

__________ If not random, how were the representative reaches selected? Why?

____

____

__________ Critical reaches, if present, have been identified and marked on the map (may include reaches less than 10% of total stream length in segment).

What is the nature of the critical reach? (e.g., culvert, shallow bar inhibiting passage, or spawning areas).

____

____

__________ Selected reaches have been inspected, redundant reaches eliminated and new reaches added where unrepresented portions of the river are detected.

__________ Landowner permission to work at selected reaches has been obtained (if applicable).

CHECKLIST (Concluded)

______ If landowner permission to work at selected reaches is denied or the selected reaches are inaccessible, alternate reaches have been selected (if applicable). If so, how were the alternate sites selected?

____

____

______ Lengths of stream represented by representative reaches have been determined.

______ Lengths of stream represented by critical reaches have been determined.

____

FORM A

Stream name: ______________________________

Segment number: ______________________________

Segment boundaries: upstream ____________ downstream ____________

Number of representative reaches in segment: ________

Number of critical reaches in segment: ________

Nature of critical reach(es): ________ ________ ________

Passage barriers downstream? yes ____ no ____

Computation of represented segment lengths

Study site ID	River miles to bottom of represented section from lower segment boundary	River miles to top of represented section from lower segment boundary	Length of segment represented

Streamflow characteristics:
Dominant discharge for segment ________
(attach flood frequency recurrence interval curve)

Monthly streamflow distribution:
[attach monthly flow duration or recurrence interval curves (12)]

Exceedance probability	Month O	N	D	J	F	M	A	M	J	J	A	S
10%												
50%												
90%												

FORM B

Stream name: ______________________ Evaluation species: ______________________

Segment ID: ______________________ Life stage: ______________________

Month or season: ______________________

A	B	C	D	E	F
Discharge	Reach or study site ID	Unit WUA for reach or study site (WUA/1,000 ft × 5.28)	Length of represented segment having suitable water quality and temperature (miles)	Segment subtotal habitat (c × d)	Segment total habitat (sum E for each Q)

FORM C

Optimization and trade-off analysis of habitat availability over available range of flows. Record segment total WUA for each life stage beneath each recorded discharge.

Month:

Discharge					
% Exceedance	90%	80%	70%	60%	50%
Target species and life stage					
minimum WUA value in column					

APPENDIX B. MATHEMATICAL DERIVATION OF FOOD REQUIREMENTS AND SUPPLY

Balancing the food supply to the food requirements for optimum production of fish has long been a problem in fish culture. The manager of a natural stream fishery has an additional problem rarely faced by the fish culturist, namely that the total food supply only consists of what is available in the stream. Manipulation of the food supply in a natural stream follows the same rules as management of the fish population in the absence of stocking. That is, changes in the food supply can be affected by management of the environment, but usually not through direct intervention, such as artificial feeding. The following discussion presents one possible method of determining the food requirements of the fish community and the adequacy of the total food supply to meet those needs. All the data needed to use this approach are not available at this time, so the method cannot be used in instream flow or impact studies. The discussion is included as a subject for future research.

On the surface, the problem seems quite simple. The investigator needs only(!) to determine how much food a single fish requires, how much food is grown per square meter of habitat, how many square meters of food producing habitat are required to support one fish, and how many fish are present. Unfortunately, the first two steps involve a number of factors which are not constant, even in the same stream. The resolution of these factors becomes even harder when extended over many streams and geographic areas. However, there are some generalizations that can be made regarding both the food requirements of the fish and the food producing capability of a stream.

There are three principal methods of determining the food requirements of fish: (1) the whole biomass method; (2) nitrogen budgets; and (3) energy budgets. The common weakness of all three methods is that food consumption and assimilation are measured under laboratory conditions. These measurements must be extrapolated to the field situation, which often requires assumed correction factors to accommodate differences in activity, temperature, season or other environmental variables. A good description of all three methods, including a discussion of their strengths and weaknesses and method verification, if any, is given by Mann (1967). The energy budget approach developed by Winberg (1956) appears to be the easiest and most applicable method for use with the IFIM.

The energy budget approach avoids several of the disadvantages inherent to the whole biomss and nitrogen budget methods, especially variations in the maintenance ration due to size and temperature. The energy budget method is based on the assumption that the energy content of the food equals the sum of the energy contents of: (1) the material lost in egestion and excretion; (2) the material retained in growth; and (3) the material metabolically broken down. Egestion, excretion, and growth are measured directly; the metabolic rate is determined by measuring oxygen consumption. Assuming that the diet contains a mixture of fats, carbohydrates, and protein, the consumption of 1 ml of oxygen is the energy equivalent of about 4.8 calories (Mann 1967).

The primary contribution of Winberg (1956) to the development of the energy budget approach was the standardization and generalization of oxycalorific data. Two general principles were evident once these data were standardized to a common temperature. The first was that the resting metabolic rates of virtually all species of fish were close to, or coincided with, Krogh's normal curve. This curve illustrated the nonlinear relationship between resting metabolism and temperature. The metabolic rate, as measured by oxygen consumption at 20°C, can be corrected to any other temperature by dividing it by the appropriate factor from Table B-1. The second principle is that the metabolic rates for a species can be expressed as an exponential function of the weight as follows:

$$Q = aW^K \tag{B-1}$$

where Q = the resting metabolic rate at 20°C expressed in ml oxygen/hr

a = the proportionality constant, equal to the total metabolism of an animal of unit weight

W = the weight of the animal

K = a constant that indicates the rate of change in metabolism with increase in weight

Table B-1. Correction factors for adjusting metabolic rates as a function of temperature (from Winberg 1956). Divide the known metabolic rate for 20°C by K_T to obtain the rate at T.

T	K_T	T	K_T
5	5.19	18	1.20
6	4.55	19	1.09
7	3.98	20	1.00
8	3.48	21	0.920
9	3.05	22	0.847
10	2.67	23	0.779
11	2.40	24	0.717
12	2.16	25	0.659
13	1.94	26	0.609
14	1.74	27	0.563
15	1.57	28	0.520
16	1.43	29	0.481
17	1.31	30	0.444

Table B-2 contains the proportionality values and rate coefficients for numerous species at 20°C. Winberg (1956) noted that, with the exception of Cyprinodontiformes, most species conform approximately to the equation:

$$Q = 0.3\ W^{0.8} \quad \text{(B-2)}$$

This generalization was extended to several species for which there were insufficient data to determine the proportionality and rate coefficients. Data for these species were plotted along the line representing the general Equation (B-2). The fit of the data to the line was very good for perch (assumed to be yellow perch, Perca flavescens) and pike (assumed to be northern pike, Esox lucius). The fit was not as good for other freshwater percidae, with many of the data points below, but roughly parallel, to the line. This indicates that the rate coefficient of 0.81 is about right, but that the proportionality coefficient is slightly less than 0.3. Unfortunately, the species included in Winberg's (1956) data for "other percidae" are unknown. The assumption of a proportionality coefficient of 0.3, while arguable from a theoretical standpoint, is probably well within the acceptable error bounds of the IFIM.

Table B-2. Proportionality and rate coefficients of metabolic change for various families of fish (from Winberg 1956).

Family or Species	Proportionality coefficient (a)	Metabolic exponent (K)
Carp	0.343	0.85
Sturgeons	0.391	0.81
Salmonids (general)	0.498	0.76
Atlantic salmon (fingerling)	0.400	0.81
Cyprinids (except carp and goldfish)	0.336	0.80
Cyprinodontiformes	0.192	0.71
All freshwater fishes	0.297	0.81

Winberg (1956) also synthesized published data on the proportion of food energy assimilated and egested. He concluded that about 80% of the food intake was actually assimilated, and 20% was lost through egestion and excretion. Therefore, the total food energy intake must be increased by the inverse of 0.80, or:

$$FE = 1.25\ [EM + EG] \quad \text{(B-3)}$$

where FE = the total food energy required by the fish

EM = the energy used in metabolism

EG = the energy used in growth

Active metabolism in natural stream situations was assumed by Winberg (1956) to be about double the resting rate under laboratory conditions. Mann (1967) noted that the active metabolism rate for other animals varies from 1.5 to 2.5 times the resting rate and agreed that a factor of 2.0 is appropriate for active metabolism in fish. Warren and Davis (1967), while not taking exception to the doubling of the laboratory rate, noted that the metabolic rate in natural streams depends on the activity of the fish, the availability of food (i.e., the amount of foraging required to obtain food), the energy value of the food, and the conversion efficiency. Warren and Davis (1967) presented caloric values for several food organisms typical of trout streams and many cool and warmwater streams. The mean value of midge (chironomidae) larvae was 5.27 kcal/gram dry weight. The caloric values for stonefly naiads, tubificid worms, and sculpins were 5.36, 5.49, and 5.29 kcal/gram dry weight, respectively. These mean caloric values, representing a broad spectrum of food items, are remarkably similar. An assumed value of 5.3 kcal/gram dry weight would be acceptable in an instream flow analysis of food requirements. This translates to an approximate value for potential energy stored in growth of 1 kcal/gram fresh weight (Mann 1967; Warren and Davis 1967).

Variations in conversion efficiency can be confusing, perhaps needlessly. In a heirarchy of trophic levels, approximately 10% of the total energy at each trophic level is transferred to the next higher level (Odum 1957). Winberg's (1956) equation refers to assimilation efficiency, which is the ratio between energy assimilated and energy consumed. Efficiency terms that describe the ratio between growth and consumption are largely irrelevant to Winberg's equation because food energy assimilated but not used for metabolism will be used in growth.

The food requirements of one age group of fish for one month can be calculated from data already available from other steps in the application of the IFIM. The data needed are:

1. The mean temperature for the month;

2. The average weight and approximate number of fish in the cohort at the beginning of the month; and

3. The average weight and approximate number of fish in the cohort at the end of the month.

The average weight of the fish at any time during the growing season can be approximated from the age-weight relationship used to compute habitat ratios between life stages. The average weight at the beginning and end of the growing season must be known or estimated. The growth rate may be assumed to be linear or exponential, and growth during the winter may or may not be zero. Assuming linear growth rates, the growth coefficient (G) is estimated as follows:

$$G = (W_2 - W_1)/T \qquad \text{(B-4)}$$

where G = the growth coefficient

W_2 = the average individual weight at the end of the growing season

W_1 = the average individual weight at the start of the growing season

T = the length of the growing season, in months

The weight of an individual at the beginning of any month is calculated as:

$$W_m = W_o Gt \qquad \text{(B-5)}$$

where W_m = the weight of the individual at the beginning of month m

W_o = the weight of the individual at the beginning of the growing season

G = the growth coefficient

t = the time in months from the beginning of the growing season to the month of interest

The growth coefficient (G) can be solved for exponential growth by the following equation:

$$G = \frac{\ln \; W_2/W_1}{T} \qquad \text{(B-6)}$$

where G, W_2, W_1, and T are the same values used in Equation B-4.

The average weight of an individual at the beginning of any month can be calculated as:

$$W_m = W_o e^{GT} \qquad \text{(B-7)}$$

The actual amount of growth during a month can be calculated by subtracting the beginning weight for that month from the beginning weight for the next month.

The food requirement for one individual of an age group for a month is computed by the following sequence:

1. Compute the resting metabolic rate at 20°C for the weight of the animal at the start of the month by:

$$Q = 0.3\ W^{0.8}$$

2. Correct the resting metabolic rate for the mean monthly temperature (from Table B-1):

$$Q' = Q/K_t$$

3. Double the value of Q' to obtain the active metabolic rate.

4. Multiply Q' by 4.8 cal/ml O_2 x 720 hours/month to obtain total caloric intake needed for metabolism:

$$EM = Q' \times 4.8 \times 720 \quad \text{(see Equation B-3)}$$

5. Multiply the growth increment (grams) for the month by 1,000 cal/gram to obtain the energy required for growth.

6. Add the results from Steps 4 and 5, and multiply the sum by 1.25 to obtain the total caloric intake requirement.

7. Divide the value from Step 6 by 1000 cal/gram to obtain the grams of food required.

The sequence described above gives the food requirements of one fish for a month. The next step is to estimate the number of fish of that size during the month. The mortality rate of older fish is commonly linear, while mortality in young fish is usually exponential. A linear mortality rate may be calculated by:

$$R = (N_o - N_t)/t \tag{B-8}$$

where R = the mortality rate

N_o = the number of individuals at the beginning of the time increment

N_t = the number of individuals at the end of the time increment

t = the time increment in months

From Equation B-8, the number of individuals during any month can be computed by:

$$N_t = N_o - Rt \qquad \text{(B-9)}$$

where N_t, N_o, t, and R are the same as in Equation B-8.

Exponential mortality rates can be expressed by:

$$R = \frac{\ln \; N_t/N_o}{t} \qquad \text{(B-10)}$$

and the number of individuals during any month as:

$$N_t = N_o e^{-Rt} \qquad \text{(B-11)}$$

where, N_t, N_o, R, t are the same terms defined in Equation B-8.

The number of individuals in a cohort during any month is calculated from either Equation B-9 or B-11, with the mortality rate computed from the annual mortality rate used in the determination of life stage ratios. This number is multiplied by the food requirement of one fish (Step 7) to determine the food requirement for the cohort. This process is repeated for each month (note that there is a food requirement even during months of no growth) for each cohort utilizing the same food source. The advantage to this approach is that food requirements may be added across species using the same food source, yielding total food requirements for that portion of the fish community.

The food producing habitat needed to support a given biomass of fish must still be determined. Mann (1967) notes that food stocks are very intensively grazed by natural populations of fish. Study results quoted by Mann indicate that the amount of food consumed by a fish population each year equals 6 to 50 times the average benthic biomass available at any time. The disparity between the annual food requirement of fish and the amount of food available at any time is largely explained by the high ratio of production to biomass among benthic invertebrates. This ratio is inversely related to the life span of the organism. Based on data from the River Thames, Mann (1967) suggested that the production to biomass (P/B) ratio for animals taking 2 years to complete their life cycle is about 2:1. The ratio for animals with a 1 year life cycle is about 5:1; for species completing several generations per year, the ratio may be ≥ 10:1. Waters (1981) reported an average P/B ratio for *Gammarus pseudolimnaes* over a 5 year period as about 6:1. *G. pseudolimnaes* has a 15-month life cycle (Mann's data would suggest a P/B ratio of about 5:1). The P/B ratio depends, in part, on the degree of cropping of the benthos. Lightly grazed benthic populations may become very dense and be limited by available food and space. Such populations may have a production to biomass ratio as low as 2:1. Conversely, the production to biomass ratio in intensively grazed populations may exceed 10:1 (Mann 1967).

The amount of variation in the P/B ratio may diminish or negate its usefulness in estimating benthic production. Variations in the P/B ratio, however, are much smaller than variations in the average biomass of invertebrates on the streambed. Multiplying the P/B ratio by the average biomass yields an estimate of annual production. Many different measurements of biomass must be made during the year in order to compute the average biomass. Therefore, it is much more efficient and accurate to have an aquatic entomologist or biologist trained in production measurement techniques to measure production directly.

Most studies of invertebrate production concentrate on one species or functional group. Data from this type of study are not very usable in an IFIM analysis because a measure of total food production within the stream is needed. This means that the entire wetted streambed is considered food producing habitat. Certain types of microhabitat produce more food than other types. The recommended approach is a guilding strategy where production for a particular type of environment is determined, regardless of which species are present, rather than determining production for one species across all environments. Microhabitat types need to be defined in such a way that they are mutually exclusive of each other in order to prevent double counting the same streambed areas in the HABTAT model (see Chapter 7). The most logical habitat characteristic on which to base a food production guild is substrate.

Variations in production rates within a substrate class are expected with changes in depth, velocity, temperature, and water chemistry, all of which are flow related. Benthic production can, in theory, be described in the same terms and in much the same way as microhabitat preferences of fish. Maximum production can be estimated for a particular substrate type under a range of optimal hydraulic and water quality conditions and then be lowered accordingly as these conditions change from the optimum. Both the development of criteria and estimates of production have to be based on time steps less than 1 year. The flow must be steady for each measurement interval in order to develop flow-related production criteria. This constraint essentially eliminates the development of these criteria in natural streams; experimental channels and flumes may be the only areas where production criteria can be developed. Furthermore, some of the more common techniques used to estimate production can not be used. For example, one technique commonly used to estimate production in lakes is to place a glass or plastic dome on the bed and measure oxygen consumption. This technique can not be used in streams because one of the variables is velocity, and the dome would shield organisms from this factor.

Needham and Usinger (1956) found that over 190 Surber samples were needed to obtain a statistically valid estimate of benthic biomass over a uniform substrate in a California stream. Some of the variation in the biomass was undoubtedly caused by differences in depth and velocity across the riffle that was sampled. However, even if only 10 samples are needed to obtain a reliable estimate of biomass, that would mean 10 samples per data point for at least 150 data points in order to develop a bivariate suitability function (Chapter 7).

If production criteria are available, the analysis of fish and food producing habitat requirements is quite simple. The food requirement is based on a target biomass, which, in turn, is related to a particular habitat area for adults, juveniles, and fry. The production of benthic macroinvertebrates for one particular habitat type on the streambed is defined as:

$$P_1 = H_1 \times P_{m^1} \quad \text{(B-12)}$$

where P_1 = the total production for habitat type 1 for one flow and time step

H_1 = the total habitat (including water quality, WUA, and temperature) area of habitat type 1

P_{m^1} = the maximum production of habitat type 1 per unit habitat

The total production of the benthos over the entire streambed is obtained by summing of the production for each microhabitat type:

$$P_t = P_1 + P_2 + P_3 + \ldots P_n \quad \text{(B-13)}$$

where P_t = the total production for one flow and time step

$P_1, P_2, \ldots P_n$ = production rates for each microhabitat type and area present at that flow and time step

The degree of food sufficiency is determined by the ratio between food requirements and food production:

$$\frac{FR \quad (f(WUA))}{H_1P_1 + H_2P_2 + H_3P_3 + \ldots H_nP_n} \quad >, <, \text{ or } = 1.0 \quad \text{(B-14)}$$

where FR = the total food requirement of the fish, which is a function of the available habitat

H_xP_x = the product of the amount of available habitat and unit production for each microhabitat type for the food organisms

As long as the ratio found by Equation B-14 is less than unity, food is not a problem. Several things can happen when the ratio approaches unity:

1. The fish will approach 100% efficiency in cropping and benthic standing crop may be decimated;

2. The fish will reduce their food intake and stop growing; or

3. The fish will emigrate in search of more food.

A ratio greater than unity indicates a severe food supply problem. Management alternatives when the ratio approaches or exceeds unity involve changing streamflow or water quality or increasing the area of food producing habitat by modifying the channel.

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This manuscript consists of two parts. Part I describes the methodological design, project scoping and site selection procedures, analytical sequences to solve various instream flow and project impact problems, and the various techniques for compiling, displaying, and interpreting the results of a study. Part II contains techniques for assembling hydrological data and anticipating channel changes due to a change in flow regime or sediment yield, methods of simulating physical microhabitat conditions at different streamflows, and an overview of channel modifications to increase habitat availability.

Stream habitat can be defined in terms of macrohabitat or microhabitat conditions. Macrohabitat characteristics include temperature, water quality, sediment size and load, channel shape, slope, and flow regime: characteristics that affect the longitudinal distribution of species and create longitudinal gradations in the microhabitat characteristics along the stream. Microhabitat characteristics refer to the distribution of depth, velocity, substrate, and cover within a specific area of the stream. The total habitat availability at any flow is defined by the area of overlap between suitable macrohabitat conditions (temperature and water quality) and available microhabitat area. This manuscript illustrates how to determine total habitat with and without a project for a wide variety of initial conditions and potential alterations to initial conditions.

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