DISSERTATION

A METHOD FOR INSTREAM FLOW WATER MANAGEMENT

Submitted by

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In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer, 1992

COLORADO STATE UNIVERSITY

June 22, 1992

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY **TERRY JAY WADDLE** ENTITLED **A METHOD FOR INSTREAM FLOW WATER MANAGEMENT** BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

A METHOD FOR INSTREAM FLOW WATER MANAGEMENT

Water management decisions concerning instream flow issues require information crossing many disciplines. An integrated framework for satisfying the information needs of many participants in instream flow decisions is developed and an application example is given.

The information needs are satisfied using a suite of simulation models covering fish population, hydraulic and hydrologic variables, and reservoir operations. The simulation models are used to describe trade-offs among instream and traditional water use objectives. The suite of models contains existing tools that were extended or refined and new models that fill information and management gaps. Several models from the U.S. Fish and Wildlife Service's Instream Flow Incremental Methodology were incorporated in the method.

The method includes a technique for efficiently managing a reserved block of storage (called an instream storage account) in a reservoir to provide instream flows. The technique incorporates a simplified fish population model

that allows forecasting of habitat needs over a one year planning horizon.

The method is demonstrated through application to the Dolores River, Colorado. The management issues there included the need for diverse interests to communicate, strong interest in resolving the instream flow debate, and interest in using a storage account of some form.

The method is shown to successfully improve the mean modeled fish population using less water than a constant minimum flow regime. Increasing the size of the storage account yields larger fish populations, but there is an inflection point and the rate of improvement decreases for large account volumes.

The method succeeds as a communication tool because trade-offs among traditional and instream water uses can be displayed in a few simplified graphs. These simplified displays should enable instream flow advocates, project operators and water users to see the benefits and costs of various alternative instream management choices.

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ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Neil Grigg for his steady support throughout this endeavor. His suggestions have been incisive, timely, and clearly focused on the job at hand. I also want to thank the other members of my committee, Dr. Darrell Fontane, Dr. Albert Molinas, Mr. Steve Puttmann, Dr. Evan Vlachos for their encouragement and advice.

Dr. Dave Harpman must be credited with joint development of the description of the effective habitat model contained in Chapter 4. A large part of that material is also in Dave's dissertation.

Several people directly involved in the Dolores River deserve thanks: Mr. Stan Powers, U.S. Bureau of Reclamation engineer for data and consultation about Dolores River operations; Mr. Kirk Lashmett, Bureau of Reclamation biologist for a tour of the river, temperature data and help understanding the biology of the system; Mr. Mike Japhet, Colorado Division of Wildlife Area Supervisor, and Corey Sue Hutchinson, U.S. Forest Service Fishery Biologist for their assistance understanding the temperature and habitat responses in the river; and Jim Carder and Maynard Brandsma

of Trout Unlimited for introducing me to the Dolores River and helping with data manipulations.

A special thanks is due to R. Barry Nehring, Division of Wildlife Fisheries Researcher for his review of my work at many stages and for answers to endless questions about trout.

Dr. Clair Stalnaker, Riverine and Wetlands Branch Chief at the U.S. Fish and Wildlife Service's National Ecology Research Center, encouraged my pursuit of this degree and incorporated part of the work in Branch study plans.

My NERC colleague Ken Bovee provided many insights into the effective habitat time series model. His suggestions led to the calibration technique I present here.

Greg Auble, John Bartholow, and Bob Milhous also of NERC reviewed early drafts and made many important comments.

Last, but most important, without the encouragement and support of my wife, Michiko, this project could not have been successfully completed.

To My Parents

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Chapter 1

INTRODUCTION

In spite of requirements enacted over the past 20 years, instream flow protagonists often have difficulty bringing instream needs into the decision process. Regulations governing water project decisions now require consideration of biological information in most aspects of construction and operation. In many situations, instream flow decisions must be considered as part of a multiple objective water resource management regime. Changes in discharge patterns often cause non-linear, multivariate responses in biological systems. Such complex responses make it difficult to incorporate biological information in water management decisions. The instream flow decision arena needs techniques to include instream objectives in planning and operating water resource projects. Better methods for communicating biological and operational responses would facilitate instream flow decision making.

This thesis focuses on developing a method for satisfying the aquatic habitat and engineering information needs for decisions concerning instream flows in reservoir

tailwaters. The method considers physical, legal, hydrological and ecological conditions in management of water stored for instream flow use. In particular, it uses basic fish life cycle requirements to set instream flow levels. The combination of institutional and environmental characteristics for a particular stream produces a locally unique mix of operational requirements and aquatic system needs. The method allows all parties involved in the decision process to explore alternative solutions satisfying those needs.

The method is directed toward water resource decision makers, water users, instream flow advocates and others who have an interest in such decisions. Its ambitious goal is to incorporate a broad range of instream water management issues in a single suite of models. It provides users with a common forum for describing the trade-offs in managing water storage for instream flow purposes.

PROBLEM STATEMENT

Minimum instream flow requirements are a commonly used means of addressing riverine ecosystem needs. They are often included in permit requirements for water projects. Water projects in the western United States often have constant (unvarying throughout the year) minimum flow requirements.

Two or three-tier minimum flow requirements that vary by season are used in some situations (cf. Chapter 2). This tendency to treat instream flows as a constraint required by a license reflects the historic emphasis on out-of-stream uses of water. The advantages to project planners and operators of simple minimum flow rules are clear. They give certainty to the amount of runoff that can be developed for traditional uses. They satisfy property right legal theories of water right laws. And, if established at sufficiently low levels, they may impact project operations during only the most severe water shortages.

An unfortunate result of focusing on "minimum" instream flows is to avoid including instream uses in multiple objective management. Minimum flows are most often treated as inflexible constraints rather than as a flexible part of a project's operational objectives. This omission increases the inherent conflict between water developers and instream flow advocates. Such conflicts arise because water developers seek low instream flows to achieve minimum impact on their operations. At the same time instream advocates seek high minimum flows to achieve maximum protection of the instream ecosystem. Developing operational agreements that meet biological objectives as well as project objectives would better focus management energies on solving complex problems rather than merely avoiding constraints.

An improvement over simple minimum flow requirements is needed. It is particularly important to move from managing to maintain streamflow to managing to maintain aquatic populations. Using aquatic populations as the objective could introduce a socially desired objective instream objective into water management. This would improve both the method for allocating water to instream uses and its social acceptance.

Recent work in the Pacific Northwest attempts to solve this dilemma. It allocates a portion of runoff called a "water budget" (cf. Chapter 2) to instream flows. This approach provides certainty of impact on the hydroelectric power industry along the Columbia River. It allows "shaping" of instream flows to promote salmon migration considering water supply and salmon smolt movement needs each year. In this thesis the term "instream storage account" is used to describe a similar idea: an account of stored water used exclusively to supply instream flows.

PURPOSE

The purpose of this thesis is to develop and demonstrate a method for supplying needed decision information for situations in which the storage account approach may apply. Improved communication between water resource decision

makers, instream flow advocates and the public at large can lead to better management decisions. The approach proposed here facilitates communication by providing a platform for comparing alternative solutions. The target user groups encompass a wide range of interests. Among them are those who have a stake in the decision, the regulators who must make choices among difficult trade-offs, and the individuals and organizations who must implement the decisions, i.e. the operators. The method must provide a means for all of these groups to recognize the benefit trade-offs involved in providing instream flows. The proposed method fills the information needs of these groups within the underlying assumptions noted below.

The method contains a new technique for managing an instream storage account to support fish populations. The technique provides a means of identifying the amount of water needed and procedures for efficient use to achieve fish population goals. By evaluating different operating criteria for supplying fish population needs the instream flow benefits of new alternatives can be explored.

Underlying Assumptions

Some necessary assumptions underlie this new approach. First, existing water management practices may not provide the long term "best" habitat conditions for the affected aquatic species. Second, construction or enlargement of a reservoir and storing of high flows will not, itself, catastrophically impact the aquatic species downstream of the reservoir. Therefore, constructing or adding storage is assumed to be an acceptable practice. The applicability of this study is limited to situations where the second assumption is true. The new approach also applies where existing storage has already eliminated those species which could be damaged by reservoir construction or operation.

HYPOTHESIS

General Hypothesis: Rules can be developed for water resource system operations that eliminate or reduce the occurrence of critical habitat shortages while avoiding adverse impacts on other (senior) water uses. Critical habitat shortages are those that cause significant decline, delay growth, or prevent recovery of a fish population.

Knowledge of water resource systems (including hydrology, legal, institutional and management conditions),

and long term aquatic habitat needs can be used to develop such rules. This knowledge can help to identify the trade-offs and impacts of alternative instream flow regimes on other water users. In many situations non-instream uses have legal or regulatory precedence. When this is true, the rules can concentrate on the best use for habitat purposes of any remaining water.

APPROACH

The approach taken here is to develop a simulation model incorporating hydrology, reservoir operations, water rights, fish population and a decision framework. The model is then used as a laboratory device to develop and test operation strategies to achieve long term habitat objectives. It incorporates the decision trade-offs needed for considering instream flows within an appropriation doctrine water right setting.

Success is evaluated by comparing the effective habitat produced by instream storage account operation with the effective habitat produced by fixed minimum instream flows. Throughout this thesis "effective habitat", as defined in Chapter 4, is used as the measure of fish population size and robustness. Long term mean effective habitat is the measure of performance of a range of alternative instream account sizes. This allows the trade-offs between storage account

size, water deliveries to traditional uses and fish population to be arrayed.

TEST CASE

The U.S. Bureau of Reclamation Dolores Project was chosen as the test case for this study because both the technical and information needs there match the ideas in this thesis. There is a high degree of interest on the part of the Bureau of Reclamation (Reclamation) in resolving conflicts between the fishery interests, irrigation interests and Reclamation. These conflicts revolve around the timing and amount of instream flow released for recreational and fishery maintenance purposes.

The Dolores Project is located in the Dolores and San Juan River Basins in Southwestern Colorado. It stores and exports water from the Dolores River to the San Juan River Basin near Cortez, Colorado. The primary storage facility is McPhee Reservoir. Its storage capacity is sufficient to control the river totally in dry years. All water developed by the Dolores Project is exported directly from the reservoir. (Cf. Chapter 6 for a description of the Dolores River and Dolores Project.)

Since all project water and all preexisting water rights are diverted to the San Juan River Basin, there are no opportunities for complementary water uses between the agricultural, municipal and industrial water uses, and instream flows. The conflicts were exacerbated by a significant decrease in the fish population that occurred in 1990 when Reclamation reduced the instream flows to previously determined dry year criteria levels. The instream flow advocates in the region, notably Trout Unlimited, criticize both the amount of flow to be released under dry year criteria and the rules Reclamation uses to switch among various instream flow regimes.

One result of the dialogue between Reclamation, Trout Unlimited, the Colorado Division of Wildlife, and the U.S. Fish and Wildlife Service has been consideration of assigning a volume of storage in McPhee Reservoir as an instream flow account. These discussions have included managing releases from the account through consultation with the fishery interests. Several issues the participants in this resource allocation problem face are addressed explicitly by the method developed here.

While the Dolores River situation captures several of the institutional characteristics the method addresses, there are no opportunities for complementary uses of instream water. Complementary uses arise when part or all of the

stream considered important to a fish population will be used to route water to a point of diversion. If some or all of the Dolores Project water users took their water from the Dolores River five or more miles downstream from McPhee dam, such complementary uses would exist. A hypothetical configuration, where some of the Dolores Project water deliveries are routed through the river channel before being diverted, is used to test the robustness of the method.

PARALLEL TECHNICAL DEVELOPMENTS

The two major areas of technical development in this project are implementation of the effective habitat concept and development of operational rules for the instream storage account. Figure 1.1 shows the parallel development and interaction of these ideas leading to the application example. Until this thesis, the literature did not contain a method for calibrating the effective habitat model to a specific watershed. Such a method is presented in Chapter 4. Once calibrated, the population responses (represented by effective habitat) are used to develop the storage account operation rules.

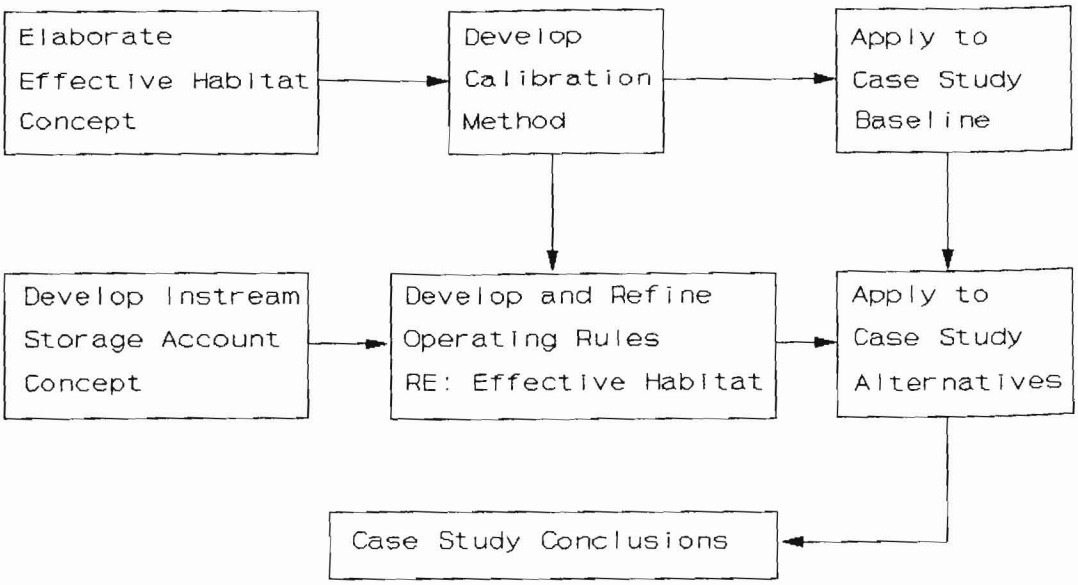


Figure 1.1. Parallel Development and Application of Models

CONTRIBUTIONS

This work contributes to water resource decisions concerning instream flows in two ways. The first is development of a framework for communication among the parties involved in instream flow decisions. Preconceived ideas about the purposes of water system operations and the intent and methods of describing instream flow needs hamper understanding and negotiations for instream flows. The proposed method improves information exchange by clearly illustrating the trade-offs to be made in managing water for instream flow. Explicit identification of these trade-offs can break down preconceptions by presenting the choices in terms of both habitat and the amount of water required to

provide that habitat. Different interest groups filling different roles in the decision process need different information. The model output includes the information needs of both instream advocates and water developers.

Second, solutions to several technical and modeling problems that were previously not available are presented. They include clarifying and applying the effective habitat model and developing a technique for using the long term memory of fish populations to determine instream flow volumes. They also include algorithms that describe how to use an instream storage account efficiently. These techniques can be used to decide if providing a limited storage account is futile or productive.

The method allows application to local conditions. Each local application may determine if fish population levels can be improved with the water available for instream flows. Knowing which storage account management approach is most successful can lead to formulating objective functions for use in analytical optimization solutions to this problem. This method will help state and federal agencies to determine if it is worthwhile to purchase storage or water rights in new or existing projects for maintaining streamflow.

THE CHALLENGE OF THIS PROJECT

This thesis project is ambitious and somewhat risky. Use of this approach requires an interdisciplinary effort. Model users from many groups must openly bring the best available information to the analysis. The success of any application of the concepts presented here depends on the will of the users to resolve instream flow issues.

Numerous issues in the instream flow decision arena cannot be addressed by the current state of science. Often high degrees of uncertainty or extreme data costs make it difficult to arrive at definitive scientific conclusions. Accordingly, this thesis cannot address all possible instream management issues. It does, however, provide a basic logical framework for managing instream flow water. The method developed here can address three major issues: (i) determining how much natural flow to store for instream use, (ii) determining how much impact managing storage for instream flows will have on water diversions and (iii) efficient management of instream flow water.

Some of the tools developed and demonstrated here are controversial. The effective habitat model is not widely known or used as a fish population model. There is a large degree of natural variability in the data from which its parameters are derived. The decision technique for

allocating instream flow within a year is a new concept. Thus, it lacks an empirical validation test. It is extremely difficult to replicate enough of the environment of a flowing stream in the laboratory to conduct controlled fish population experiments. So new management concepts must be tested using other devices such as the model study reported later in this thesis.

Two themes are woven throughout this thesis. They are the information needs of parties involved in instream management issues and development of techniques to supply those information needs. Chapter 3 gives a summary of the breadth and scope of environmental and management issues associated with instream flows and their information needs. It describes how the concepts and models developed here can address many of those issues.

The models outlined in Chapters 4 and 5 represent a framework for dealing with instream management problems. They contain new combinations of existing tools and some new techniques contributed by this thesis. These tools have the potential to help managers more efficiently use water designated for instream flows. The remaining chapters illustrate how the method can describe alternative storage account solutions to an instream management problem. The thesis concludes in Chapter 9 with interpretation of the

results and a discussion of the research needs to extend and refine the method.

Chapter 2

LITERATURE REVIEW

LEGAL AND INSTITUTIONAL ENVIRONMENT

State Instream Flow Laws: General

Several western states have enacted laws recognizing the need to protect instream flows. In a summary of instream flow laws from nine western states, McKinney and Taylor (1988) give the following summary of the purpose of state instream flow programs:

> "The general purpose of all instream flow programs is to set aside water in selected streams, unavailable for consumptive appropriation below a specified level, for the protection of instream values. ....
>
> Alaska [AS 46.15.145(a)], Hawaii [HRS 176D; Water Code 174C], Idaho [IC 42-1504], and Washington [RCW 90.54020(1)] allow for the broadest range of values to be legally protected, including fish and wildlife, recreation, scenic and aesthetic values, water quality, and navigation and transportation. Montana [MCA 85-2-316] allows for the protection of fish and wildlife, recreation, water quality, and future consumptive uses. Oregon [ORS 536.310] recognizes only fish and wildlife, recreation, and water quality as valid instream beneficial uses. Utah [UC 73-3-3] and Wyoming [WS 41-3-1001(b)] recognize only fish and wildlife as beneficial

> instream values, while Colorado's [CRS 37-92-102(3)] instream flow program is designed to protect 'the natural environment to a reasonable degree.'"

Appendix 1 contains a description of specific instream flow programs and their legal status for two western states.

Federal Laws Influencing Instream Flows

The authority to allocate and administer water rights was passed to the states at statehood. As a result, Federal laws are overlain on the patchwork of state water laws. They tend to place conditions on the construction and operation of water related projects. Federal permit constraints for instream flows force the project operator to provide water for instream flows out of the amount that was acquired under state water rights. The following summary describes a few of the Federal laws that determine how and how much water is dedicated to instream flow maintenance.

There is no Federal equivalent of instream flow water right legislation. However, several Federal authorities can be used to secure instream flows. These cover a wide range in the degree to which they directly address the issue of stream flow. The following discussion is treated in approximate order of directness.

The Federal Reserved Water Right doctrine is a legal theory which says that when the government reserves land as Federal land, for example National Forests which were never deeded to the states or individuals. It implicitly reserves sufficient quantities of water to fulfill the primary purposes of that reservation (Meyer, 1987). Such water is essentially taken out of the state water system. Any person who appropriates water from such a stream is junior to the United States. Due to the contentious nature of water issues, the courts have been cautious in dealing with this area. In Winters v. United States [207 U.S. 564, 1908] the court upheld the Federal Reserved Right doctrine. In subsequent cases, however, narrow interpretations of the "primary purpose" of a Federal reservation have limited the amount and timing of water that may be reserved under this approach [United States v. New Mexico, 438 U.S. 696, 92 S.Ct. 3012]. For example, in cases involving National Forests, judges have rejected maintenance of instream flows for fish and limited the reservation to flows for forest sustenance and channel maintenance. These choices were based on the theory that the reservation of land for forests is for trees and not for fish (Lamb, personal communication 1989).

A surprising form of direct influence of Federal law on instream flows appeared in 1973 as the Endangered Species Act. Section 7 of the Act prohibits the federal government from taking any action, even issuing any permits, which may

jeopardize the continued existence of an endangered or threatened species, or adversely affecting critical habitat for such species (Meyer, 1987). Since most water resource projects require some form of federal permit, the Endangered Species Act can effectively stop development of water resources in an area where such species exist. Negotiations to determine water management and project development strategies that will accommodate endangered species habitat needs are underway in several river basins (Dunkle, 1986).

While the endangered species act provides a blanket means of intervention in federal permitting processes, the individual permit processes can often be the source of instream flow provisions. The two permit mechanisms that have had the most impact in this area are Section 404 of the Clean Water Act and the Federal Energy Regulatory Commission hydroelectric power plant licensing authority.

A first reading of Section 404 [33 U.S.C. 1344, et seq.] which deals with dredging and filling of the "navigable waters" of the United States appears to indicate that this section has nothing to do with instream flows. However, the authority under this section has been interpreted to extend to operation of the facilities for which construction would require dredging or filling the navigable waters. As a result, instream flow requirements have become permit conditions under Section 404.

Another indirect but well used means of establishing instream flow requirements is the Federal Energy Regulatory Commission (FERC) license for construction and operation of hydroelectric power production facilities. FERC is responsible for granting these licenses under the Federal Power Act [16 U.S.C. 793, et seq.]. The act states that FERC may apply conditions to a license to protect the public interest. The public interest has been interpreted in several cases to include instream flows (Olive and Lamb, 1984).

This summary is intended to describe the most commonly used authorities for establishing instream flows through federal permit processes. Numerous other federal programs may be used to require instream flow maintenance under various circumstances.

CURRENT INSTREAM FLOW PRACTICES

This section summarizes the kinds of instream flow requirements that have been implemented in various streams in the United States. The purpose of this survey is to illustrate the forms and operational bases of instream flows that are in common use. It is intended to show the kinds of requirements resulting from instream flow determinations and permit conditions rather than to trace the sequence of negotiations that led to them. However, in some cases a

brief history of the negotiations is necessary to illustrate the logic behind the operational requirements.

A survey of "all known water development" projects in Colorado, Montana and Wyoming that have instream flow requirements (Raley, et al. 1988) provides one of the few systematic overviews of the instream flow planning and implementation process. Review of this document reveals that of the 73 water projects identified, 44 had fixed (annually unvarying) instream flow requirements. A smaller number (19) had instream requirements that consisted of a two-step arrangement, with the steps usually corresponding to winter and "other" seasons or irrigation and non-irrigation seasons. Some of the two-step patterns consisted of a winter minimum and no stated minimum for the rest of the year. In these situations it was often concluded that releases for irrigation diversions downstream of the reservoir would satisfy instream flows. Nine of the remaining ten projects had 3 or more steps within the year; some of these varied monthly. Of the 73 projects, 12 had provisions for changing the instream flow on the basis of the available water supply.

Note the observation that the majority of instream flow agreements that were actually implemented in these three states used constant values.

The report compared the negotiated instream flow requirements with project performance for all projects that had stream gages in the section of river below the project. In general, the size of the project and the frequency of meeting the instream flow requirements were correlated. That is, larger projects tended to meet their instream flow targets. In contrast, smaller projects had a greater number of discrepancies (Raley, et al. 1988).

The 930 Colorado streams with established instream water rights (Trembly, 1987) are also examples of constant minimum flow values. Under the appropriative doctrine it is really not possible to specify water rights that vary according to the available water supply, either a right is in priority or it is not.

Recent projects requiring federal permits continue to use fixed instream requirements. The Windy Gap project on the upper Colorado River must meet instream flows at three monitoring points downstream of the diversion dam. The flow requirements at these three points are fixed values of 90 cfs, 130 cfs and 150 cfs progressing downstream (Eckhardt, 1986).

Seasonally varying (greater than two-step) instream flow requirements are gradually gaining acceptance. In the Terror Lake FERC licensing process, negotiations succeeding in

defining a seasonally varying instream flow pattern, as shown in Table 2.1. This agreement does not consider year-to-year variability in available water supply. Since the project is located in a national wildlife refuge the instream flow proponents were able to argue for consistency in maintaining habitat over all years (Olive and Lamb, 1984). Ten of the 73 projects surveyed by Raley et al. (1988) had at least three seasonally varied levels of flow.

Table 2.1. Instream Flow Operating Regime for the Terror Lake Project*

Period	Discharge (cfs)
January - March	60
April	100
May - October	150
November 1 - 15	100
November 16 - 30	60
December	60

* Source: Article 43 of FERC license for Terror Lake Project, Oct. 5 1981.

Seasonally varying instream flow requirements are not new. Of the nine varying instream flows found in Raley et al. (1986) six dated from the period between 1950 and 1962. The remaining three fell within the period 1979 to 1986. The majority of these varying flow regimes were based on hydrologic and hydraulic considerations, not on the habitat needs of aquatic species.

A new concept in instream flow management has emerged from the controversy surrounding the decline of the salmon population in the Pacific Northwest. The Pacific Northwest Electric Power Planning and Conservation Act of 1980 [16 U.S.C. 839 et seq.] established the Northwest Power Planning Council. The Council developed a concept to deal with the problem of mortality at the Columbia River hydroelectric dams of out-migrating salmon smolts. Their approach allocated a specified amount of water to the indian and government fishery managers to be used to promote safe migration of smolts. This water is lost to power production as it must be spilled at most dams to keep the smolts from passing through the turbines. The delivery timing (shape) of the water budget is controlled by two Water Budget Managers representing the indian tribes on one hand and the federal and state fishery agencies on the other. The strength of this approach lies in setting the instream flows to match the needs of the fish (Lawrence, et al. 1983).

The state of practice in establishing instream flows, then, appears to focus on provision of an often constant "minimum" flow. Even negotiated instream flow values for large projects as recent as the 1980 stream flow agreements for Windy Gap use fixed minimums (Raley, et al. 1988). Stalnaker (1979) points out that using fixed minimum instream flows has resulted in avoiding multiple objective management. The use of fixed minimums may be appropriate for small

projects where the cost of equipment or personnel to deliver variable streamflows is prohibitive. However, it would seem that fish needs and water supply conditions could be considered as part of multiple objective management schemes for larger, highly automated projects. This thesis develops a method for determining variable instream flow regimes that consider fish needs, hydrologic (water supply) uncertainty, and the information needs of decision participants.

METHODS FOR DETERMINING INSTREAM FLOWS

A key component of any methodology describing management of a quantity of water is a means of determining the benefit associated with use of the water. In the instream flow arena, this problem has been cast in terms of determining the necessary stream flow to protect aquatic resources. Several methods have been advanced to provide these instream flow quantities. This section deals with examples of several classes of those methods and notes some critiques of the methods.

Hydrologic or Statistical Methods

Several methods have been developed that use historical flow records as the basis for determining instream flows. These include the Montana method developed by Tennant (1975,

976), the New England Flow Recommendation Policy (NEFRP) (U.S. Fish and Wildl. Serv., 1981), and the Northern Great Plains Resource Program (NGPRP) flow duration technique (Anonymous, 1974). All of these methods use some form of statistic derived from historical discharge records to establish instream flow quantities.

These methods are useful for first (or perhaps zeroth) order determination of instream flows when data are scarce. However, they have some serious limitations that must be considered. Such methods rely on the assumption that past hydrologic conditions are representative of likely future events. They imply management of aquatic resources based on past conditions rather than dealing with issues of stream productivity or minimizing adverse impacts of managed flow regimes. None of them can predict the habitat or population impacts of altered flow regimes.

Tennant's procedure involves calculation of the mean annual flow rate (MAF) at a proposed development site and expression of the instream flow needs in terms of a fixed percentage of the MAF. The basis for the method is an extensive set of observations on streams in the states north of the Mason-Dixon Line between the Atlantic Ocean and the Rocky Mountains (Tennant, 1976). Various levels of flow needs are identified, including flushing flows (200% MAF), optimum flows for all instream water uses (100 to 60% MAF),

and a ranking of poorer conditions ranging from excellent (60 to 40% MAF) to severe degradation (less than 10% MAF). The 10% MAF value is suggested to be the minimum short term survival value for most aquatic biota and represents very stressful conditions (Wesche and Rechard, 1980).

The NEFRP approach uses a constant yield statistic or the median monthly flow to establish recommended instream flow values. For unregulated streams with a drainage area greater that 50 square miles and more than 25 years discharge records, the median monthly discharge is used. When those defining conditions are not satisfied, the constant yield factors shown in Table 2.2 are used. Variations of this method have used values as low as the 7 day 10 year low flow and 0.15 cfs per square mile (Loar and Sale, 1981).

Table 2.2. New England Method Yield Factors for Watersheds With Area Less Than 50 Square Miles or Less Than 25 Years Gage Records (Units: cfs/sq. mile).*

Season	Yield Factor
Spring	4.0
Summer	1.0
Fall/Winter	0.5

*Source: U.S. Fish and Wildl. Serv., 1981

The third hydrologic method was developed for warm and coldwater rivers in the Midwest. The NGPRP method uses the Student's t distribution to eliminate extreme (flood and drought) events from the period of record (Anonymous, 1974).

After high and low observations have been thrown out of each month's record, the instream flow recommendation is chosen as the value equalled or exceeded by 90% of the remaining observations. During high flow months the median rather than the 90% exceedance value is chosen. The product of this method is a minimum instream value for each month. Variations of this approach have changed the exceedance statistic and the method of determining the data sample used to derive the flow values (Loar and Sale, 1981, Wesche and Rechard, 1980).

Methods Based on Hydraulics

Several methods consider parameters related to the physical flow conditions in a stream segment as the criteria for determining needed instream flows. Several offices of the U.S. Forest Service have developed methods to related stream flow and physical environmental parameters. Site-specific field data are collected at one or more flows along transects placed across a stream channel. Instream flow recommendations are based on the actual habitat conditions observed at the field sites. Methods developed by U.S.F.S. regions 1, 2, 4 and 6 fall into this category. These methods all have the disadvantage of being difficult to extrapolate beyond measured discharge values due to dependence on observed habitat values at each discharge (Loar and Sale, 1981).

The difficulties associated with extrapolation noted above are addressed by various methods that attempt to develop some form of habitat-discharge curve. The habitat is represented as stream width, wetted perimeter, average velocity, or cross-sectional area at each transect. The data are presented in a graphic format which allows two approaches to be used in determining instream flow recommendations. The first is to establish a percentage of a reference amount of habitat as the criterion for setting the instream flow. For example, allow 20% reduction in cross-sectional area relative to a reference discharge. The second approach searches for an inflection point such as that which typically appears on a wetted perimeter plot of a "U" shaped channel when the banks begin to be wetted (Loar and Sale, 1981).

Extensions of the simple hydraulic methods described above use simulation models to reduce the amount of data collection needed. An example of this approach is the U.S. Forest Service R-2 Cross method (Wesche and Rechard, 1980). This method uses Manning's equation modified for discharge (Equation 2.1). Measurements for a single discharge at a single transect are used to derive Manning's n by assuming the stream energy slope is equal to the measured water surface slope. Depth is incremented in 0.1 ft. or smaller steps to derive a range of hydraulic radii from the cross section measurements using equation 2.2. A wetted perimeter versus discharge function is then developed by substituting

$$Q = \frac{1.486}{n} * A * R^{2/3} * S^{1/2} \qquad (2.1$$

$$R = P / A \qquad (2.2$$

where: Q = discharge

n = Manning's n

A = cross sectional area of flow

P = wetted perimeter

R = hydraulic radius (area / wetted perimeter)

S = energy slope of the stream

those hydraulic radii from equation 2.2 into equation 2.1 assuming Manning's n and energy slope are constant for all discharges of interest. The inflection point is then used to determine the instream flow value (Loar and Sale, 1981). The method is sensitive to the location of the transects used to define the wetted perimeter. It depends on the assumption that important habitat types are maintained by the discharge derived at the reference transect.

Methods Based on Aquatic Species Preferences

Common concepts among these approaches are the use of representative transects or reaches and derivation of a function relating potential productive area and discharge. The term usable area (UA) has come to describe this approach.

Palmer and Snyder (1985) give the general equation for usable area for these models as:

$$UA_{Q,S,R} = \sum_{i=1}^{n} P_v(v_i)\ P_d(d_i)\ P_c(o_i, b_i, s_i, d_i) \qquad (2.3$$

where:

$UA_{Q,S,R}$	usable area at discharge Q for species S in reach R;
$P_v(\ )$, $P_d(\ )$, $P_c(\ )$	functional relationship between usability (or suitability) of a unit area in a cell element and the velocity, depth , and channel index in that cell;
v_i	velocity in cell i;
d_i	depth is cell i;
o_i	overhead cover in cell i;
b_i	instream objects (such as boulders, fallen trees) in cell i;
s_i	substrate in cell i;
i	cell i;
n	number of cells in study area.

Some hydraulic simulation models such as HEC-2 and the U.S. Bureau of Reclamation PSEUDO step-backwater model have been brought into service in instream flow determination (Loar and Sale, 1981). They are used to derive the hydraulic conditions that, when combined with an index of species preference, will lead to development of a habitat index versus discharge curve. The species preference values used with these models are often associated with average

conditions, i.e. $P_d(\ )$ is applied to average depth at several simulated discharges. Loar and Sale (1981) note that the use of such step-backwater models is particularly useful in modeling large, unwadable rivers.

The Washington Method developed by Collings et al. (1972) uses numerous measurements to develop detailed maps of the hydraulic conditions at all discharges of interest. Species preference values are applied to each cell using Equation 2.2 to derive habitat values for each discharge; resulting in a habitat - discharge relationship (typically derived for salmon spawning). In most situations the spawning habitat - discharge relationship is unimodal. The peak of that curve is used to select the recommended instream flow for the spawning season (Wesche and Rechard, 1980).

An extension of the UA method for deriving instream flows is the weighted usable area (WUA) approach (Stalnaker and Arnette, 1976; Milhous, 1979). This method combines the hydraulic modeling and area mapping concepts. The species preference criteria P( ) are derived from the frequency with which members of the species are found inhabiting areas with various combinations of hydraulic parameters (Palmer and Snyder, 1985). The cell by cell evaluation of habitat worth provides a means of describing habitat conditions based on species preference. Hydraulic modeling allows habitat to be calculated over a range of flows that could not be measured

due to resource constraints or physical danger. Computer programs that implement this method of creating a habitat - discharge relationship are available from the Aquatic System Branch of the U.S. Fish and Wildlife Service as the Physical Habitat Simulation System (PHABSIM) (Milhous et al., 1981, Milhous and Updike, 1990).

The WUA approach is part of a larger methodology for dealing with instream flow decisions. The Aquatic System Branch of the U.S. Fish and Wildlife Service proposes the Instream Flow Incremental Methodology (IFIM) (Figure 2.1) as

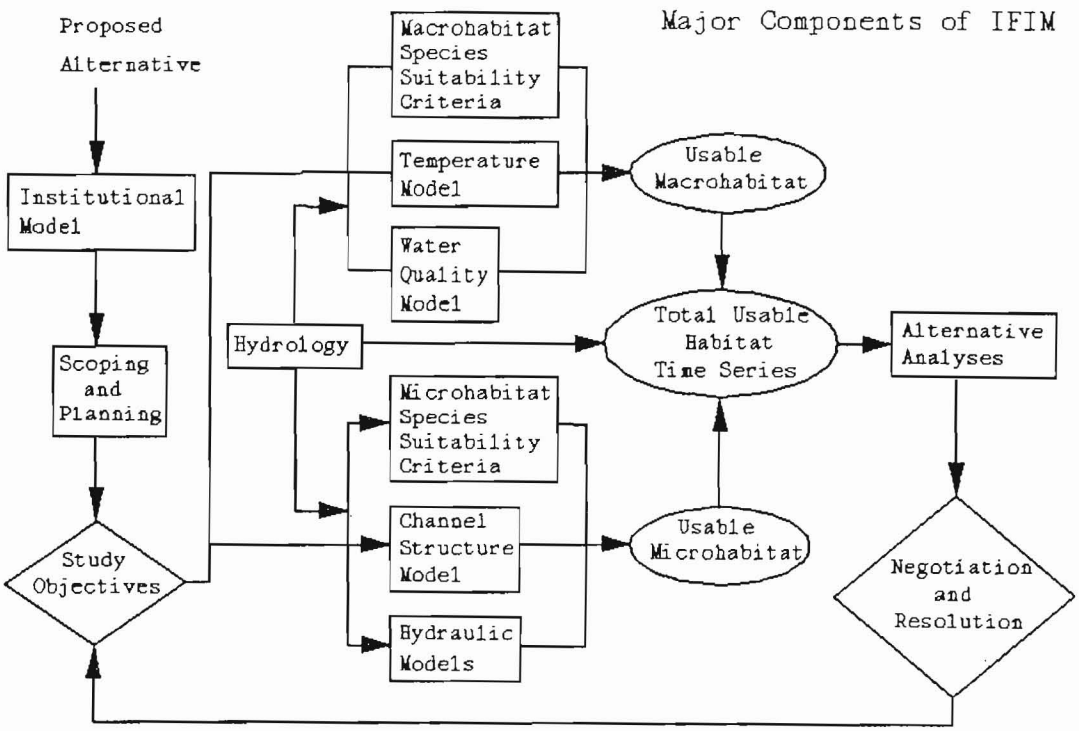


Figure 2.1. Conceptual Overview of the Instream Flow Incremental Methodology

a conceptual approach to establishing instream flow requirements (Bovee, 1982). The IFIM emphasizes development of time series of habitat events in formulating alternate instream flow regimes. Thus, when negotiating instream flow requirements, long term habitat effects rather than instantaneous effects are considered. This explicit methodological consideration of habitat time series and seasonally varying instream flow needs is unique among instream flow methodologies advanced to date.

Palmer and Snyder (1985) describe the IFIM as the "best known" among "quasi habitat approaches" to instream flow determination. They point out that none of the available methods considers water quality impacts, food limitations, or changes in channel morphology. Advances in IFIM since 1985 have incorporated water temperature and the capability to modify habitat values based on water quality parameters. However, research to provide explicit description of species interactions and food relationships is only now beginning to be funded (Stalnaker, personal communication 1989).

As the best known among instream flow methodologies, the PHABSIM portion of IFIM has been the subject of numerous critiques. The central theme of these critiques has been the degree to which the method predicts biomass or numbers of fish. Common among several of the critiques has been the use

of correlative statistics in determining the applicability of the method.

Nehring (1979) compared the discharges derived from five instream flow methods including PHABSIM for 18 locations on 15 Colorado Mountain Streams. He found that the instream discharge values produced for adult brown trout (Salmo trutta) and rainbow trout (Oncorhynchus mykiss) were in close agreement (within 25 to 35% of the mean annual flow) for most streams. He concluded that simple hydrologic methods such as R-2 Cross could be used on less important streams but that PHABSIM be applied to the more important stream reaches. Part of his work was directed to establishing beneficial use for instream water rights to preserve the environment "to a reasonable degree" under Colorado's instream flow statute.

Critiques of the IFIM that expressed disappointment with the degree of correlation of WUA with biomass have been presented by Mathur et al. (1985), Shirvell (1986) and Scott and Shirvell (1987). Responses to these criticisms have noted that intervening variables such as floods that altered habitat, fishing pressure and changes in water quality occurred during the periods when data collection for the correlative analysis occurred (Orth and Maughan, 1986; Bovee, 1985).

Perhaps the best commentary to date was provided by Gore and Nestler (1988). They point out that derivation of habitat values is the current state of the art among methodologies to determine instream flows. They note "Previous studies suggest that IFIM appears to perform defensibly in coldwater systems but less well in more complex cool water and warmwater systems" (Gore and Nestler, 1988). They state that definition of some form of quantified biological value (habitat) - discharge relationship is necessary to satisfy the information needs of many instream decision processes. They recommend that when a method that more satisfactorily links biomass or population numbers to flow management is developed it should be adopted and habitat based methods should be discarded. Until then, they suggest that while "IFIM maximizes generality ... at the expense of ecological reality" it still has "utility to analyze water resource issues" (Gore and Nestler, 1988).

Methods for Describing Fish Population Response

Research on methods to describe fish population response to stream flow regime management is currently underway. The Environmental Sciences Division of Oak Ridge National Laboratory is working on individual-based population models that will describe the response of the fish in a population to changes in the flow regime (Deangelis, et al., 1991). EA, Engineering, Science, and Technology, Inc. has developed a

population that responds to flow changes using the physical habitat models of IFIM as one driving component (Cheslak and Jacobson, 1989). This proprietary model is not publicly available at this time. The U.S. Fish and Wildlife Service has embarked on an effort to develop a population model that links population response to discharge through identifying flow events that produce limiting habitat "bottlenecks" (Williamson, et al., 1990, Bartholow, et al., 1992). The model developed as part of this dissertation anticipates such population descriptions will be generally available in the future.

Since population models that respond to discharge management are not readily available other approaches to approximating population effects of flow management must be considered. Bovee (1982) proposed a simple model that responds to flow regimes using a habitat transformation of population. This model is described in detail in Chapter 4 and is used in this thesis in lieu of a more complete population model.

SELECTION OF MODELING METHOD

Numerous mathematical models have been developed for water resource operations. Yeh (1985) and Wurbs et al. (1985) provide extensive reviews of state-of-the-art

reservoir operations models. Both reviews cover a wide range of algorithms and methods including linear programming, dynamic programming, nonlinear programming and simulation. Simonovic (1992) extends the range of methods to include a review and application of expert systems in water resources. Each of these techniques can be used to find optimum or near optimum operating rules for reservoirs.

The main issue addressed in this study involves the reservoir operation rules needed to derive maximum fishery benefits downstream of a reservoir. The desire to obtain "maximum" benefits implies the use of a mathematical optimization model. Such operations research models, however, require statement of a set of objectives and constraints that describe the system to be modeled (Yeh, 1985). Currently, the form of an analytic objective function that incorporates long term fish population benefits is unknown. Applications of operations research techniques to reservoir management where fishery benefits have been included in the objective function have not included long term fish population memory relationships. Sheehan and Russell (1978) relied on empirical fish population data to derive a probabilistic relationship between salmon escapement in one year and the number of adults returning 4 years later. Sale, et al. (1982) optimized reservoir operation for production of fish habitat but relied on instantaneous weighted usable area as an indicator of population potential.

Before operations research models can be applied, an objective function considering fish population memory must be derived.

Yeh (1985) states that

> "the simulation model provides the response of the system for certain inputs, which include decision rules, so that it enables a decision maker to examine the consequences of various scenarios of an existing system or a new system without actually building it."

This descriptive characteristic of simulation models lends itself to experimentation with decision rules for a water budget. One purpose of this research is to define reservoir operating rules that incorporate fish population memory. Such rules must be developed to consider trade-offs between conflicting uses of water. Palmer and Cohan (1986) point out that simulation models are effective in evaluating such choices. These characteristics of simulation models led to the choice of simulation as the model paradigm for this study.

Chapter 3

EFFECTS OF PROJECTS AND REGULATIONS: DEVELOPING TECHNICAL INFORMATION TO IMPROVE COMMUNICATION BETWEEN WATER RESOURCE SYSTEM OPERATORS AND HABITAT MANAGERS

This chapter briefly summarizes the effects water resource projects have on stream ecology. It also summarizes the effects environmental regulations have on water projects. It describes the limitations of current instream flow practices considering these effects. The chapter concludes with a discussion of how models can help satisfy information and communication needs regarding instream flows.

The need for participants in water resource decisions to understand each other's resource and operations concerns is often overlooked. Analysts often approach regulatory questions from the narrow viewpoint of satisfying technical information requirements. As a result, many project permit negotiations begin without a common understanding of the issues involved. This can lead to protracted adversarial proceedings about the nature of the technical information. Such disputes omit consideration of the broader issues involved.

Simulation Models provide a mechanism that allows the quality and magnitude of system effects to be evaluated. They provide an integrated approach to evaluate the respective concerns participants in these decisions may have. Application of such models can improve communication about causes and effects and provide opportunities to consider alternative solutions that may be mutually satisfactory.

Water resource projects can exert strong effects on stream biota. Conversely, instream flow based environmental regulations can exert strong effects on project operations. This discussion is intended to provide a general background for readers who may be familiar with one, but not both viewpoints. A general introduction to these effects is merited to illustrate the diversity of issues involved. This discussion is presented as a preface to describing the use of models to address these concerns.

BIOLOGICAL EFFECTS OF RESERVOIRS

Construction and operation of a reservoir induce a wide variety of effects on the ecosystem of a stream. These effects can be divided into three broad categories: (i) the effects of inundation, (ii) the effects of blockage of material transport and (iii) the effects of streamflow regulation. This section summarizes those effects.

When a dam is constructed and its impounding reservoir filled, several changes to the inundated portion of the river occur. Running water is transformed into an artificial lake and the ecological community of benthos and fishes is radically altered. Deposition of organic and inorganic particulates and sediments changes the nature of the stream, now lake, bed. Fish and invertebrate species that do poorly or cannot tolerate running water can survive. Those species that must have flowing water to satisfy their life cycle needs perish or move out of the reservoir. Baxter (1977) provides a more complete review of these changes.

When a reservoir replaces part of a naturally flowing stream, several material transport phenomena are interrupted. The most obvious of these is reduction of sediment loads. Large reservoirs may reduce downstream sediment loads by 95% (Leopold et al., 1964, page 454). Clear water released from such an impoundment has a high transport capacity and may induce scour of progressively coarser material from the channel immediately downstream of the reservoir (Vanoni, 1975, p. 181). Such scour may persist until a new equilibrium is reached where the size of the remaining coarse material exceeds the transport capacity of the discharge (Simons and Senturk, 1976, p. 52). A generalized schematic of the sediment transport effects of a dam and reservoir are shown in Figure 3.1. Sediment availability and size distribution play an important part in the ecology of the

stream below the reservoir. Examples of this include production of benthic organisms which are dependent on certain particle size distributions, and spawning and egg maturation of certain fishes that depend on a gravel substrate (Carlander, 1969).

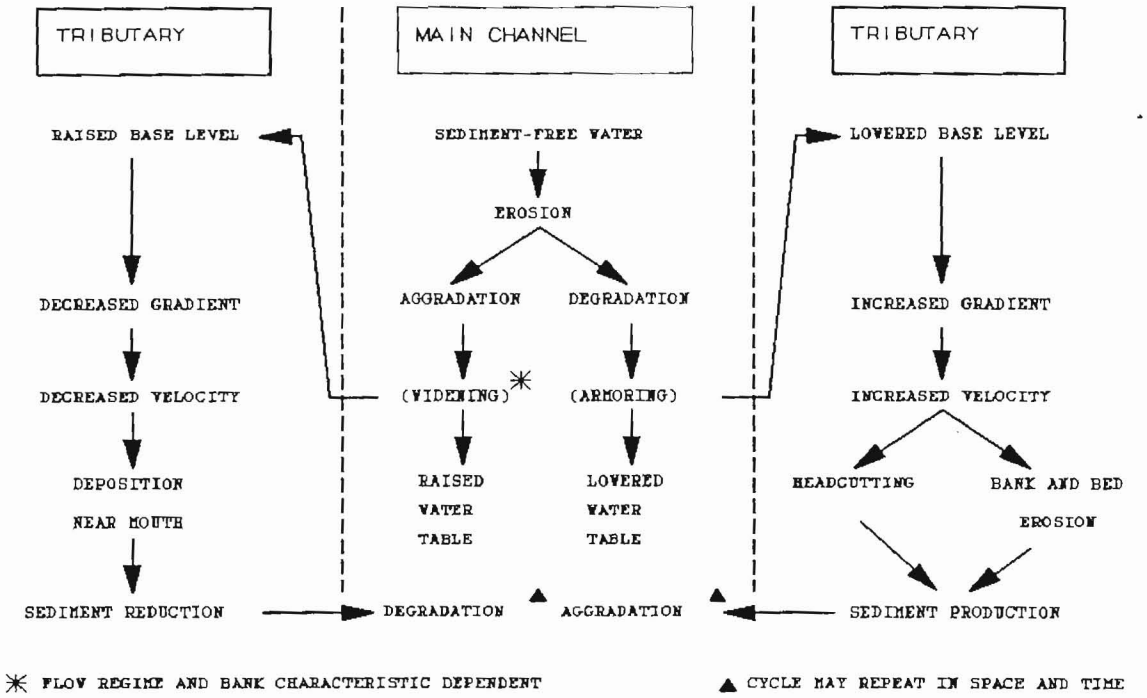


Figure 3.1 Generalized Sedimentation Effects of River Impoundments (Expanded from Ward, 1982)

A second and equally important effect of transport interruption is the blockage of downstream transport of organic detritus. Ward (1982) gives the following summary of these effects:

> "Much of the detritus in stream systems is derived from headwater terrestrial communities and is sequentially processed downstream. The truncation of detrital transport and processing significantly

> alters the energy base of the lotic system. Although few data are available it is apparent that quantitative (total transport) and qualitative (particle size composition, nutritional quality, chemical diversity) components of organic detritus may be altered and that temporal patterns are modified in regulated lotic reaches."

When sediment trapping is so severe that project operations are hampered, reservoirs may be rapidly emptied to release the trapped sediment. Such flushing can result in low dissolved oxygen, increased turbidity and suspended solids for a significant distance downstream from the dam. Hesse and Newcomb (1982) found that flushing can also result in fish kills and smothered benthos. Trapping sediment in a reservoir followed by flushing tends to keep the river in a continuous sediment disequilibrium with adverse consequences to most riverine species.

In addition to transport interruption, chemical changes in the water stored in a reservoir due to limnological effects can result in altered water quality downstream. Reservoirs act as sinks for some constituents (nutrients, heavy metals), but as sources for others (hydrogen sulfide, reduced species). Nutrient levels increase with depth so surface release exacerbates nutrient trapping (Ward, 1982).

Thermal changes also occur that influence stream biota. The extent of temperature modifications varies with reservoir

characteristics, operational practices and with latitude. Important reservoir characteristics include the surface to volume ratio and the azimuth of the reservoir. Both of these factors influence the amount of radiative and convective heat gain and loss. Reservoir depth and latitude influence the timing and intensity of thermal stratification. The design of the outlet works and the operational practices determine how reservoir temperatures influence the tailwater stream.

The overall effects of stream regulation on stream biota are mixed. Local conditions can cause a particular group of organisms to be favored or adversely affected by stream impoundments. The Table 3.1 summarizes those effects. Note that many of the effects are dependent on flow regime. In some cases fish abundance and size immediately below a reservoir may be enhanced over natural conditions. This may happen if the reservoir serves as a breeding place for food organisms, either small fish or invertebrates that are preyed on by riverine species.

The major operational variables that influence downstream conditions are the release depth (where adjustable), and timing and magnitude of releases. The combination of these management variables dictate the environmental conditions that exist in the tailwater. Thus they serve to limit the numbers and diversity of the tailwater fauna. Management of the water quality aspects of

this environment is beyond the scope of this thesis but is a potentially fruitful area of research. The present work focuses on management of discharge to maintain fish populations downstream from a reservoir.

Table 3.1. Common Responses of Riverine Organisms to Stream Impoundments (adapted from Ward, 1982)

Biotic-Component	General Effects	Comments
Macroinvertebrates (benthic insects)		
Abundance	Variable	Dependent upon flow regime and nutrient supply
Diversity	Reduced	Often due to thermal alterations
Composition	Altered	Trophic, thermal, and flow alterations
Vertebrates (fish)		
Standing Crop	Variable	Effects on vertebrates are temperature, flow regime, nutrient supply, sediment regime and channel morphology dependent.
Species Composition	Altered	
Species Diversity	Reduced	
Exotic Species	Increased	Local conditions dictate the specific nature of the changes of these components.
Growth	Poor to excellent	
Spawning Success	Variable	

THE RANGE OF DISCHARGE REGIME EFFECTS ON FISH

Due to the sensitivity of fish populations to the specific mix of local conditions, each instream flow requirement determination must be made with knowledge of the local environment. The range of possible effects is summarized to assist in understanding the habitat evaluations pursued later in this thesis.

Seasonal Flow Constancy (Buffering of Flow Extremes)

Buffering of seasonal discharge extremes induces several changes in a natural stream channel. Reduction of high scouring flows can lead to vegetation encroachment, increased bank stability and establishment of algae mats. In a natural stream the mix of benthic macroinvertebrates changes as the discharge fluctuates. Greater flow stability leads to greater specialization and less diversity. This may result in either high or retarded production of food organisms for resident fish and in turn, large or stunted fish populations (Ward, 1976).

Lack of flow fluctuation may result in the fish being unable to complete needed developmental life stages due to lack of the right environmental stimulus or conditions. Carlander (1969), and Schlosser (1985) note that different life stages of a species exhibit widely differing tolerances

for the same discharge regime. If buffering of seasonal flow fluctuations produces favorable conditions for the most limited life stages, the population may benefit; the converse is also true.

Short Term Flow Fluctuations

Operation of a reservoir facility for short term variations in discharge (eg. peaking power) production may lead to several kinds of changes in the downstream fishery. Direct physical effects such as bank instability and rapid velocity changes may change the channel morphology and bed material composition. This may in turn lead to fewer and less diverse benthic macroinvertebrates as they cannot tolerate rapid velocity fluctuations (Ward, 1976). Small fish and immature life stages of larger fish suffer increased mortality when flows fluctuate (Cushman, 1985). Larger fish, however, can tolerate discharge fluctuations by hiding in pools or behind large boulders. While larger fish are more adapted to surviving discharge extremes, their survival may be limited by lack of food organisms in a rapidly fluctuating stream (Fraley et al., 1986).

Reduced Streamflow

A general reduction in streamflow occurs when water is diverted out of the channel. A pervasive discharge reduction

will lower average velocities and lead to a shift in the benthos (Ward, 1982). Sedimentation may result in clogging of spawning gravels and higher temperatures may result due to longer travel times allowing greater exposure to solar flux. Higher temperatures and lower velocities may favor algal growth which in turn can further retard velocities. These changes may result in inhibiting or eliminating entire fish life stages. Fish species that are more adapted to the modified conditions may become abundant and out-compete native species. The local combination of these effects may reduce or eliminate the populations of fish originally present before the streamflow was reduced (Cushman, 1985).

Increased Streamflow

Increased stream discharge may be the result of a trans-basin diversion of water. Often, seasonally increased streamflows are the result of reservoir releases. When such releases result in out of season peaks in discharge and accompanying changes in temperature the life cycles of resident fish and invertebrates may be disrupted. Movement of coarse sediment and excessive transport of organic particulates may result in reduction in the number and diversity of the benthos. When managed flows occur out of phase with fish species needs, the population is likely to suffer some degree of decline (Nelson, 1986).

Conflicts Between Project Purposes and Downstream Fisheries

Operation of a water resource project can produce one or more of the categories of discharge related effects described above. Even omitting questions of the ecological value of the within-reservoir fishery it is clear that conflicts can arise between reservoir operations for power production or water supply, and maintenance of robust fish populations.

EFFECTS OF ENVIRONMENTAL REGULATIONS ON WATER PROJECT OPERATIONS

Any regulation that requires designers and operators of water resource projects to consider water uses outside of the project purposes cannot avoid imposing some kind of constraint. Environmental regulations are no exception. This section summarizes the effects of regulatory constraints on water projects in terms of reduced yield, reduced flexibility, and size constraints.

Reduced Yield

Firm yield is the net increase in dependable supply achieved by storing peak flows for use during drier periods (James and Lee, 1971, p. 287). Estimates of firm yield are often based on a design drought taken from the known period

of inflow records. An improved approach is to identify a drought by its frequency of occurrence based on a specified acceptable risk of shortage. The risk levels and water supply rules are usually determined using some form of a system model in what is called an operation study.

When environmental regulations require releases from a reservoir to supply instream flows, firm yield for other purposes can be reduced. These reductions can be viewed from several different perspectives. Perhaps the simplest is to look at them as project purposes that are added to those of the original water resource project. From this viewpoint, instream flows can be seen to consume a portion of the firm yield available to a project. Much of the debate over environmental regulations concerns the amount of a project's yield that should be devoted to water quality, instream flows and environmental maintenance.

Reduced Flexibility

In addition to firm yield, two other aspects reservoir operations may be affected. They are secondary yield and operational rate constraints.

Secondary yield is the water supply that can be provided by a project in excess of the firm yield. By its nature, secondary yield cannot be supplied in all years. Operation

studies are also required to determine the amount and frequency of secondary water supplies.

When regulations impose instream flow releases as additional project purposes, the flexibility available to project operators to manipulate secondary yield is reduced. This may be in the form of required releases when that water would otherwise be stored. It may also require water to be retained in storage for later use (yield) when the operator would prefer to release it. The net effect is to reduce secondary yield.

Operational rate constraints restrict the manipulation of reservoir releases for short term benefits. The most readily apparent of these is peaking power. Substantial revenue can be generated by supplying electrical power at the times of peak demand. When environmental regulations constrain power plant operations the power revenues may be reduced.

Constraints on powerplant operations can be grouped into two broad categories. They are reduction in peaking capacity and reduction in average power output. Peaking capacity can be reduced in several ways. The breadth of the peaking power cycle, the rate of change of releases and the allowed frequency of peaking power production may be constrained by

regulations designed to meet some of the biological objectives described above.

Average power output is indirectly affected by environmental regulations. Instream flow requirements may cause reservoir storage to be lowered during the periods when power production is most desired. Lower reservoir elevation results in less water pressure to turn the turbines so more water must be released to obtain the same instantaneous power output. When water supplies are limited, using more water to produce a given amount of power reduces the total amount of power that can be generated. Less total power over a year implies a lower average power capability.

The points raised in this section regarding reduced yield and reduced flexibility are highly dependent on the water resource system configuration. Where instream flow releases can also supply base power revenue there is less impact on operational yield. Where all water supply uses draw water directly from a reservoir, the impact of environmental regulations on project firm yield is most severe. Often the system configuration serves as an index of the degree of conflict between instream flow, other environmental water uses and the project purpose.

PROBLEMS WITH HISTORICAL INSTREAM FLOW MANAGEMENT APPROACHES

As noted in Chapter 2, existing reservoir operation practices frequently treat instream flow issues as minimum required flow constraints. While this approach may be easily implemented within the existing legal constraints, it does not hold promise for improving the conditions for a fishery downstream from a reservoir. The use of fixed minimum flows does not provide a means of treating fishery maintenance flows as an objective rather than a constraint. Basing instream management solely on discharge does not directly consider the benefit to the fish of a particular instream flow. The minimum flow approach does not allow trade offs related to the timing and volume of delivery of instream water. This has largely been the rule in the past because the long term benefits to the fish population were not known.

Use of the Instream Flow Incremental Methodology (IFIM) approaches the goal of considering long term population benefits. The suitability of use index (SI) criteria are based on statements or observations of the conditions the fish need to survive. The suitability functions are then used to describe the relative worth of the physical habitat generated at a range of discharges. From that information, a preferred range of discharges can be selected.

Minimum instream flow requirements are frequently based on studies using IFIM. Unfortunately, those flows are essentially statements of instantaneous habitat values and do not consider long term memory effects (cf. Chapter 4) that exist in natural populations. Since preceding conditions influence the current state of a population and thus the current habitat needs, a population based instream management scheme is needed to incorporate long term fishery effects and allow instream benefits to be traded against more traditional benefits such as power production or irrigation.

USING MODELS TO SATISFY THESE INFORMATION NEEDS

From this overview it is clear that the effects of water projects and environmental regulations can be the source of management conflict. Water storage projects that are operated for maximum project benefits can have many significant impacts on stream ecosystems. Similarly, zealous application of regulatory constraints designed to protect the environment can reduce project yield and flexibility. This may result in lowering profits, even to the point that some projects become infeasible.

Simulation Modeling has several characteristics that make it a useful technique for dealing with complex problems. They can integrate diverse phenomena into a single tool while

preserving cause - effect relations. They can be used to identify sensitive and insensitive parts of river systems. Model designers and users can draw together expertise from many disciplines and interest groups, thus building trust. Models can be used to conduct "what if?" tests of alternate problem solutions. These uses can all contribute to problem solving.

Two aspects of models make them a particularly good tool for dealing with instream flow issues. First, they can serve as communication tools. That is, they can show the effects of water use choices on aquatic species and on water uses. They can capture important aspects of the impacts described in this chapter and display those effects in terms that users from either camp can recognize. Second, they can provide a common forum for dealing with instream problems. Their "what if?" capability can speed negotiations by allowing possible settlements to be tested in a commonly accepted manner. These communication and alternative testing characteristics are particularly useful in decision arenas, such as instream flow determination.

The next two chapters describe models that were developed, refined or extended to deal with the instream flow issue. Those models address some, but not all, of the issues raised in this chapter. They provide a general framework for considering instream flow water allocation problems in

reservoir tailwaters and demonstrate approaches to resolving several technical problems.

Chapter 4

FISH HABITAT AND POPULATION ANALYSIS METHODOLOGY

Chapter 2 contains a summary of habitat methodologies developed for various purposes. This chapter describes the habitat methodology selected for this study. The methodology was selected because it allows development of a simple fish population index model.

Conceptually, use of the physical habitat analysis tools within the Instream Flow Incremental Methodology (IFIM) can be broken down into three steps as shown in Figure 4.1 below. Application of each of these steps to this study is briefly discussed in the sections which follow. Then, two extensions to the basic habitat modelling methodology are introduced.

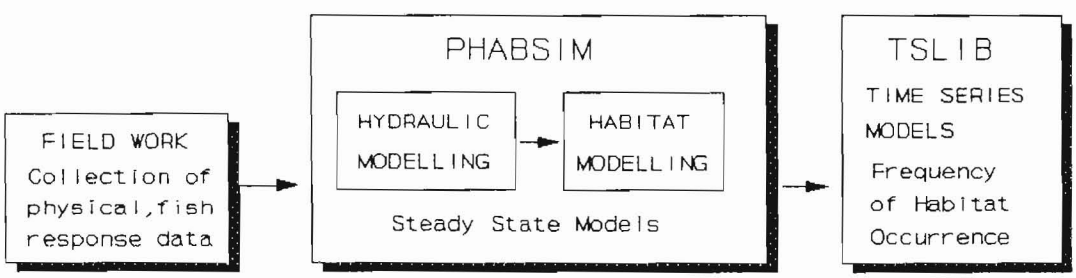


Figure 4.1 Physical Habitat Analysis Tools in IFIM

The first of these extensions translates habitat-discharge relations into time series of habitat. That process is the Time Series Library (TSLIB) portion of IFIM.

The second of the extensions is a technique to transform habitat time series into a simple population model. One of the contributions of this thesis is this first complete description of the population model and an empirical calibration technique for it.

PHYSICAL HABITAT SIMULATION

Data Collection

The first step in application of PHABSIM is the collection of data in the field. On each stream of interest one or more reaches are selected to represent the full range and distribution of habitat conditions. Along each of these reaches, several survey transects are located to capture the representative hydraulic and habitat features of the site. Depending on the anticipated application, measurements of various data are taken along each transect. Commonly, at each measurement point (vertical) the depth and velocity are measured. At the same time the type of substrate present and other features that provide cover for aquatic species are recorded. (See Trehey and Wegner (1981) for a description of

IFIM field methods.) Each of these verticals defines the edge of a rectangular cell. Within each cell, conditions are assumed to be homogeneous (See Figure 4.2). Ideally, this procedure is repeated at the same site using the same verticals at three or more widely differing flow rates.

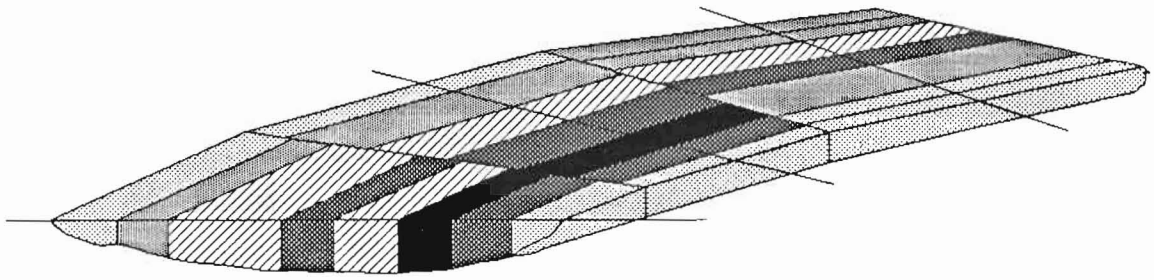


Figure 4.2. Treatment of Stream Areas in IFIM

Hydraulic Modelling

The data obtained in the field are next used to develop a hydraulic simulation model of the study reach. The Physical Habitat Simulation (PHABSIM) software library contains several hydraulic simulation routines. The three most commonly used are the IFG4 model, the MANSQ model, and the WSP model (Milhous et al. 1989). Selection of the hydraulic simulation model depends on the characteristics of the study reaches, the quality of the field data, and presence of a hydraulic control in the study reach. After the appropriate model has been selected, it is calibrated to

the flow data measured in the field. Then, the model is used to simulate the depths and velocities which would occur at different discharges within the study reach.

Steady State Habitat Modelling

Next, suitability index curves are selected or constructed for the targeted species and life stage. These curves relate factors such as depth, velocity, substrate, and temperature to suitability for the target life stage. The curves are scaled from 0.0 to 1.0 and may be derived in a variety of ways (Bovee 1986). Figure 4.3 illustrates an

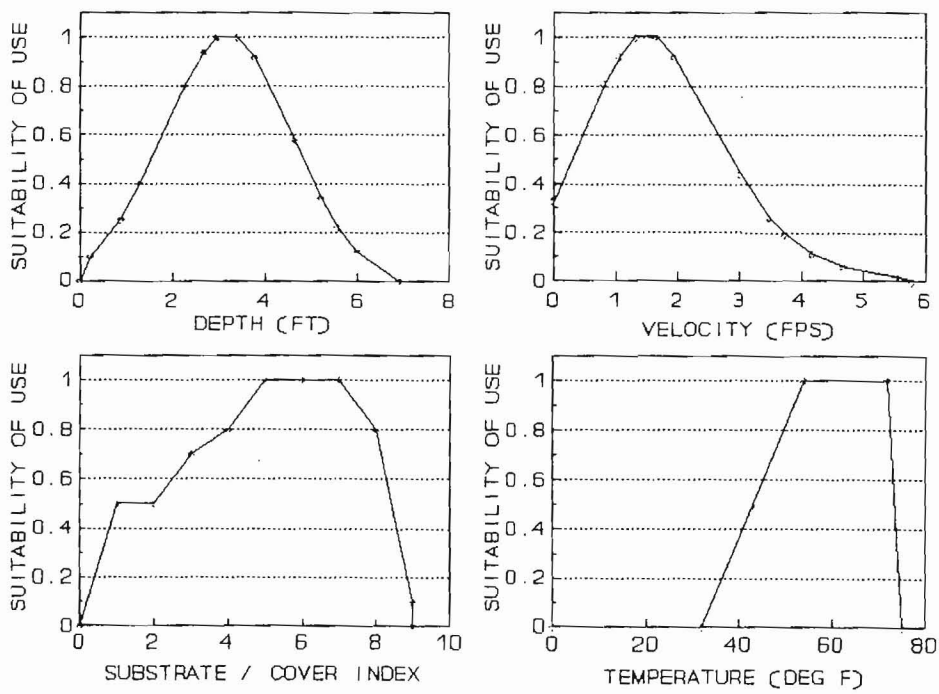


Figure 4.3 Suitability Curves For Brown Trout Adults

example of suitability curve of use index (SI) curves for adult brown trout, Salmo trutta.

Several steady state habitat models are available in the software library. They are selected by the analyst to reflect the known behavior of the target species, the life stage of interest, special characteristics of the study reach, the biological information needed for the issue to be decided and other factors. The habitat model uses the suitability index curves, the simulated depths and velocities, and the recorded substrate and cover information to produce a measure of the physical habitat available in the study reach. This measure is known as weighted usable area (WUA) and has units of square feet per 1000 linear feet. WUA is defined as:

$$WUA = \frac{\sum_{i=1}^{n} (\prod_j S_{jk})\ A_i}{L} * 1000 \qquad (4.1$$

Where: A_i = the surface area of the cell i,

S_{jk} = the suitability of use criteria value for life stage k,

i = the cell index, which runs from 1 to n,

j = the index for SI characteristic, and

L = length of study site.

Alternative methods for calculating WUA exist. Equation 4.1 is the default method.

The result of simulating a range of stream discharges using the hydraulic model and calculating the weighted usable area for all of the simulated cells over the length of a

stream is a relationship between habitat and discharge. An example of such a relation is shown in Figure 4.4.

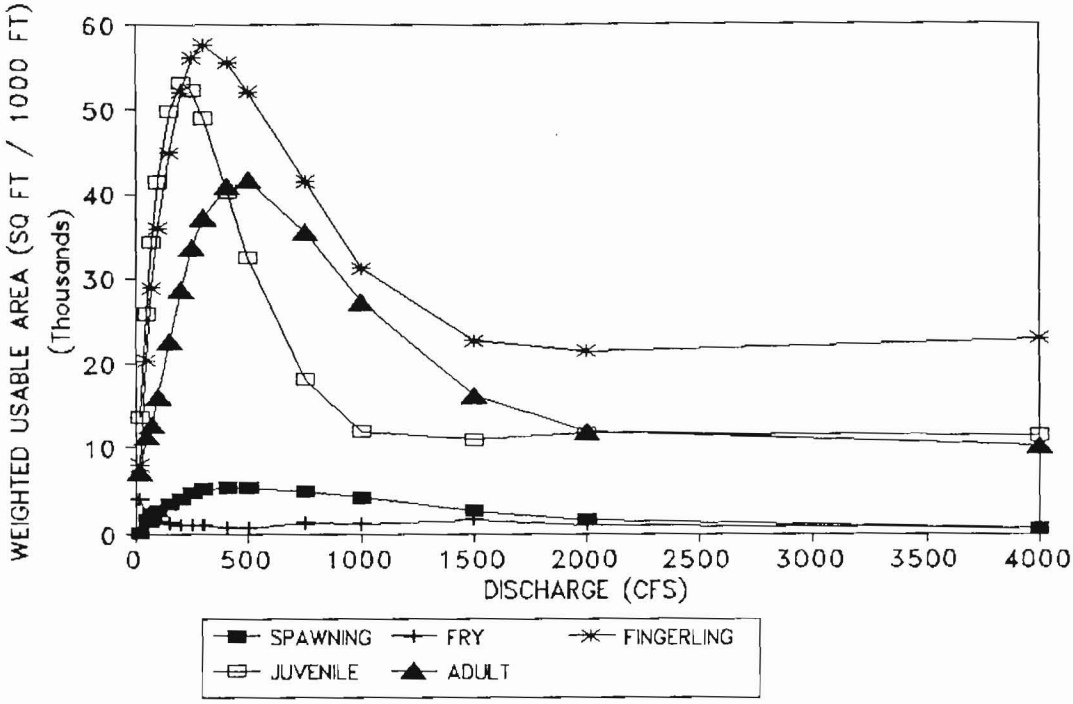


Figure 4.4 Example Habitat Flow Relationships for Five Life stages of Brown Trout

TIME SERIES HABITAT MODELLING

The habitat simulation model relates the amount of physical habitat to the quantity of flow. For each value of flow there is a unique amount of habitat produced. In nature, stream flow is a stochastic variable. Since habitat is a function of flow, it too is highly variable. For this reason the usefulness of the steady state habitat - discharge relation for analysis is somewhat limited. To describe the

stochastic nature of habitat the Instream Flow Incremental Methodology includes several habitat time series programs in a separate software library, the Time Series Library (TSLIB) (Milhous, et al., 1990). These programs use a series of average monthly flows to generate a time series of average available habitat through interpolation as shown in Figure 4.5. The discharge time series can reflect historical records, projected flows, or can be synthesized by the analyst. The habitat values generated by these time series programs will be referred to in the remainder of this discussion as gross available habitat values (GAH).

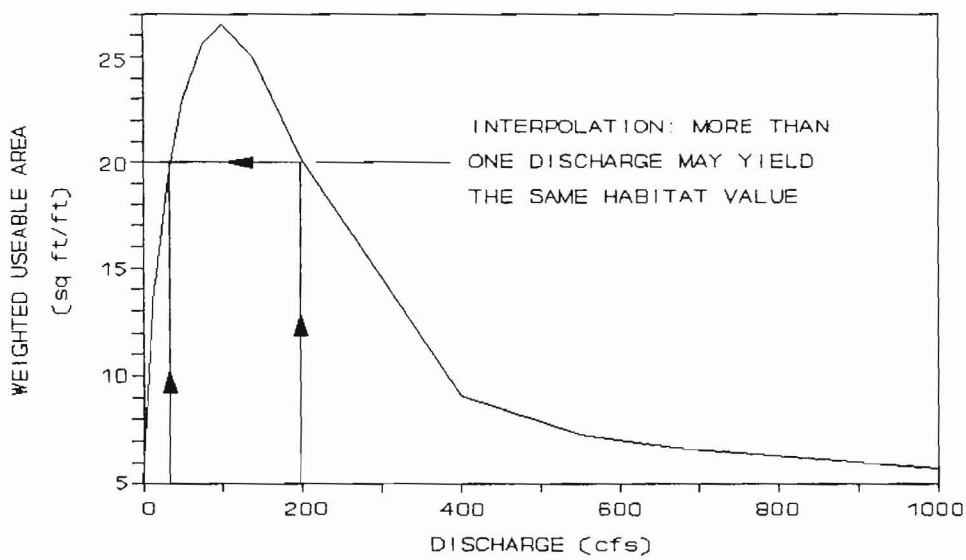


Figure 4.5. Interpolation from a Habitat - Discharge Relation

One use of habitat time series analysis is to simulate available habitat with and without proposed water development projects. This type of analysis allows the available habitat generated by these two conditions to be compared through a

full range of historical, projected, or simulated flow conditions. Programs within TSLIB allow frequency of occurrence analysis so alternative project operating scenarios can be compared.

Definitions of Time

It is often convenient to define different year types for analytical or management purposes. The models used in this study are based on a biological (fish) year. For brown trout, a fish year in Colorado refers to the period 1 April through March 31. This period begins at the approximate time brown trout eggs hatch. That is, the time the life span of a this species begins. Figure 4.6 illustrates these various definitions of a year. For this study, when the term year is used, it refers to a fish year.

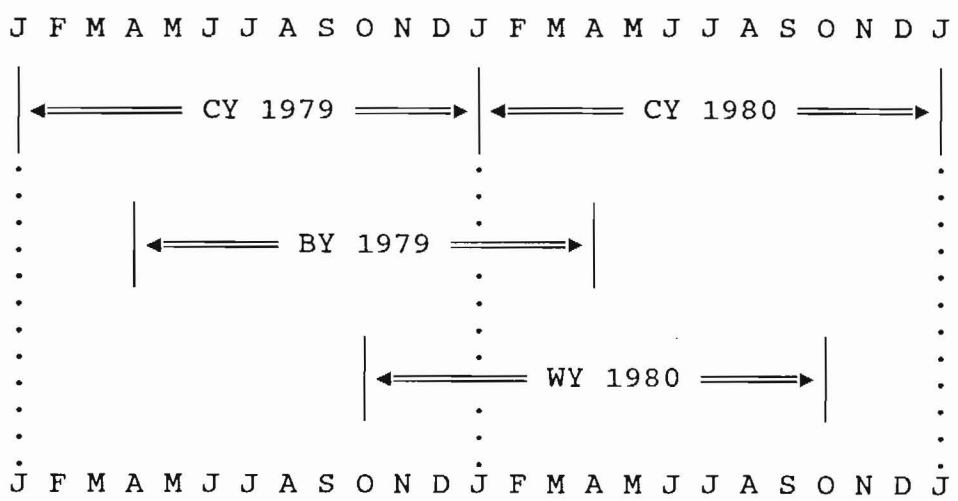


Figure 4.6. Definitions of Different Time Measures. CY = Calendar, BY = biological year, WY = water year.

BIOLOGICAL SYSTEMS AND THE MEMORY EFFECT

The time series habitat models previously discussed have one important drawback as tools of analysis. Each simulated value generated by these models is an instantaneous estimate of the habitat available in that time period. The TSLIB models currently support monthly time steps. Each monthly estimate is independent of the estimate in all previous periods. While this may be an adequate portrayal of physical habitat, biological systems which exist in this habitat space are also characterized by memory.

The term "memory", or the memory effect describes the measurable persistence or duration of population influencing events. In a stream environment, gross deviations from mean flows may constitute such an event. When these events constrain the size of the fish population, they are called limiting flow events or limiting events. A limiting flow event in any year (y) may affect the population in several subsequent years. The magnitude and duration of this effect is a function of the physical and biological parameters of the system. For example, the effect of a limiting event is related to its timing, the quantity of flow, and the response of the biota to flow conditions. The duration or persistence of this event is determined by the life history characteristics of the habitat dependent biota, their life spans, and their reproductive capabilities.

The memory effect is not captured by a time series analysis based on gross available habitat (GAH) values. For this reason, time series habitat analyses of pre-project and post-project conditions can overstate or understate project impacts.

An analysis based solely on gross available habitat may understate project impacts if the project causes the frequency of limiting flow events to increase. In such a case, a gross available habitat analysis could show little project impact on the average. However, an analysis which incorporated the memory effect may show that the population of the indicator species would remain depressed for several years after each occurrence of a limiting flow event. Thus, the population impact can be understated by an analysis of GAH alone.

Gross available habitat analysis may also overstate project impacts. For example, if a project reduced the average flows in a river system, gross habitat analysis may indicate that the amount of habitat available has declined significantly. However if this project buffers high spring flows, which are a limiting flow events for some species and life stages, these populations may respond positively. Thus a gross habitat analysis could also overstate project impacts.

EFFECTIVE HABITAT, AN APPROXIMATION OF POPULATION

Bovee (1982) proposed a model that incorporates the memory effect in the habitat time series context. This model uses simple life stage survival and habitat use relationships to describe the amount of habitat occupied by adults of a fish species. The effective habitat model allows limiting habitat events for sub-adult life stages to be reflected in terms of reduced adult habitat use potential. In his original presentation, Bovee provided a numerical example only. The components of the effective habitat time series model are defined below.

Limiting Available Habitat ($LAH_{\ell,y}$)

During any given year the amount of physical habitat in the stream varies as the flow varies. For example, during periods of high flow the surface area of the stream is larger and the depth is greater. Gross adult habitat area may also be high. Conversely, during periods of low flow the size of the stream and its depth are reduced. The amount of gross adult habitat during these periods is often low. In streams where physical habitat is limiting, the size of the population is limited by the amount of habitat available during critical periods. This explicitly assumes that other factors such as temperature, food supply or water quality alone do not limit the population. For the purposes of this

study limiting available habitat is defined as the minimum amount of habitat available during periods critical to each life stage (ℓ).

Limiting available habitat of type (ℓ) in year (y) is defined as the minimum of the gross available habitat for that life stage which occurred in that fish year. Using monthly time steps (t), limiting available habitat is given by:

$$LAH_{\ell,y} = MIN(GAH_{\ell,t}, GAH_{\ell,1}, GAH_{\ell,2} \ldots GAH_{\ell,12}) \qquad (4.2$$

Population Limits in the Effective Habitat Model

The underlying hypothesis of the effective habitat model is that physical habitat limits the size of the fish population in the study streams. Explicitly, factors such as food availability and water quality are assumed not limiting. The physical environment of most trout streams is highly variable. Thus, it is likely that population size is not the causal mechanism for limiting events. Physical habitat (as WUA) is essentially determined by discharge and water quality, which are not driven by fish population. For these reasons, the fish population model used in this study is based on the premise that severe physical habitat events govern the size of the population.

The Assumption of Constant Population Density

An important simplifying assumption is required to develop the population model employed here. The density of the fish population occupying a given habitat type is assumed to be a constant and this constant is assumed to be stable over time. This highly simplified approach ignores density dependent mortality and growth effects that are known to affect fish populations. For this study, the constant population density for a life stage ($DENS_\ell$) is calculated as $\Sigma POP_\ell / \Sigma WUA_\ell$, over the period for which observations are available.

This assumption implies that fish populations are linearly related to physical habitat. Consequently, if the amount of fish habitat changes, the size of the fish population will change in proportion. That is, individuals of a given life stage are, on average, uniformly distributed within the available habitat (defined as weighted usable area). The known tendency of fish species to seek the best habitat conditions is accounted for in the suitability of use curves. Thus, this assumption places more fish at locations with high habitat suitability than at locations with low suitability.

Habitat Multipliers

Using electroshocking and other sampling techniques, fisheries biologists can estimate the population of the fish present in a river reach at a particular time. The age structure of the population can then be determined from fish scales taken during the sampling operation. Sampling is often repeated at the same location over a period of years thereby generating a time series of population and age data. These data may be summarized in the form of a life table.

Using a life table, the number of fish in a particular cohort can be tracked through time. Average survival rates ($s_{\ell-1,\ell}$) between life stages can be estimated from the life table. Given the population ($POP_{\ell-1,y-1}$ of life stage (ℓ-1) in year (y-1), and these estimated survival rates, the population ($POP_{\ell,y}$) of life stage (ℓ) in year (y) can be expressed as shown in equation 4.3.

$$POP_{\ell,y} = POP_{\ell-1,y-1} * s_{\ell-1,\ell} \qquad (4.3$$

Given the constant population density assumption, relationship 4.3 can be expressed using the habitat area ($H_{\ell,y}$) and a multiplier ($M_{\ell,y}$). Equation 4.4 relates the habitat area used by life stage (ℓ-1) to that potentially used by the succeeding life stage (ℓ).

$$H_{\ell,y} = H_{\ell-1,y-1} * M_{\ell-1,\ell} \qquad (4.4$$

Use of a linear multiplier ($M_{\ell,y}$) lumps all density dependent survival and mortality effects into one coefficient. This is consistent with the assumption of constant population density. Derivation of the multipliers is critical to the modelling process. Data on fish population, age structure, and physical habitat availability are necessary for a period of years. This chapter concludes with a detailed description of the process used in this study to derive these multipliers.

Habitat Demand ($HD_{\ell,y}$)

Equation 4.4 describes the amount of habitat occupied in year (y) as a function of the habitat occupied in year (y-1) by the previous life stage (ℓ-1). Conceptually, this expression may be interpreted as yielding a measure of the amount of habitat demanded or required in year (y) given the amount of habitat in year (y-1). Altering Equation 4.4 to reflect this interpretation yields Equation 4.5.

$$HD_{\ell,y} = H_{\ell-1,y-1} * M_{\ell-1,\ell} \qquad (4.5$$

Equation 4.5 ignores the existence of habitat limits. The amount of habitat demand ($HD_{\ell,y}$) in year (y) could be greater than, less than, or equal to, the amount of limiting

habitat available ($LAH_{\ell,y}$) in year (y) as defined by Equation 4.2. The ability of the available habitat to support the population maturing from previous life stages is considered in the next section.

Effective Habitat

Effective habitat $EH_{\ell,y}$ is a measure of the amount of the available habitat in year (y) which is actually occupied. Effective habitat cannot exceed the amount of limiting available habitat for obvious reasons. However effective habitat can be less than the limiting available habitat. Effective habitat can be understood by tracking the effects of habitat demand and limiting available habitat through successive time periods.

Consider the amount of habitat actually occupied by life stage $\ell-1$ in year y-1 to be $EH_{\ell-1,y-1}$. From equation 4.5, the amount of habitat demanded by life stage ℓ in the next year would be $HD_{\ell,y} = EH_{\ell-1,y-1} * M_{\ell-1,\ell}$. The possibility that the demanded habitat does not equal the available habitat is incorporated by defining effective habitat for lifestage ℓ in year y ($EH_{\ell,y}$) as the minimum of the limiting available habitat and the quantity of habitat demanded:

$$EH_{\ell,y} = MIN(LAH_{\ell,y}, HD_{\ell,y}) \qquad (4.6$$

That is, the habitat that is actually occupied ($EH_{\ell,y}$) is the minimum of the amount of habitat demand derived from the previous year's habitat use ($HD_{\ell,y}$) or the physically limiting habitat ($LAH_{\ell,y}$).

Since each lifestage is populated by individuals maturing from a previous lifestage, the effective habitat should be calculated as an on going process. Thus the habitat demanded for lifestage $\ell+1$ in year y+1 is calculated using equation 4.7. Then the effective habitat in year y+1 is calculated using equation 4.8.

$$HD_{\ell+1,y+1} = EH_{\ell,y} * M_{\ell,\ell+1} \qquad (4.7$$

$$EH_{\ell+1,y+1} = MIN(LAH_{\ell+1,y+1}, HD_{\ell+1,y+1}) \qquad (4.8$$

Given the assumptions of the model, the effective habitat in year (y) is a surrogate for the population in year (y) and reflects cumulative habitat conditions, including the limiting effects of all previous flow events. That is, effective habitat as described in equations 4.6 and 4.8 embodies the memory effect described earlier.

The Effective Habitat Time Series Model

The effective habitat time series model is useful as an analysis tool because it simultaneously reflects the variable nature of physical habitat and the memory of the underlying biological system. This effective habitat approach portrays discharge induced impacts on population in a more realistic fashion than a time series of limiting available habitat. Figure 4.7 contains limiting available habitat time series

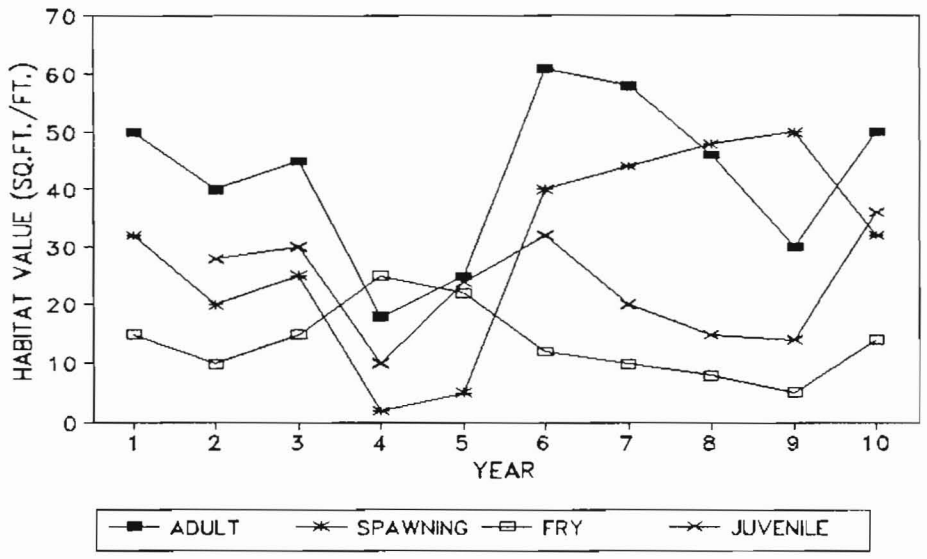


Figure 4.7. LAH Time Series for Four Life Stages of Brown Trout

for four life stages of brown trout. It is difficult to discern the overall population effects of the constraining event in year 4. Those effects occur both immediately and over the next four years. The population effects in years following the year 4 event can only be shown when the

population memory is considered. The importance of the effective habitat time series model lies in its ability to condense the effects of limiting events on multiple life stages to a single state variable using the memory effect. That variable is the adult effective habitat time series.

Figure 4.8 illustrates the interaction of adult limiting available habitat (LAH) and adult effective habitat (EH) .

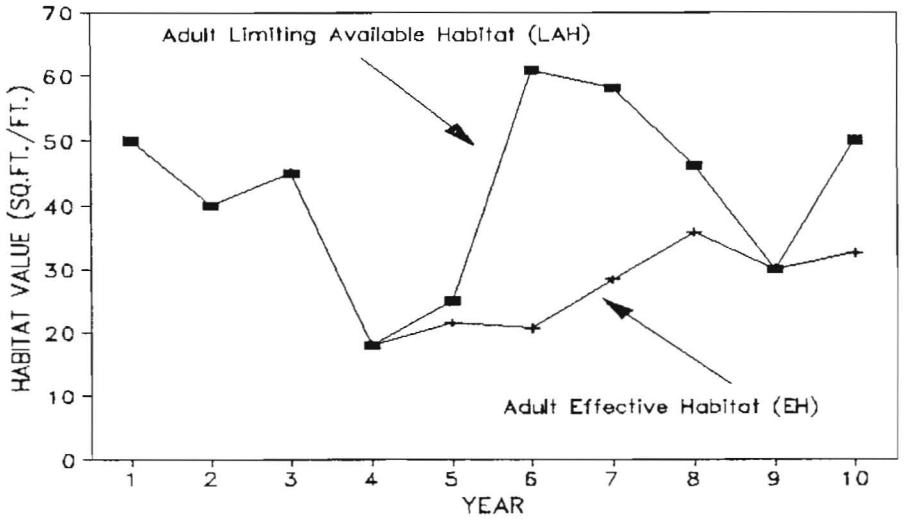


Figure 4.8. Limiting Available Habitat (LAH) and Effective Habitat (EH)

This figure summarizes several of the concepts previously discussed. As shown, limiting habitat events occurred in years 4, 5 and 9. As a result of these limiting events, the population was depressed below the available habitat space in years 5 through 8 and 10.

Flow conditions and available habitat improved markedly in years 6, 7 and 8. However, habitat as measured by EH, did

not improve by the same magnitude. This reflects the reduction in the stock of fry, juveniles and adults in years 4 and 5. Fewer eggs, fry, and juveniles were produced than would have been the case if the stock of adults were higher. The slow recovery of adult EH in years 5 through 8 reflects the lag structure or the memory of the system. An analysis based on the plot of LAH alone would underestimate the impact of low flow events on the fishery.

DERIVATION OF EFFECTIVE HABITAT MULTIPLIERS

At the beginning of this project, the effective habitat time series concept had been offered by Bovee (1982) but a calibration technique for habitat multipliers was not available. To fill this gap, the following procedure for deriving habitat multipliers was developed.

It is extremely difficult to accurately sample the very small life stages of a fish population. Due to difficulties in obtaining representative population samples of all life stages, some assumptions must be made regarding the numbers and production of sub-adult fish. Those assumptions were based on selecting values within the ranges suggested by the literature and by experts on the local populations of the fish species. In this example, parameter ranges for brown

trout (Salmo trutta) and the selected values are summarized in Table 4.1.

Table 4.1. Sources and Assumed Values of Survival Parameters for Brown Trout

Parameter	Range/Source	Assumed Value
Fecundity eggs per spawning female	144 to 6000 Carlander (1969)	1000
Spawning Age	Age 3 and older sexually mature Behnke (1990)	Age 3 and older
Sex ratio	1 : 1 Carlander (1969)	1 : 1
Egg survival	1.3% to 65% Carlander (1969) 50% Behnke (1990)	46%
Fry survival:	0.1% to 6% egg to juvenile Nehring (1990)	1%
Juvenile and Adult Survival	5% to 50% Carlander (1969)	50%

In Table 4.2, age and population data provided by Anderson and Nehring (1985) are arrayed chronologically in units of numbers per 1000 ft of stream to match the PHABSIM units of ft^2 per 1000 ft of stream. Note that the observed data contain only the adult and juvenile life stages. The

numbers for the other life stages are derived from assumed parameters. The numbers are expressed as numbers of fish per 1000 ft of stream or ft^2 per 1000 ft of stream. Units of numbers of fish or ft^2 are used for brevity in the rest of this discussion. The data are assumed to have the time orientation of biological (fish) year with the beginning of the year corresponding to hatching of the eggs.

Table 4.2. Calculation of Survival from Observed Data and Assumptions, Units: Numbers per 1000 ft of stream

Fish Year	Number Spawning Adults	No. Eggs Per Pair	No. Fry at 46% Survival	Number Observed Juveniles	Observed No. Adult Recruits	Total Obsvd. Adults
1979	249	124500		105	189	438
1980	112	56000	57270	147	293	405
1981	167	83500	25760	51	149	316
1982	200	100000	38410	85	98	298
1983	119	59500	46000	82	315	434
Averages:						
Observed	169	--	--	94	209	378
Calculated		84700	41860	419	209	379

For brown trout, spawning and egg maturation are assumed to occur in the same year as the adult fish that were available for spawning. The fry (N0) life stage occurs in the following year (year 0), the juvenile (N1) stage in year 1 and the first adult stage (N2) in year 2. All adult stages are lumped into an N2+ (N2 and older fish)

value to find the average density of adults. The total number of spawning adults is the number of N3+ (N3 and older fish).

This sequence is slightly modified for rainbow trout. Rainbow trout spawning, egg maturation and fry are all assumed to occur in the same fish year.

The survival rates were determined by a trial and error process, beginning with values from Table 4.1 suggested by Behnke (1990). The trial and error solution was carried until calculated numbers of adults converged on the observed numbers. This calibration process using survival rates is described following an important assumption about averaging.

A further assumption is required to complete the habitat multiplier calculation. Averages of the annual physical habitat values for the (biological) year obtained during the period when the population data were being collected are assumed to be representative of the physical limits of the river system. Although other variables influence the fish population, the averages of the annual limiting available habitat conditions were assumed to be an adequate first order approximation of the limiting phenomena.

Survival Calculations

Based on these assumptions, the following calculations are performed on the age and population data to derive average survival rates between life stages. The results are shown in Table 4.2 as the calculated numbers per life stage.

Given the number of spawning adults (Nsp = N3+ age fish), the number of eggs produced is calculated as Nsp/2*Fecundity for each year. For example, this yields 124,500 eggs from the 249 spawners in fish year 1979. The average of the calculated numbers of eggs (84,700) for the five years is shown an the last row.

Of the 124,500 eggs in 1979, 46% are assumed to survive to become 57270 fry in 1980. The average number of fry is calculated as 41860 over the adult population sampling period.

Since capture data for the juvenile life stage appears to under-sample the juvenile population, the survival from fry to juvenile is based on the assumed value of 1% survival yielding an average of 419 juveniles. This estimated average number of juveniles is more than four times the average number captured, but is consistent with

the average number of adult recruits sampled and the assumed juvenile survival rate.

Since fewer juveniles were sampled than adult recruits in the same cohort, their survival to adult recruits was assumed to be 49% rather than averaged from the available observed numbers of juveniles. This yielded an average of 209 adult recruits, which matches the average observed number of adult recruits.

The model is calibrated by adjusting assumed survival values by trial and error within the ranges shown in Table 4.1. The survival rates are adjusted to obtain calculated numbers for the sub-adult and adult life stages that are consistent with the observed numbers of adult recruits and total adults.

Average Density Calculations

Table 4.3 shows the density (as numbers of fish per unit of WUA) per life stage and the average limiting available habitat (LAH) area that occurred during the data collection period. The density values are determined from the numbers of eggs, fry, juveniles and adults observed in the respective years. Density and limiting available habitat values are averaged over the years for which life table data were collected.

Table 4.3. Calculation of Average Limiting Available Habitat Values* and Average Densities**

Year	Spawning Habitat	Spawning Density	Fry Habitat	Fry Density
1979	5847	0.0213	16026	-----
1980	4541	0.0123	12282	4.66
1981	4492	0.0186	29354	0.88
1982	6131	0.0163	14684	2.62
1983	6826	0.0087	12921	3.56
Avg.	5567	0.0154	17053	2.93

Year	Juvenile Habitat	Juvenile Density	Adult Habitat	Adult Density
1979	18112	0.0058	12240	0.0358
1980	14095	0.0104	14273	0.0284
1981	27483	0.0019	11718	0.0270
1982	16702	0.0051	11606	0.0257
1983	14829	0.0055	14213	0.0305
Avg.	18244	0.0057	12810	0.0295

* Limiting Habitat units: ft^2/1000
** Density as Number of fish per ft^2 of WUA

Habitat Multiplier Calculations

Ratios among the habitat needed by each life stage (habitat multipliers) were calculated as shown in Table 4.4. The average amount of habitat occupied by the various life stages during the sampling period is assumed to produce

habitat ratios that represent the response of the population to available habitat conditions.

Table 4.4. Calculation of habitat multipliers

Habitat Multiplier	Habitat Area*	Number of Fish	Description
	12828		Adult WUA
		378	Number of N2+ adults
		209	Number of N2 adults
0.703			Juvenile- adult multiplier
		418	Number of N1 juveniles
	18244		Juvenile WUA
		41800	Number of N0 fry
1.278			Fry - juvenile multiplier
	14271		Fry WUA
		90870	Number of eggs (Negg)
		91	Number of redds (Nredd)
39.261			Spawning - fry multiplier
	363		Spawning WUA
0.028			Adult - spawning multiplier

* Units: WUA (sq. ft. / 1000 ft.)

Habitat area occupied by adults (effective adult habitat) is calculated by using the average number of observed adults and the average adult density from Table 4.3, ie. (12562 ft^2 = 378 adults/0.0295 ft^2 per adult). The number of N2 adults is calculated from the ratio of average observed N2 adults to total adults (209 N2 adults/378 total N2+ adults = 0.553).

The number of juveniles (N1) is calculated from the juvenile to adult survival rate (418 juveniles = 209 N2

adults/0.50 [assumed juvenile-adult survival rate]). The effective juvenile habitat area is taken as min(N1/average juvenile density, average available juvenile habitat) eg. min(418 juveniles/0.0051 juveniles/ft^2, 18244 ft^2 [average habitat area from Table 4.3]). That is, the average effective juvenile habitat is calculated from the number of juveniles and the available habitat. Use of the minimum avoids assuming that more habitat was used than was available.

The number of fry (N0) are calculated from the fry to juvenile survival S0 as N1/S0. The fry habitat area is taken as min(N0/average fry density, average fry habitat).

The number of eggs (Negg) is calculated from the assumed egg-fry survival (Segg) as N0/Segg. The number of redds (egg nests) is calculated from Negg/fecundity, assuming one female builds one redd.

The spawning habitat area is taken as min(Nredd * 4 ft^2/redd, available spawning area). The minimum is again used to avoid assuming more habitat was used than was available.

The ratios between the habitat values for succeeding life stages become the habitat multipliers. That is, the spawning - fry ratio is 14271 ft^2/363 ft^2 or 39.261.

Using this approach, the habitat multipliers are dependent variables and the survival rates are independent variables. This approach permits the model to be calibrated using population parameters that are familiar to fishery biologists. At the same time, it directly produces the habitat multipliers needed for the model.

The Resulting Effective Habitat Time Series

Using the habitat multipliers derived in Table 4.4 and applying them to sequential calculations derived from equations 4.7 and 4.8 produces the effective habitat time series shown in Figure 4.9. Note that in most years the adult effective habitat values are equal to the available habitat values. This may indicate that the habitat for adult brown trout is the limiting factor at this site. In 1971 the effective adult habitat is less than the available habitat. During 1971, the model suggests that previous year limits on sub-adult life stages restricted the ability of the adult population to respond to increased available habitat.

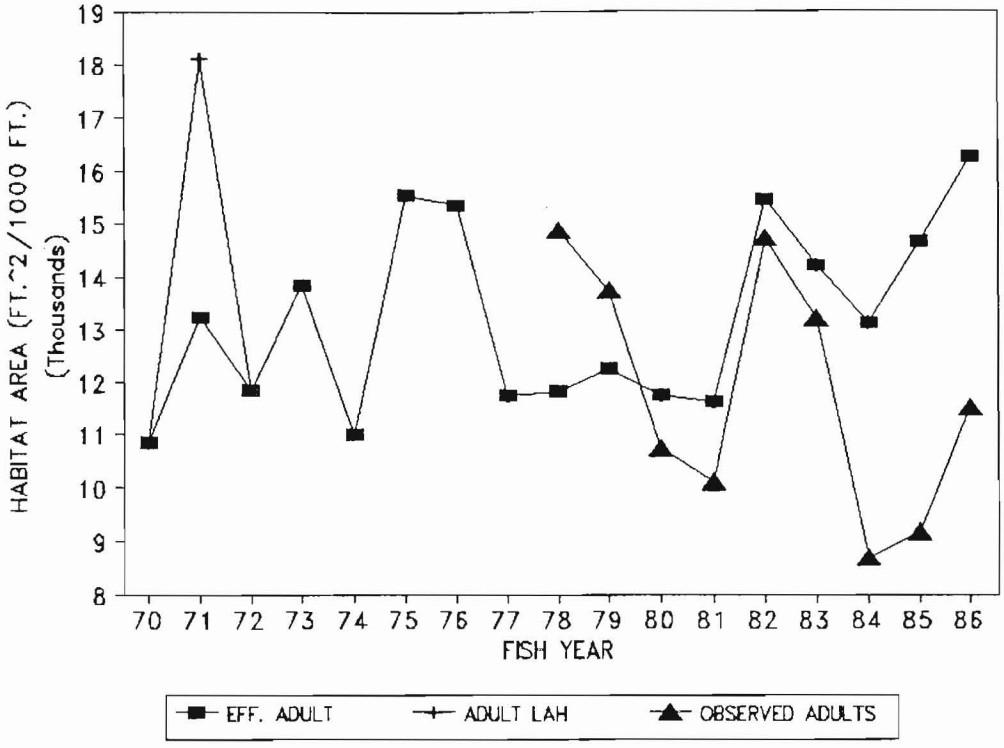


Figure 4.9. Adult Effective Habitat Time Series for Lower Cheesman Canyon

DISCUSSION

The effective adult habitat trace shown in Figure 4.9 exactly follows the limiting available habitat trace except in fish year 1971. This suggests that there is sufficient habitat available for the sub-adult life stages to produce enough adults to use all available adult habitat in all years except 1971. Under such conditions, the population may be limited in most years by the available adult habitat rather than by habitat for earlier life stages.

The effective habitat time series model provides a surrogate for population in terms of habitat use. In the Cheesman Canyon example, management of flow to raise the annual available habitat minimums for adults could potentially allow that stream segment to produce more brown trout. Since this model can approximate the effects of discharge management on fish numbers, it offers a means of determining the fishery benefit of alternative reservoir release rules using available fish population sample data.

Technical Contributions

Bovee (1982) presented the algorithm for this model as a numerical example. His example used arbitrary habitat multipliers for the sake of illustration. The preceding presentation is the first definition of the terms and equations describing this model. This presentation of the model's functional relations and the calibration technique given below are part of the technical contributions of this thesis.

Satisfying Information Needs

The physical habitat and effective habitat models provide a response to several of the information needs described in Chapter 3. Changes in sedimentation and water quality can be represented as part of the channel condition

included in the habitat simulation. Suitability index criteria for those variables can be included in the WUA calculation in Equation 4.1. Changes in channel morphology caused by impoundments or modification of the flow regime are not directly addressed. However, their habitat effects can be included by supplying empirical data for each discharge in the analysis.

The effective habitat model directly responds to changes in the magnitude and timing of managed flows. As noted earlier, it incorporates the species memory of flow events. It can give a better indication of the population response to increased or reduced discharge.

These habitat and population models can deal with the stated effects of a water resource project on the aquatic environment. However, they cannot describe the effects of environmental restrictions on project operations. That is the domain of the models described in the next chapter.

Chapter 5

TWO SIMULATION MODELS FOR MANAGING STORED WATER FOR INSTREAM FLOWS

Two models are presented in this chapter. The large model is a Fortran operations study model intended to test various storage account management policies over long periods of record. It is similar in concept to numerous deterministic operations study models in use throughout the United States today. The second model is a spreadsheet designed to allow gaming with an instream flow storage account to evaluate effective habitat consequences over the current year. Technical contributions and contributions to enhancing communication in instream decisions are discussed in the chapter's conclusion.

MODEL SCOPE

The models presented in this chapter provide a platform for considering several of the issues raised in Chapter 3. Their structures allow evaluation of the impact of proposed instream flow requirements on water projects. By applying

these models over a wide range of water supply conditions, reductions in project yield due to allocating water to instream flow can be evaluated. Reductions in water delivery flexibility can also be simulated. This is accomplished by comparing feasible water project deliveries with different instream flow and storage account requirements.

The models explicitly represent discharge regime effects on fish. They do so through the physical habitat relationships from IFIM (cf. Chapter 2) and the effective habitat time series (cf. Chapter 4). They are designed to deal with the specific issue of managing storage to mitigate the effects of reduced streamflow. They do not address control of high flows as a habitat management option. The water routing model is based on mass balance principles. Thus these models are not capable of representing short term flow fluctuations such as peaking power releases.

Other issues such as sedimentation, changes in invertebrate population and reservoir ecology are beyond the scope of these models. Some aspects of sedimentation, and invertebrate population can be incorporated in the IFIM analysis as noted in Chapter 4. Any application of these tools should include consensus on the form and validity of the information used in the IFIM analysis. The same applies to the other data used in the model.

The Fortran version accommodates numerous water rights over a user defined length of river and a reservoir with an instream storage account. The spreadsheet version deals with a single river reach and reservoir with an instream account. The Fortran version contains a decision algorithm for managing the storage account. The spreadsheet allows users to perform the function of the decision algorithm themselves. The spreadsheet is intended to allow fishery managers and project operators to game with the system interactively while negotiating current year water releases.

FORTRAN MODEL STRUCTURE

As noted in Chapter 2, simulation models provide a base for exploring ideas and testing relationships. The overall model concept presented below is generalized in the larger Fortran model as to the number, location, and priority of water uses. The generalized approach is intended to allow experimenting with various system and water demand configurations. Natural flow is allocated among water uses using a priority system based on the appropriation doctrine. Four water right types are recognized. They are: natural flow diversion rights, storage rights for diversion, natural flow instream flow rights and storage rights for instream flow. The storage account concept applies to the last of these.

There are six component models which are implemented in the Fortran computer program. They are: 1) a description of reservoir inflow (treated as a deterministic data stream), 2) a model of the appropriation doctrine water right priority system along a stream, 3) a model of a water storage reservoir with instream storage rights, 4) a mass routing scheme that separates natural flow rights from storage right releases, 5) the effective habitat model, and 6) a decision framework model which determines efficient use of storage for instream flow purposes. A general schematic of the stream system layout of the model is provided in Figure 5.1.

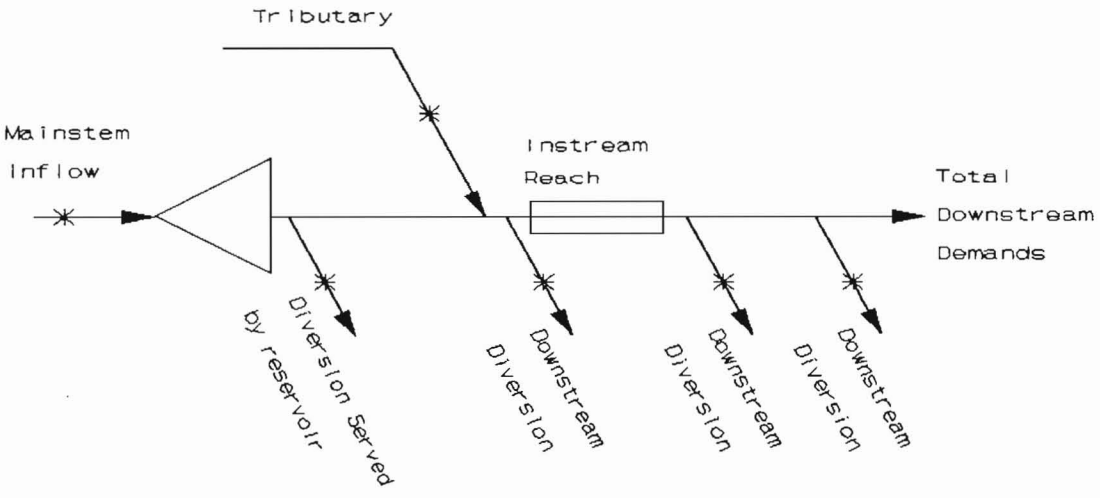


Figure 5.1. Generalized Stream for Water Budget Tests

In the model, the decision algorithm for managing the instream storage account treats effective habitat as being equivalent to fish population. It attempts to maximize effective habitat by allocating stored water from the account

in the form of "make up" releases to raise the flow when population restrictions due to low streamflow are detected. Two general rules are included as options. Option 1 considers the population state at the beginning of each decision year and allocates instream water within the year on the basis of that state. Option 2 delivers instream water in a user specified seasonal pattern without considering preceding conditions. The general decision algorithm is shown in Figure 5.2.

State and Decision Variables

The following water volume and habitat related variables are required to implement the overall modeling concept. State variables include total available water as described by inflow and current storage ($S_t + QIN_t$), and storage right volumes ($S_{i,t}$, i = 1,number of water rights and $\Sigma S_{i,t} = S_t$). The population status measured as effective habitat values for the each life stage in the stream ($EH_{\ell,t}$) is also a state variable. The subscript ℓ indicates the life stage and t indicates the current time step. Decision variables include releases for all purposes (R_t), and the releases for each water right ($R_{i,t}$). The amount of inflow allocated to each storage right ($QIN_{i,t}$) is determined by the water right priority of the diversion to storage and the total inflow QIN_t. Constraints include the usual physical constraints on reservoir size, outlet works capacity and the effects of

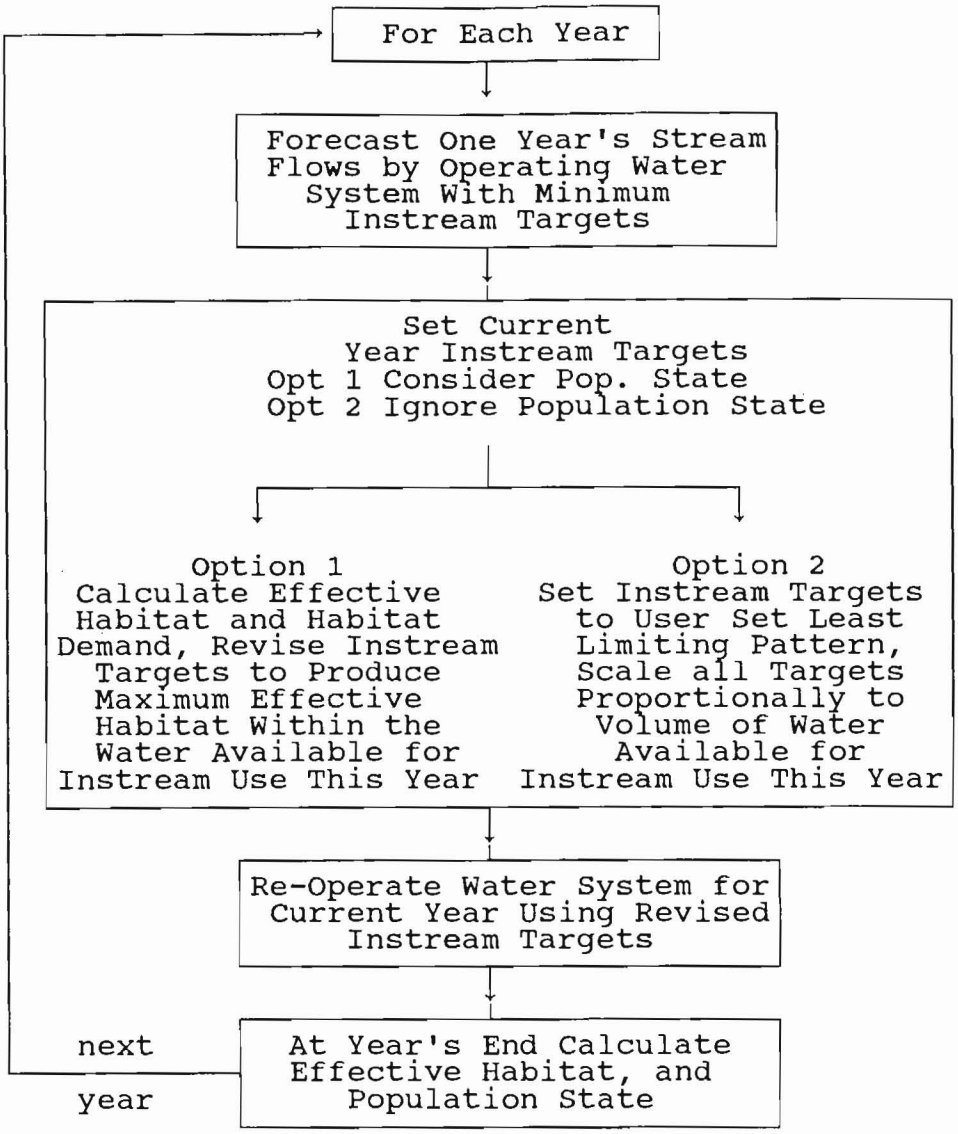


Figure 5.2. Model Decision Algorithm

higher priority water rights. Each of the component models is described below.

The model algorithm uses a decision year based on the approximate beginning of life of the target fish species. This fish year begins when the eggs hatch. The year can be

divided into a user-selected number of time steps. In the case study (cf. Chapter 6) monthly time steps are used. However, up to 52 periods per year of varying length may be used. Since the model considers mass routing only, the time step should be at least as long as the low flow travel time of a slug of water through the system.

The overall algorithm sets water use delivery targets and attempts to make those deliveries. Water right targets for all rights are supplied for the entire study as data. The model makes two passes through each year. The first is a pseudo forecast of inflow and non-instream water uses. The second pass occurs after the storage account decision algorithm has determined the instream flow allocation for the year.

At the beginning of each year, initial instream flow targets are set to user supplied initial values. For each month, natural flow right deliveries are made following the appropriation doctrine. Next, the amount needed from storage to satisfy storage right demand targets is calculated. Then, a mass balance on each storage right is calculated and deliveries to the storage dependent demand targets are routed. Finally, the first pass concludes by making instream flow deliveries at the times when routing other deliveries does not meet instream flow targets.

After the first pass, the decision algorithm evaluates the year and revises the instream flow targets. The revised targets are constrained to:

$$\sum_t TARG_t \leq SAVAIL \qquad (5.1$$

where: $TARG_t$ = instream target at time t, and

SAVAIL = volume of water available in storage account for current year.

The revised instream targets are used in the second pass to determine final stream flows and storage volumes.

Effective habitat is calculated at the end of each pass. The revised instream targets are determined using the population state (option 1) or user input (option 2) as described below.

The Inflow Model

The stochastic nature of hydrologic systems is beyond the scope of this study. Since the purpose here is to deal with management of instream flows below the reservoir, inflow component is limited to deterministic sequences of flow events. The period of record may be selected to correspond with that used by a reservoir managing agency such as the U.S. Bureau of Reclamation or to capture a particularly important series of events. A stochastic inflow generation

scheme could replace this approach with no loss of model generality.

The Water Right Model

Using the doctrine of prior appropriation, the water right model selects which water rights are to receive water in each period t based on inflow (and lateral inflow accrued to the point of diversion of each right). The water right model is highly generalized so any configuration of water rights and locations can be simulated by merely changing input data. The model uses the strict "first in time, first in right" concept to divide up natural streamflow. There are no provisions for exceptions to that rule. The water right priority model considers relative location, up and downstream so upstream junior rights cannot use water destined for downstream senior rights. It ensures that lateral accumulations and return flows are available to downstream users in priority order. The basic algorithm is summarized in Figure 5.3.

Each right is identified by a water right type index. This allows the algorithm to recognize four "colors" of water to operate the various natural rights and storage rights with different priority dates. The four types are: 1) storage account for diversion, 2) storage account for instream flow, 3) natural diversion right, and 4) natural instream flow

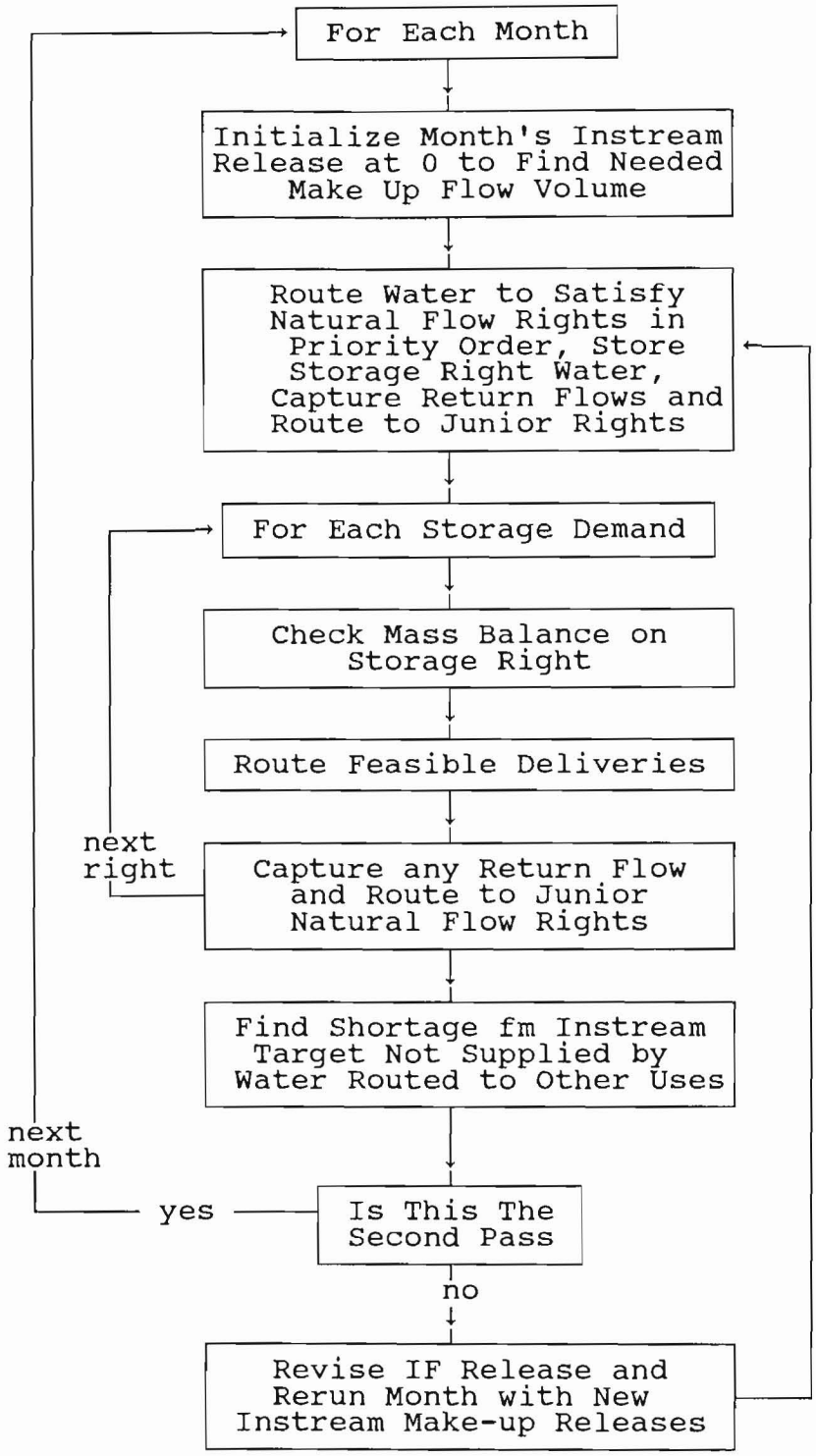


Figure 5.3. Water Right Allocation and Routing Algorithm

right. All storage rights are filled from natural streamflow in priority order. Stored water is kept separate from natural flow water when it is routed through the stream channel to its point of use. That procedure is described below.

Storage Right Accounting and Routing

Once the natural flow has been allocated to all uses, sufficient information exists to perform reservoir and storage account mass balances. The reservoir model performs the standard mass balance calculations for each storage account. Mass balance calculations for the entire reservoir are performed to determine outlet works capacity and as a check on the storage right calculations. The general mass balance equation is:

$$S_t = S_{t-1} + I_t - E_t - R_t \qquad (5.2$$

Where: S_t or S_{t-1} = Storage at end of period t (or end of period t-1),

I_t = Inflow during period t,

E_t = Net evaporation and precipitation from/to reservoir surface during period t, and

R_t = Release from reservoir for any purpose during period t.

The total mass balance considers S_t as the sum of several $S_{i,t}$ based on having storage rights for several water uses (subscripted i - the 'colors'), one of which is the instream storage account. Similarly, R_t will consist of several $R_{j,t}$ representing the release to water right j in time t. Thus, both direct diversion rights and storage fed rights are considered by passing inflow to senior water rights first and only allowing releases from storage after natural flow rights are satisfied. The model performs a mass balance for each storage right $S_{i,t}$ prior to finding the total storage.

The storage accounts are treated as independent reservoirs, each with its own inflow, evaporation, releases and carry-over capability. By being separate, the accounts exclude use of a block of storage by other users when the they are not full. Figure 5.4. is a conceptual diagram of a reservoir with three storage accounts.

Under the appropriation doctrine, all return flows revert to the stream. Thus return flows from storage rights become natural flow when they reach the stream. In the event that junior water right holders were not satisfied from the system inflow, the return flow accruing to the stream may satisfy their water rights. This phenomena is constrained by the location of a unsatisfied water rights and their priority order. The algorithm contains a recursive scavenging routine to glean all natural flow for unsatisfied water rights that

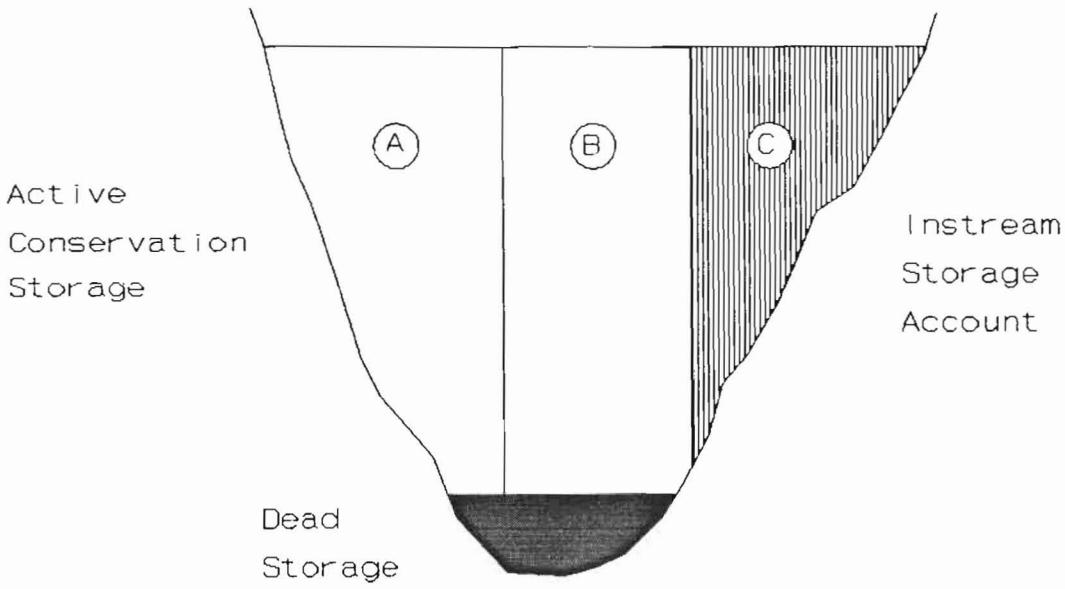


Figure 5.4. Conceptual Diagram of a Reservoir with Storage Accounts

are physically able to use it without injuring senior rights. The storage right algorithm is shown in Figure 5.5.

Calculation of Effective Habitat

The effective habitat model depends on knowing the discharge pattern for the entire year so it follows the water routing algorithms. First, the gross available physical habitat (GAH) for each life stage of each species is calculated for the designated instream flow location. These values are interpolated from habitat discharge relationships derived from IFIM. (cf. Chapter 4) The limiting available habitat (LAH) is calculated as the minimum GAH that occurs for each species during the year. Some life stages do not

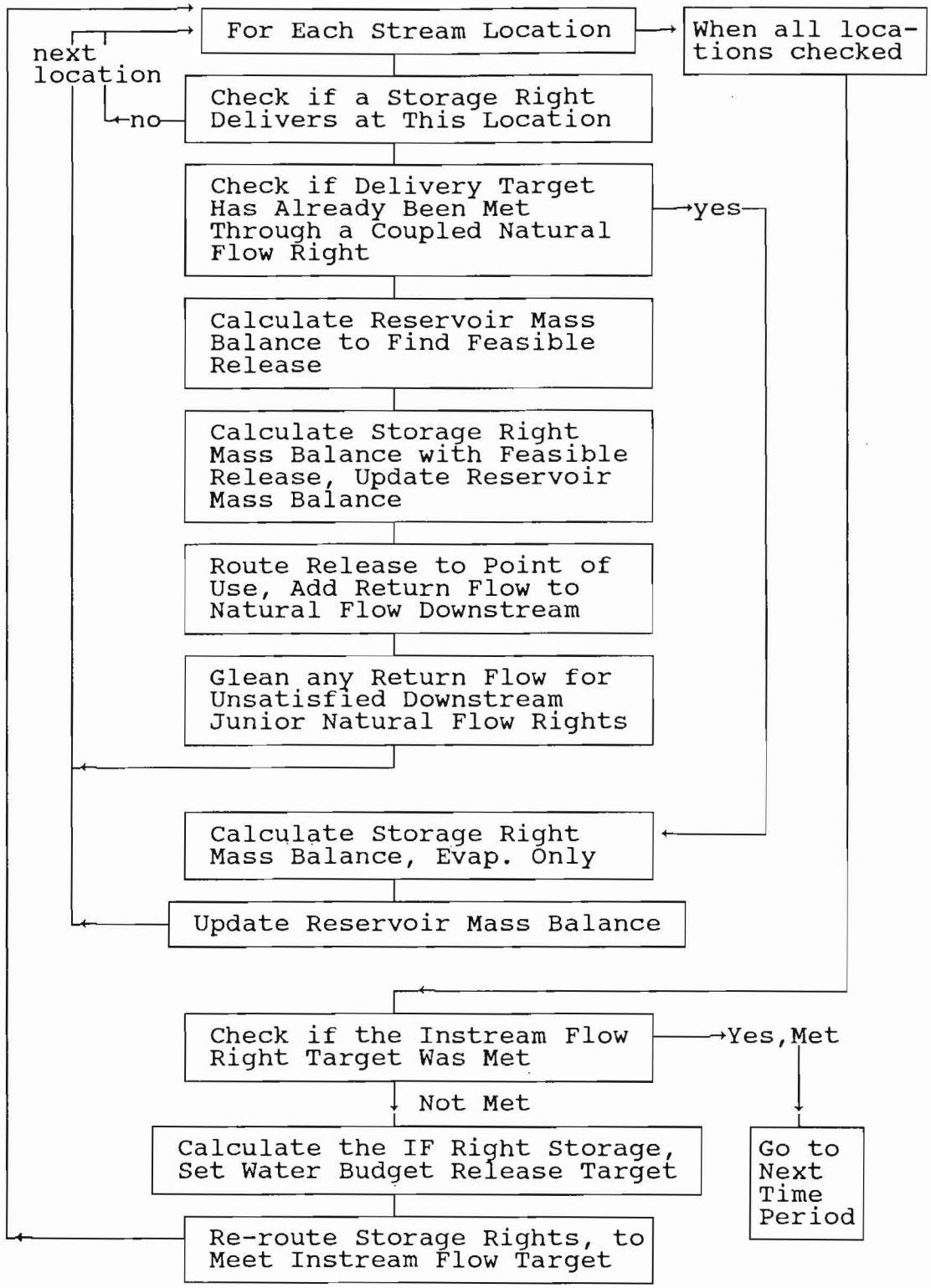


Figure 5.5. Storage Right Accounting and Routing Algorithm

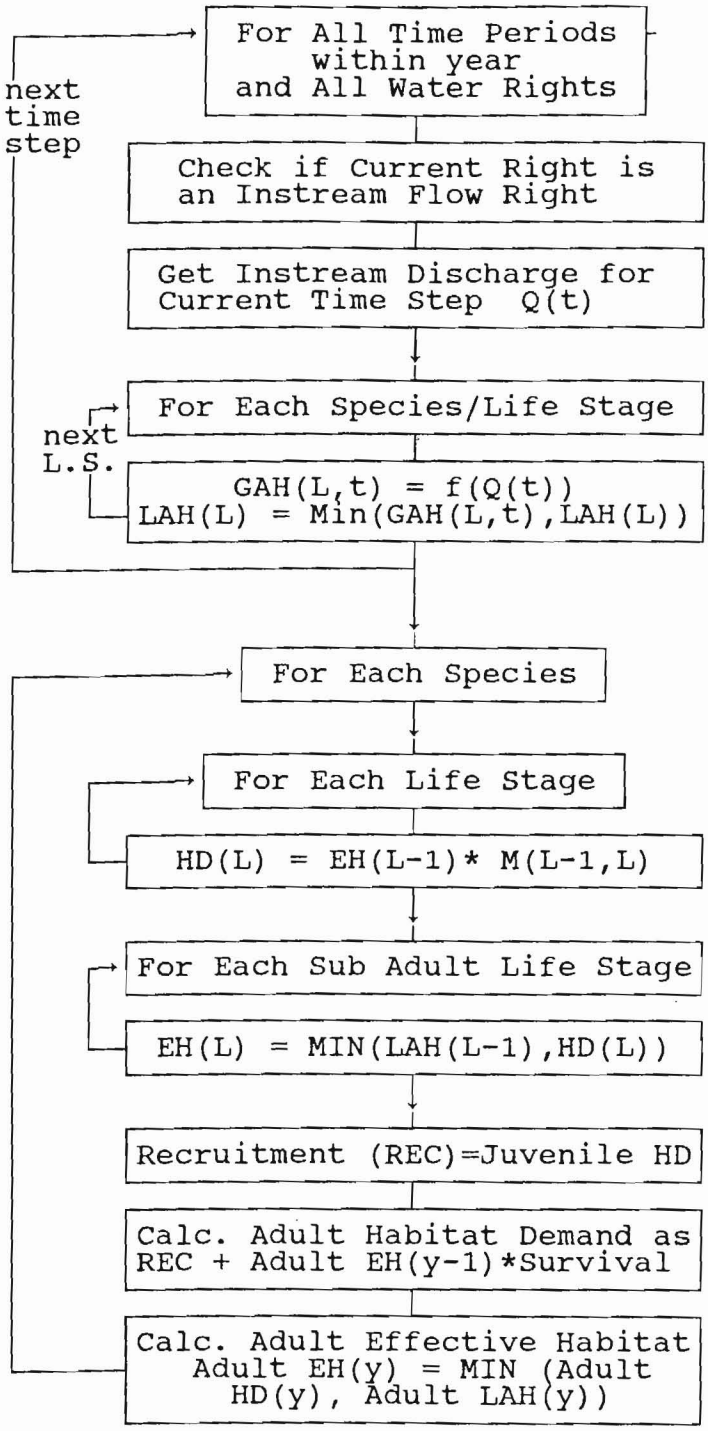
persist throughout the year. Thus, the GAH and LAH calculations are only performed for the periods each life stage is present.

For each life stage of each species, the Habitat demand is calculated using Equation 4.7. For the sub-adult life stages, effective habitat is calculated using Equation 4.8.

The adult population consists of older fish that survive from previous years and fish that have matured to the adult stage in the current year. The accumulation of the newly matured adults is called recruitment. The total adult habitat demand is the sum of recruitment and adult survival from the previous year. Adult effective habitat is then calculated using Equation 4.8. The effective habitat calculation algorithm is shown in Figure 5.6.

Decision Algorithm

The decision algorithm allocates water stored for instream flows to achieve population maintenance objectives. It is designed to use two optional decision schemes. Option 1 considers the population state at the beginning of each decision year and allocates instream water across the year on the basis of the state. Option 2 delivers available water to supply instream flow following a user specified pattern.



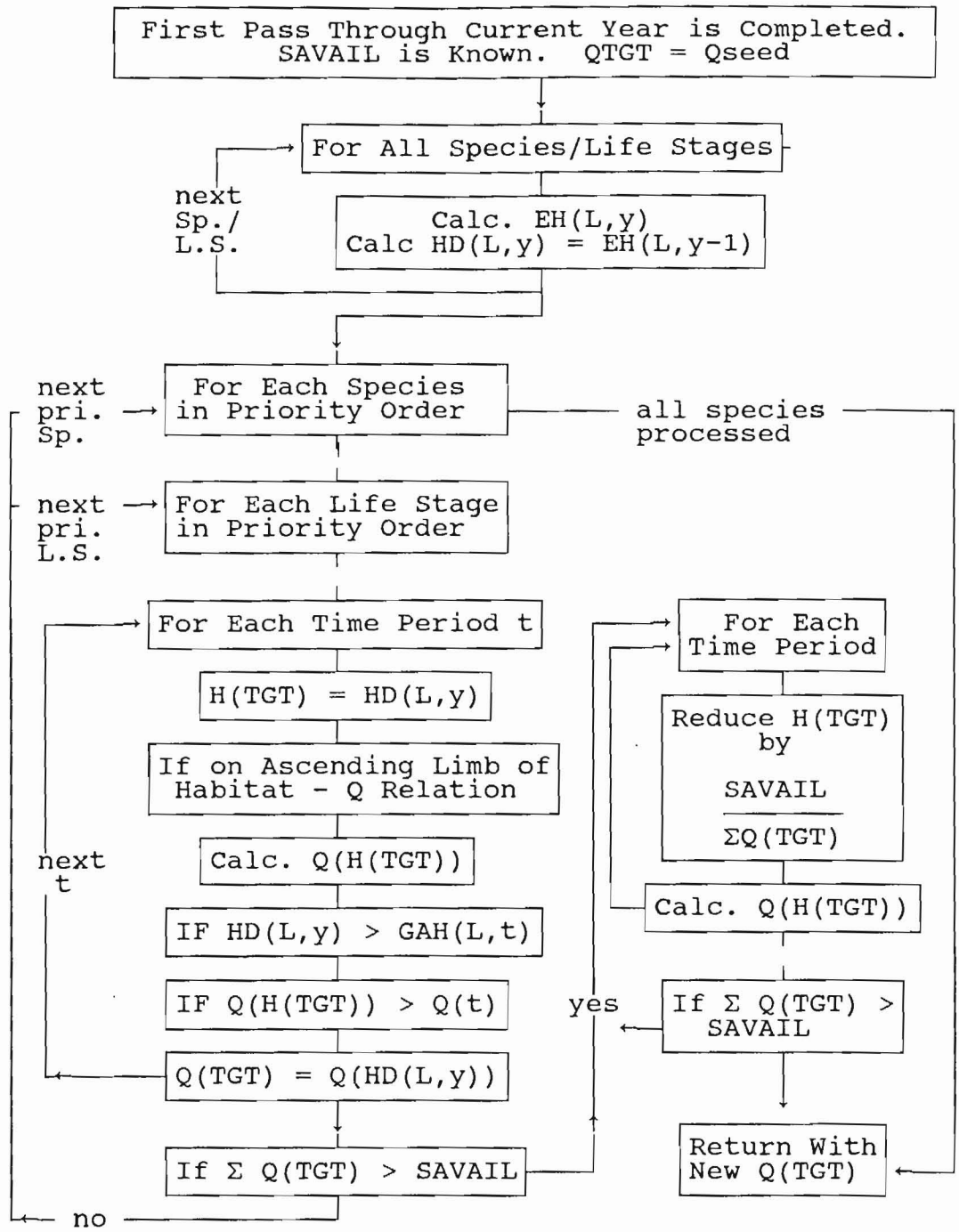
Where: t = model time step,
y = fish year, and
all other terms defined in Chapter 4.

Figure 5.6. Effective Habitat Calculation Algorithm

That pattern can be constant to imitate traditional instream flow rules. It also can be set to maximize within-year population potential (maximum LAH) based on knowledge of the habitat limits found in the stream.

Under option 1, the algorithm attempts to satisfy habitat demand (cf. Chapter 4) for each life stage of each species. Habitat demand for the highest priority life stage of the highest priority species is supplied first. It is followed by the other life stages and species in descending order of priority. The priorities are supplied by the user for each model run. If there is not enough water to meet the habitat demand for all life stages, the algorithm makes a proportional reduction in habitat deliveries. This reduction is applied to the lowest priority life stage to receive marginal amounts of additional instream flow. The resulting target discharges for each time period are used in the second pass through the year. The logic flow of the algorithm is summarized in Figure 5.7.

The algorithm shown in Figure 5.7 iterative solves the allocation problem shown in Equation 5.3 for each species. The constraints represent mass balance on the storage account, using only the ascending limb of the habitat - discharge relation, and avoiding reducing flows below those required by senior water rights. The allocation is solved in



Where: SAVAIL = water available in instream account,
t = within year time step,
y = fish year,
Qseed = user supplied algorithm starting value, and
Q(TGT) = vector of target instream flows for each t.

Figure 5.7. Storage Account Allocation Logic for Option 1

the order of descending species and life stage priority. This allows the user to direct the algorithm to consistently support the most limiting life stages.

$$\begin{aligned} &\min_{\ell,t} \left(HD_{\ell,t} - H_{\ell,t} \right) \\ &\text{S.T.} \\ &\sum Q(H_{\ell,t}) \leq SAVAIL \\ &\frac{\Delta H_{\ell,t}}{\Delta Q_t} > 0 \\ &Q(H_{\ell,t}) \geq Q_t \\ &Q_t \geq Q_{seed,t} \end{aligned} \qquad (5.3$$

Where:

$H_{\ell,t}$ = habitat for life stage ℓ at time t,

$HD_{\ell,t}$ = habitat demand for life stage ℓ in current year,

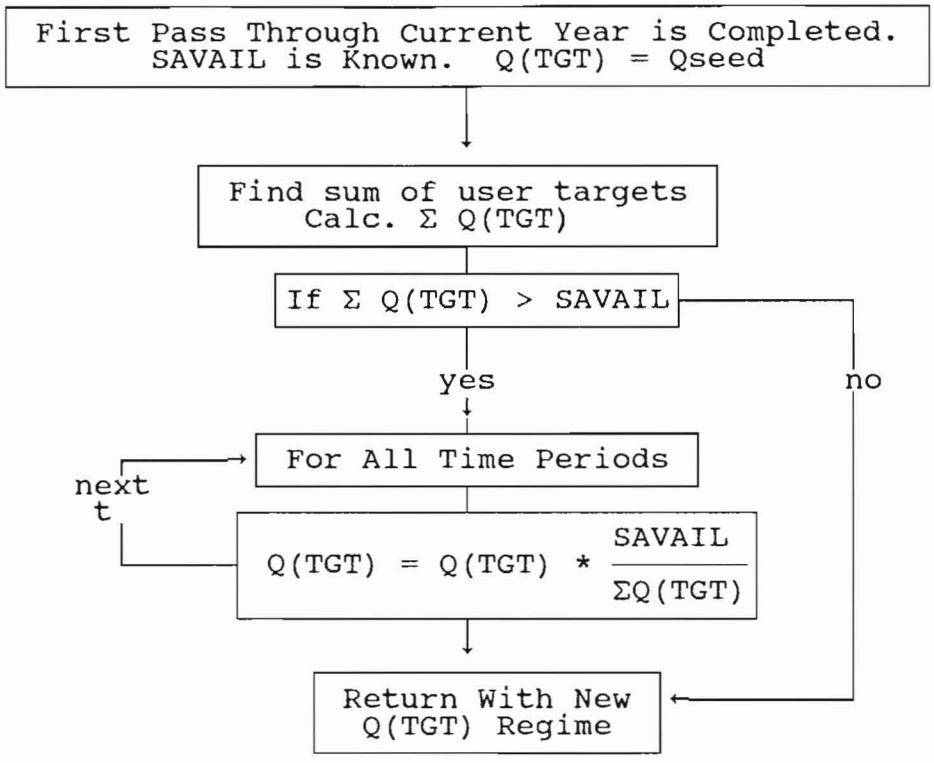
$Q(HD_{\ell,t})$ = discharge required to supply habitat $H_{\ell,t}$ or habitat demand $HD_{\ell,t}$,

Q_t = resulting target discharge for time t, and

$Q_{seed,t}$ = initial user supplied algorithm seed value.

Option 2 does not consider the preceding year population state. It simply attempts to allocate the available water among all life stages using a regime pattern set by the user. As shown in Figure 5.8, it begins with the base flow regime supplied by the user. If there is sufficient water to meet that regime the base pattern is used as the year's instream targets. When there is insufficient water, the base pattern

is proportionally reduced so the sum of the instream targets match the supply.



Where: All terms were previously defined.

Figure 5.7. Storage Account Allocation Logic for Option 2

Using the FORTRAN Model

Use of the model consists of defining the parameters for each study, calibrating to local conditions, executing the model and evaluating the results. The study planning process is an opportunity for the parties in an instream issue to work to understand the stream system as a whole. The impacts

and issues identified in Chapter 3 can be addressed by planning simulations of alternative system and operating rule configurations.

The calibration process must include effective habitat reservoir, and water right model parameters. The effective habitat multipliers should allow that model to replicate observed fish population events. The storage right hedging levels should be adjusted so model performance matches known operations. Finally the water right priorities, diversion timing, and volumes should be checked to ensure the local situation has been replicated to the maximum extent possible within the model's design.

Executing the model consists of three phases: setup and preparation of input, running the model, and checking the output for accuracy and consistency. Quality assurance is expected at each step. When a model run is judged successful, that is it accurately represents natural conditions and it is consistent with the input conditions, the output is passed to the parties in the issue for evaluation.

When evaluating the results users should look for the degree of impact of the project on environmental variables and of environmental constraints on the project. The ability of simulation models to help quantify or scale these impacts

is the basis for their appeal. Examples of the kinds of alternatives that can be evaluated are given in Chapter 8 where case study results are presented.

SPREADSHEET VERSION OF THE MODEL

The spreadsheet model is a smaller version of the main model. It is designed for interactive gaming with water storage, project deliveries and instream decisions. The spreadsheet format was selected due to the popularity and wide availability of microcomputers and spreadsheet software. These factors may enable this model to reach a wider audience than the larger Fortran version.

The spreadsheet model performs a monthly calculation of reservoir mass balance, water demand deliveries, storage account mass balance, instream flow deliveries and temperature conditioned effective habitat for two species. The reservoir mass balance includes provisions for spill when storage reaches reservoir capacity and for restrictions on releases when it reaches minimum pool. The operating algorithm supplies water to three demands until storage is exhausted. The user is expected to modify demands to avoid exhausting the supply.

The calculations cover a span of seventeen years. The year boundaries run from April to March to represent the

approximate fish year for trout in Colorado. Calculations of effective habitat are performed for all years. The mass balance calculations are performed from year 8 to 17. Thus a historical period is used to establish the initial fish population (effective habitat) conditions. Gaming with alternative project operations begins in year 8.

Demands are configured as shown in Figure 5.9. The three demands consist of diversions at locations 1 and 2 and instream flows between them. The location 1 demand is considered higher priority than the location 2 demand. Thus shortages are applied to the location 2 demand first. In the default configuration, all water delivered from the reservoir is supplied at location 1 and the demand at location 2 is zero. The default demand patterns can be derived from the project planning documents.

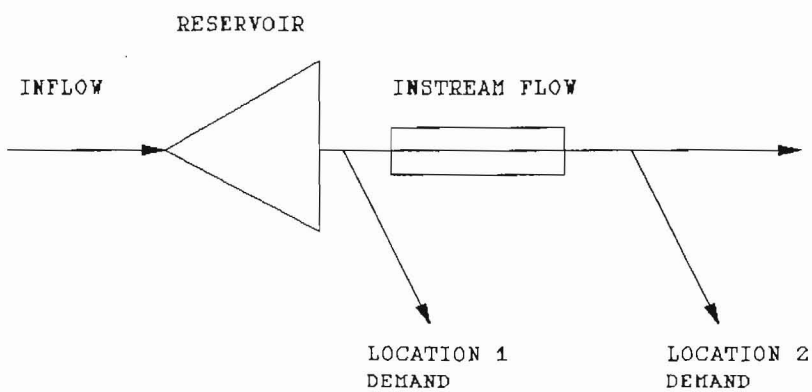


Figure 5.8. Water System Geometry Used in Spreadsheet

Water for instream flow is supplied from the instream storage account. The account is filled once per year and kept separate from the other water uses. The account is treated as a portion of the main reservoir. In contrast to the Fortran model, it has a limited carry-over capability and other users may use its storage when the account is not full.

The user supplies the instream account size and target instream flows in units of cubic ft. per second (cfs). The model converts those values to acre ft. (AF) and decrements the account for each month's flows. The instream flows are supplied from the storage account until it is exhausted. The user is expected to modify instream flows to avoid exhausting the account before the end of each fish year. It is possible for demands at locations 1 and 2 to exhaust all water in the reservoir except the instream storage account. Under those conditions, instream flows would be satisfied but diversions to location 1 would not. Diversions to location 2 will only be satisfied when they can be met by diverting instream flow.

The effective habitat time series is calculated from user supplied habitat - discharge relations and habitat multipliers for the river system being studied. Default values derived for the Dolores River are included in the spreadsheet. Interpolation of habitat values from the habitat - discharge relations is performed for each time period. The limiting available habitat (LAH) and effective

habitat (EH) calculations are performed for all life stages of brown and rainbow trout.

As with the large model, use of this model requires understanding of both water delivery contract requirements, reservoir operation constraints, water temperature effects on fish and fish population responses to discharge patterns. These issues cover a broad spectrum of disciplines. The model can serve as a tool to facilitate communication among the agencies and groups interested in an instream flow management issue. It can help each to realize what kind of information is needed by the others. For example, if water supply is not sufficient to meet the demands at location 1 or 2 what rules do the water managers use to reduce demand early in the year to avoid exhausting storage later. Similar questions must be asked of the fishery managers regarding the timing of water deliveries to best support the tailwater fish populations.

Following seven years of the historical flows used to establish the population state users may game with alternate system operations. From year 8 forward, anticipated values of inflow and water uses may be entered. The spreadsheet contains default values for initial storage in year 8. It also has defaults for inflows, water demands, and instream targets for years 8 to 17. Those defaults may be adjusted to represent different initial conditions or different reservoir

systems. The user games with the system by replacing the defaults with current year values beginning in year 8 and observing the results of those choices. Results are displayed as time series graphs of water system and effective habitat performance.

The gaming process requires the user to make the decisions for allocating water to the instream use. By running more than one consecutive year, ie. years 8 to 17, the value of carrying storage over to future years can be considered. An example "game" is given in Appendix 5.

DISCUSSION

Technical Contributions

The main technical contribution of this thesis is the model using habitat demand to manage stored water for instream flow needs. This development provides an analytical approach to efficient management of instream flows needs over the current decision year. With a forecast of habitat needs based on the population state, the timing and magnitude of instream flow deliveries can be accurately planned. The power of this development comes from its save instream flow water for use when it is most needed. In addition it can satisfy the reasonableness water law doctrines of many

states. It does so by allowing water to be used most efficiently to produce population benefits.

A second contribution is the concept of handling shortages by applying uniform reductions in habitat. When uniform reductions in instream discharge are applied across the year, habitat may be greatly reduced during critical periods. The uniform habitat reduction approach attempts to make no one part of the year more stressful for the fish population than any other. This also contributes to maintaining the highest population levels possible during periods of water scarcity.

Improving Communications

The models described in this chapter can be used to answer questions regarding instream account size, fishery benefits, and storage yield. These are issues commonly faced by planners of water resource use on one hand and operators of water resource projects on the other.

The two models presented here can address these questions by trial and error (gaming) simulations of various situations. In general, when the volume of storage assigned to instream flows is known, the models can address efficient use of that water. The strategy is to fix the size of the instream account and maximize the utility of its use. When

the instream account size is unknown and fish population or effective habitat objectives are known, the models can be used to address the sizing question. That strategy is to run either model several times over a range of storage account sizes. This allows construction of a trade-off array of instream benefits and yield for other project purposes. Decision makers can then select the storage account size that supports the desired population objective with an acceptable effect on project yield for other purposes.

The algorithms in the Fortran program address the efficiency of use question directly, but that model will be difficult for many people involved in instream decisions to use. The spreadsheet version does not contain the decision logic of the large model, but it is more accessible to a broad group of users.

Two uses for the spreadsheet are anticipated. The first is as an instructional tool for biologists to gain insight into water management problems. Engineers can also gain insight into the long term population effects of instream flow decisions. In this use past inflow and water demand patterns can be revisited to understand possible alternative instream flow strategies. Different account sizes can be tested to evaluate the trade offs between the amount of water set aside for instream flows and possible deliveries to other project water uses.

The second use is as a current year planning tool. In this use, the beginning of year conditions are supplied to the model and the instream flows for the current year are determined by gaming. By altering the outyear flow patterns, the range of outyear effective habitat conditions can be considered. The spreadsheet can potentially serve as a laboratory for testing and discussing alternative instream operation policies.

In either use, the ease of interactive gaming is expected to serve as communication tool between water managers and instream flow advocates. Instream flow policies can be roughly formulated using the spreadsheet and refined using the larger model. Once all parties have a basic understanding of system performance from gaming with the spreadsheet, it should be easier to work with or extend the larger model.

The next three chapters deal with a test case demonstrating the models. Chapter 6 describes the test project and Chapter 7 demonstrates various aspects of the effective habitat model. Chapter 8 contains the results of applying the Fortran model described in this chapter.

Chapter 6

DESCRIPTION OF CASE STUDY

The U.S. Bureau of Reclamation Dolores Project was chosen as the test case for this study for several reasons. Several data collection efforts by various organizations provided most of the data needed for this method. There was considerable interest on the part of private groups for maintaining and improving the tailwater fishery below McPhee Dam. Existing water rights under the appropriation doctrine are passed through project facilities. The Dolores Project provides irrigation water both to supplement those existing water rights and to irrigate new land. And, there is a high degree of interest on the part of the Bureau of Reclamation (Reclamation) in resolving conflicts between the fishery interests and Reclamation. These conflicts revolve around the timing and amount of instream flow for recreational and fishery maintenance purposes. Overall, these factors provided both the technical data and opportunity for using the method to improve communication among the interested parties.

DESCRIPTION OF PROJECT

The Dolores Project is located in the Dolores and San Juan River Basins in Southwestern Colorado. (See Figure 6.1) It stores and exports water from the Dolores River to 61,600

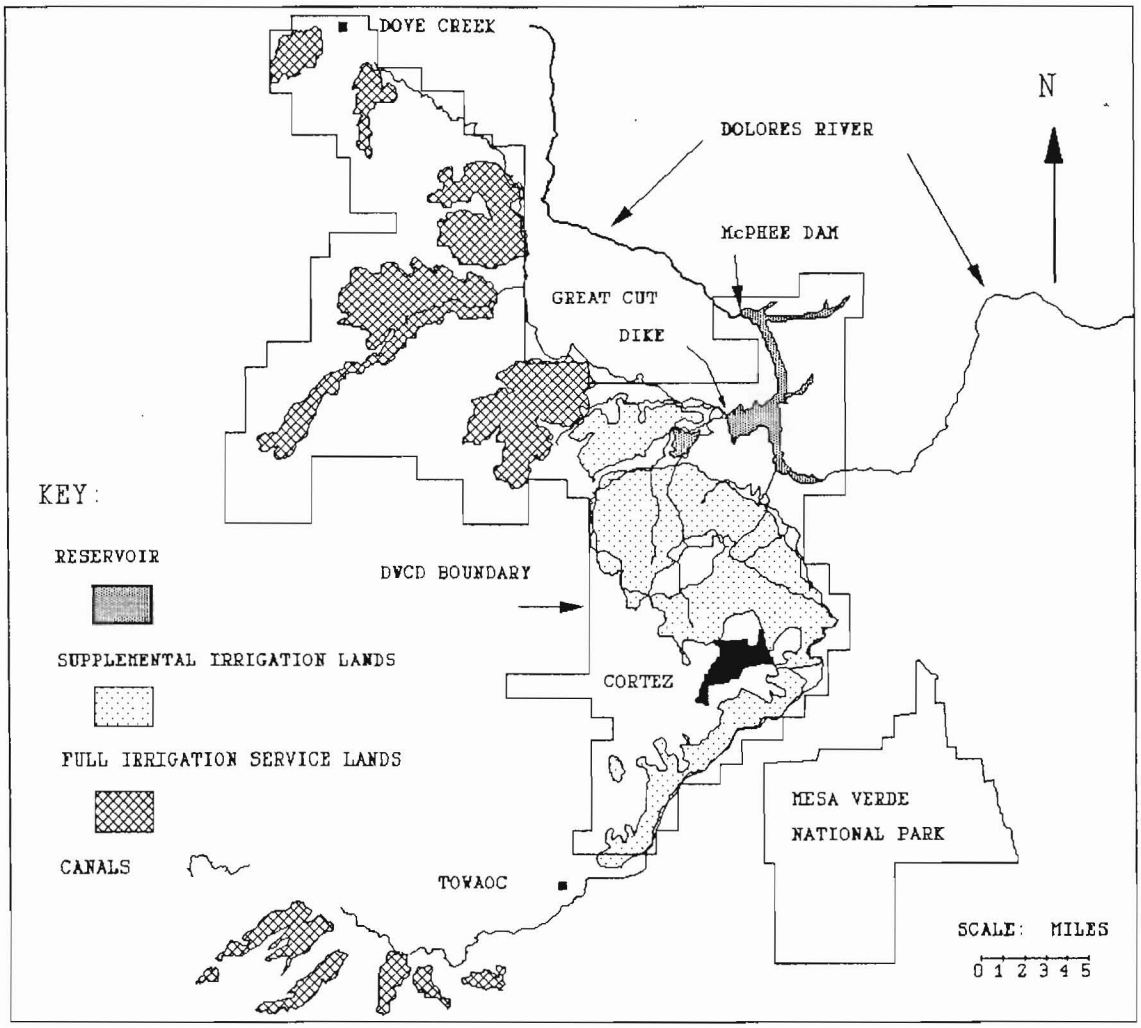


Figure 6.1 Map of Dolores Project Area

acres of land in the vicinity of Cortez, Colorado. The primary storage facility is McPhee Reservoir which has a capacity of 381,100 acre ft. and an active storage capacity of 229,200 acre ft. The storage capacity is sufficient to

totally control the river in dry years. All water developed by the Dolores Project is exported directly from the reservoir via the transbasin Dolores Tunnel and releases from the Great Cut Dike. Project deliveries are through a series of canals and pressure pipelines leading from the canals to various parts of the service area. (cf. Appendix 4 for a detailed description of the Dolores Project facilities.)

Impetus for the Dolores Project may have come from the severe drought of 1955-1956. In 1962 the Southwestern Water Conservation District filed for project water rights under the Colorado appropriation system. The rights were assigned priority dates of September 10, 1940. The Southwestern Water Conservation District transferred these rights to the Dolores Water Conservancy District in 1970. Project rights in the Dolores River total 625 cfs at various reservoir inlets and 757,800 acre feet for storage in McPhee Reservoir and Monument Creek Reservoir.

Initially the project followed the typical federal water project course of study, congressional authorization, funding, and construction. By 1970 the Dolores Water Conservancy District had been formed to contract for water deliveries from Reclamation. The planning and study process concluded in 1977 with the Definite Plan Report (DPR) (U.S. Bureau of Reclamation, 1977a).

Construction was delayed by two unrelated events. The project was placed on President Jimmy Carter's hit list for two months in 1977. After a series of hearings the project was removed from the list. The first construction contracts for the Dolores Project began in 1977. However, the failure of Teton Dam led to reevaluation of the McPhee Dam design. The redesign delayed the start of construction until 1980. McPhee Dam was completed in 1986; a small hydropower plant is currently being added. (Porter, Personal Communication, 1992)

The geometry of the Dolores Project induces direct conflict between diverted and instream uses. All project deliveries and the vast majority of preexisting water rights are diverted to the San Juan River basin. There are essentially no opportunities for complementary water uses between the agricultural, municipal and industrial water uses, and instream flows.

That conflict was exacerbated by a significant decrease in the fish population that occurred in 1990. In March 1990, Reclamation reduced the instream flows to dry year criteria levels. The dry year instream flow rates and rules for switching to them had been previously established in project planning documents. (U.S. Bureau of Reclamation, 1977a and 1977b) Instream flow advocates in the region, notably Trout Unlimited, criticized both the amount of flow to be released

under dry year criteria and the rules Reclamation uses to switch among various instream flow regimes.

One result of the dialogue between Reclamation, Trout Unlimited, the Colorado Division of Wildlife, and the U.S. Fish and Wildlife Service has been consideration of assigning a volume of storage in McPhee Reservoir as an instream flow account. These discussions included allowing that account to be drawn upon in consultation with the fishery interests. Thus, the questions of the size of an instream storage account and the best management regime using that stored are being raised about the Dolores Project. These questions can be addressed explicitly by the method developed here.

Water Rights

The earliest water rights for water from the Dolores River are dated May 31, 1879. The Montezuma Valley Irrigation Company (MVIC) holds the largest significant block of early water rights. Their rights total 1400 cfs. MVIC serves 37,500 acres of irrigated land in the center of the Dolores Project area. There are ten rights senior to the MVIC rights totaling 10.7 cfs and six rights senior to the project rights totalling 9.2 cfs. Appendix 3 describes Dolores River water rights and the arrangements made to contribute those rights to the project in exchange for project deliveries.

DEFINITE PLAN REPORT (DPR)

The Dolores Project Definite Plan Report (U.S. Bureau of Reclamation, 1977a and 1977b) is the final planning document prepared for the project. It contains designs, cost estimates, operation and maintenance requirements, water supply analysis, drainage analysis, economic and social assessment and financial analyses. The water supply analysis was performed using two operations simulation models developed by Reclamation. These models describe without project and with project operations of the system for a fixed period of hydrologic record. The period of record selected by Reclamation was 1928 to 1973. This period includes a severe drought that occurred in 1955 and 1956 and several years of very high runoff.

Definite Plan Report Projections

Simulation studies conducted in support of the Definite Plan Report show that it is possible to make full delivery to MVIC water rights for 26,300 acres of land. This 100% water delivery in all but two years over the period of record reflects the benefit MVIC received for contributing its water rights to the project. Even though MVIC rights have high priority, the river does not provide enough water for full deliveries in all years. So, MVIC gained certainty of delivery in trade for use of its water rights.

Project deliveries supplement the water MVIC would have received without the project. Thus, MVIC lands are called the supplemental service area. The DPR study shows 86.8% of the ideal irrigation requirement (about 130,300 acre-feet annually) can be achieved without the project. Project water deliveries of 13900 AF provide an additional 13.2%. So MVIC receives a total of 99.8% of ideal irrigation requirements over the 46 year study period. There are only 2 shortages and the maximum shortage is 5.1% in one yr.

The full service delivery area covers lands near the towns of Dove Creek and Towaoc. The average delivery to this area is 54,300 AF to Dove Creek and 22,900 to Towaoc respectively. This is about 98.3% of their ideal irrigation requirement. They experience shortages in 4 yrs, and the maximum shortage is 39.1%.

The instream flows described in the DPR are treated as fixed minimum flows that vary according to water supply. The instream flows were set at 20 and 50 cfs for dry and average years respectively. In wet years the minimum flow was to be maintained at 50 cfs, but controlled spring releases to avoid spills raised the annual average to 78 cfs. These levels, 20, 50 and 78 cfs, were included in Reclamation's contract with the Dolores Water Conservancy District (U.S. Bureau of Reclamation, 1977c). On page 28 of the DPR and page A-34 of the Dolores River Final Environmental Statement (U.S. Bureau

of Reclamation, 1977d) these minimum flows are described as adequate to maintain the fishery.

DOLORES PROJECT CONSTRUCTION AND OPERATION THROUGH 1991

McPhee Dam was constructed between 1980 and 1986. It began controlling streamflow in 1984. During the period from 1984 to 1989 Reclamation maintained the minimum instream flow at 78 cfs or greater for all but short test periods. The 1986 to 1991 release hydrograph is shown in Figure 6.2. 1990 was a low runoff year and in March of 1990 Reclamation reduced the instream release to 20 cfs. This change based on previously established runoff and forecast reservoir content criteria. Protests from the local chapter of Trout Unlimited led to reevaluation of the instream flow criteria and an interim increase in the amount of water allocated to instream uses. The immediate result was an increase in instream release from 20 cfs to 50 cfs in mid June 1990. Sufficient water was available in 1991 to allow a controlled spring release for river rafting and to maintain summer discharges at 70 cfs.

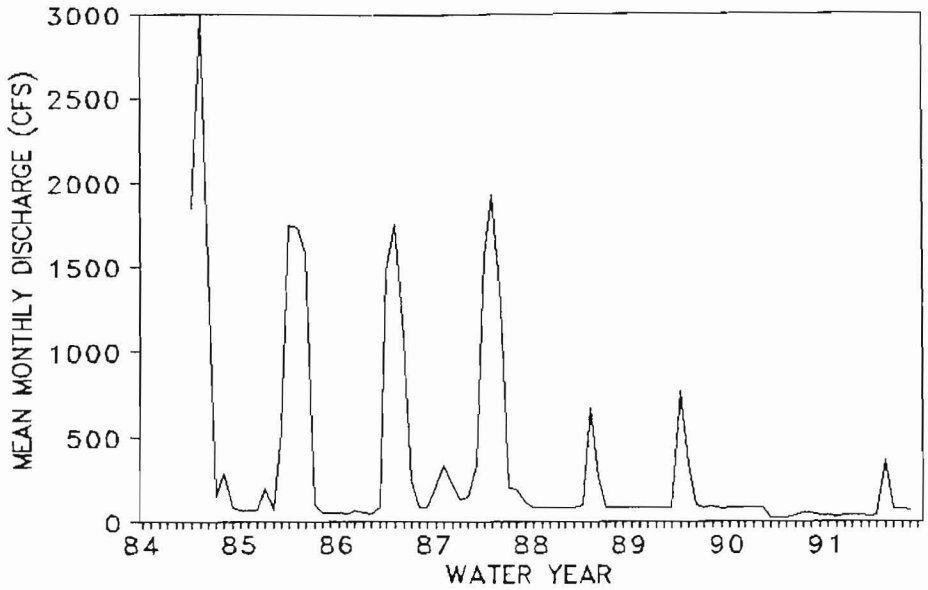


Figure 6.2. McPhee Dam Releases to Dolores River 1986 to 1990.

DESCRIPTION OF THE DOLORES RIVER DOWNSTREAM FROM MCPHEE DAM

For the twelve miles downstream of McPhee Dam the Dolores River has a wide, nearly rectangular, cobble lined channel. There are few deep holes and the meander pools are shallow. At low discharge the river is generally less than one foot deep and 60 to 120 ft wide.

Some channel improvements have been added to enrich the fish habitat. These consist of two areas where artificial point bars have been constructed using large boulders and filling behind the boulders. This forces the river into more of a meandering pattern. This pattern produces scour pools and a wider variety of depth and velocity conditions than a trapezoidal channel. At another location, several large

boulders have been placed in the middle of the stream to simulate colluvial deposits.

Several factors contribute to marked warming of the water in the first 12 miles below the dam. From the dam to Bradfield Bridge the direction of flow is west north west (azimuth -60 degrees) so there is little shading from the canyon walls. The channel is also wide and shallow. After the first mile below the dam the gradient flattens, so residence times increase. There is little bank vegetation because cattle were allowed to trample the stream banks for several years prior to construction of the dam. Reclamation has purchased the riparian land and restricted grazing so the bank vegetation is becoming reestablished.

The gravel - cobble bed of the river is periodically covered with fine sediment from ephemeral tributaries. This material is primarily silt and can cover the bed to a depth of 2 to 4 inches (5 to 10 cm). The material arrives in the stream as the result of thunderstorm runoff. Due to the stochastic nature of thunderstorm activity, the silt load varies widely. Observation by biologists working on the river indicate that flows in excess of 500 cfs are needed to move significant amounts of the fine material and much higher flows are needed to adequately flush fines from among the larger substrate.

Location of the Instream Management Area

The instream flows released from McPhee Reservoir are intended to maintain a fishery in the tailwater area. The 12 miles from Mcphee Dam to Bradfield Bridge is being managed to support a trout fishery. This area is shown in Figure 6.3.

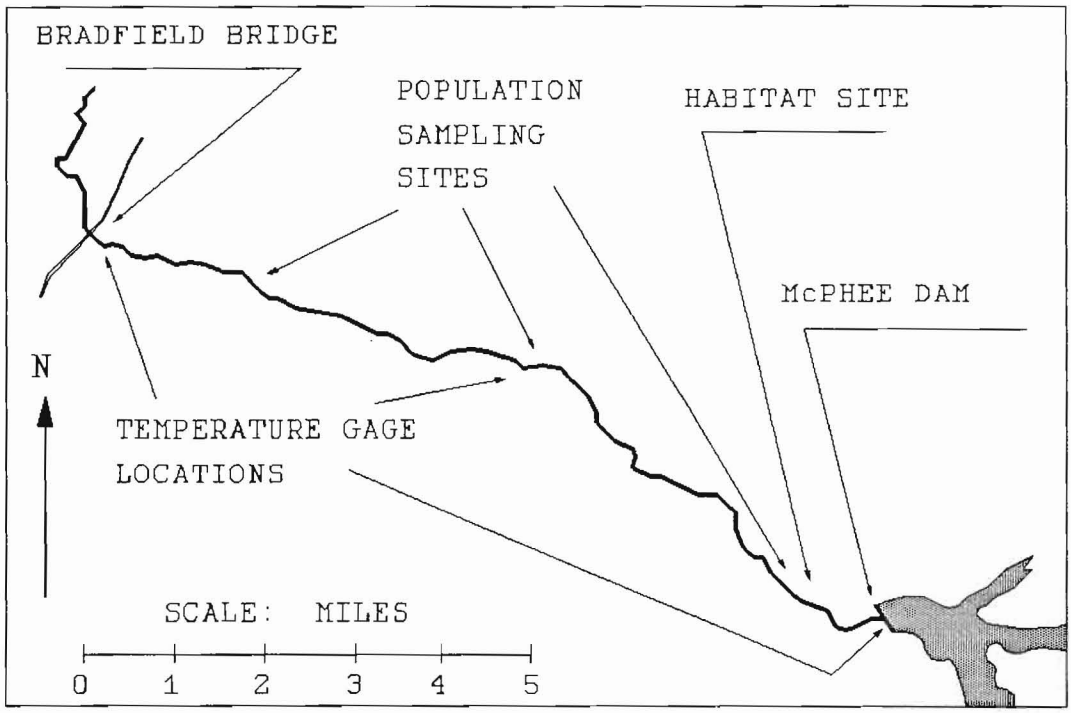


Figure 6.3. Fishery Maintenance Section Below McPhee Dam Showing Various Study Locations

Description of the IFIM Site

The Colorado Division of Wildlife (DOW) provided the data from a PHABSIM analysis. That study site is located about 1/2 mi below McPhee Dam. The study site has a slightly

steeper gradient than most of stream so it may be somewhat unrepresentative of the entire distance from the dam to Bradfield Bridge. The hydraulic measurements were taken at 405 cfs. Other PHABSIM sites have been measured on the river at low discharges less than 80 cfs by Reclamation. However, these low discharges restrict the useful range of backwater model extrapolation so the one site was used to represent the entire 12 mile section of river.

Examination of the data set showed that there were problems with the original hydraulic and habitat simulations. One of the channel improvements was conducted at the same location. Since the channel was altered it was not possible to obtain additional measurements to clarify data quality issues. One of the most difficult challenges in using any model is extracting meaningful information from questionable data. Appendix 2 contains a record of the problems encountered with this data set and their resolution.

Dolores River Habitat - Discharge Relations

The final habitat - discharge relations for brown trout (Salmo trutta) and rainbow trout (Oncorhynchus mykiss) are shown in Figures 6.4 and 6.5. Several model calibration approaches were used to resolve the data problems. A sensitivity analysis showed the habitat - discharge relations

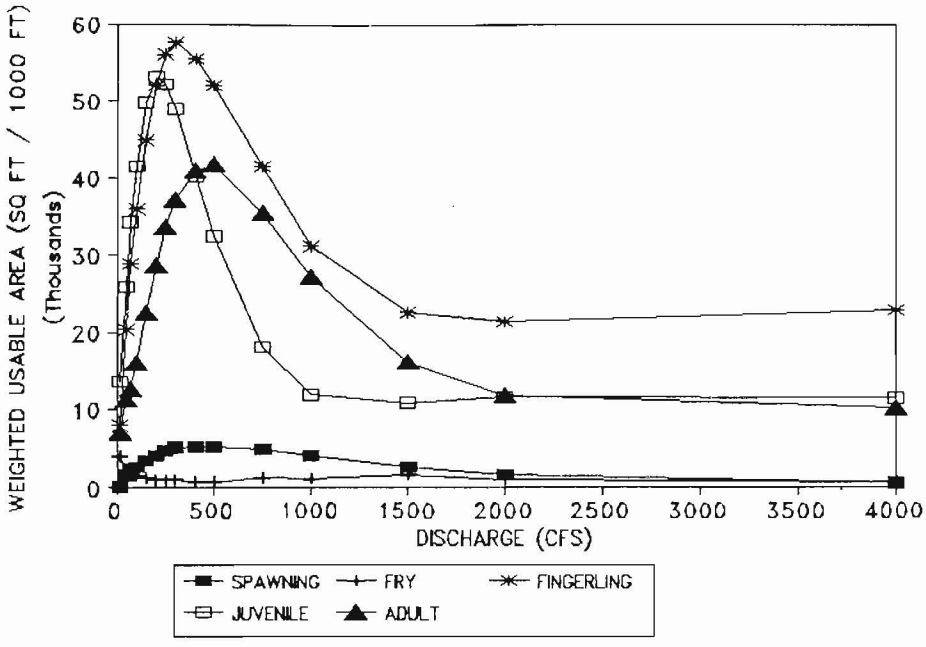


Figure 6.4. Final Habitat - Discharge Relation for Brown Trout

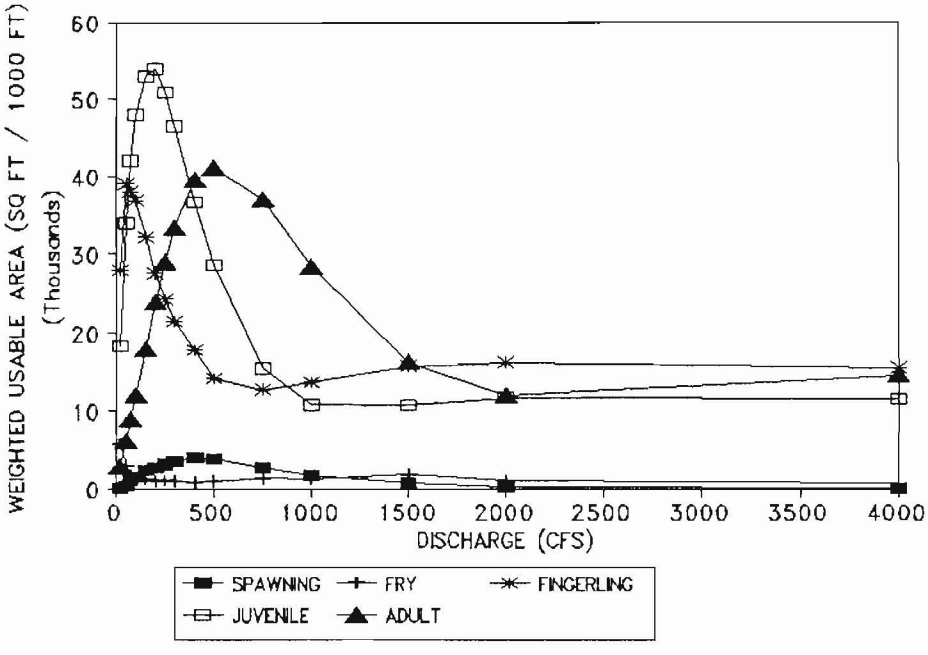


Figure 6.5. Final Habitat - Discharge Relation for Rainbow Trout

to be relatively insensitive to hydraulic data and simulation errors.

WATER TEMPERATURE MEASUREMENTS AND HABITAT EFFECTS

Reclamation has conducted a water temperature sampling program since closure of the dam. Temperatures are recorded at the dam, a point 6.2 river miles from the dam, and at Bradfield Bridge, 12.2 miles from the dam. These measurements are continuous over each period of sampling. However, sampling periods have varied from year to year. The three sampling locations are sufficiently separated to allow approximation of a longitudinal temperature profile by curve fitting techniques. The sampling periods for each location are shown in Table 6.1. An example of a longitudinal temperature profile is shown in Figure 6.6.

Table 6.1. Temperature Sampling Periods

Location	Period					Year
McPhee Dam Outlet	July	1	to	October	2	1987
	July	13	to	September	15	1988
	March	5	to	December	31	1990
	January	1	to	July	3	1991
Mid Point	May	27	to	October	2	1986
6.2 mi. from dam	June	30	to	October	2	1987
	July	15	to	August	24	1988
	March	6	to	December	31	1990
	January	1	to	July	17	1991
Bradfield Bridge	May	28	to	July	28	1986
12.1 mi. from dam	July	1	to	September	30	1987
	July	13	to	September	15	1988
	March	23	to	December	31	1990
	January	1	to	July	25	1991

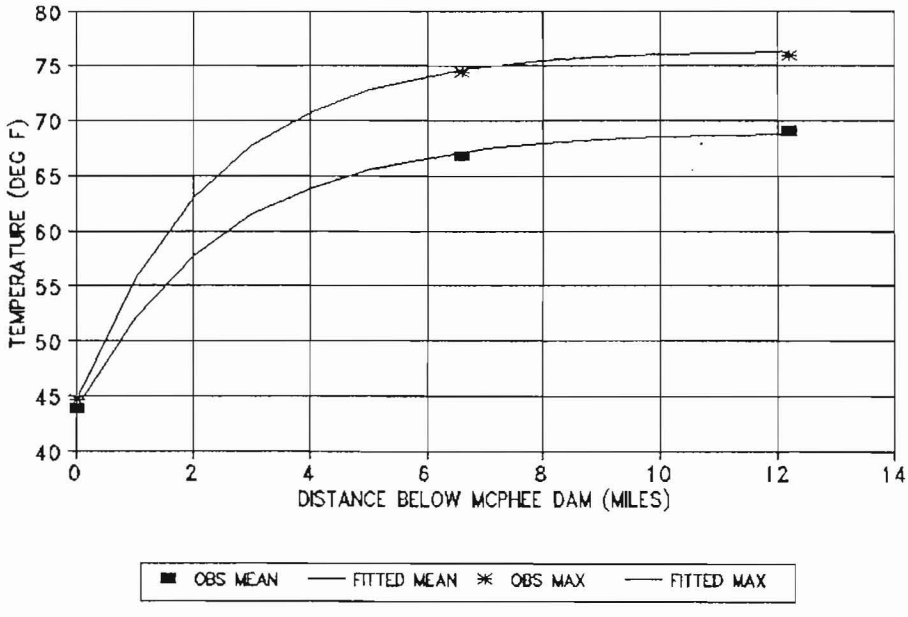


Figure 6.6 Temperature Profiles for June 8, 1990.

Several fishery biologists familiar with the Dolores River were consulted regarding the effects of water temperatures. They provided three possible temperature suitability relations for adult trout of both species. Those relations are summarized in the Figure 6.5. The line labeled

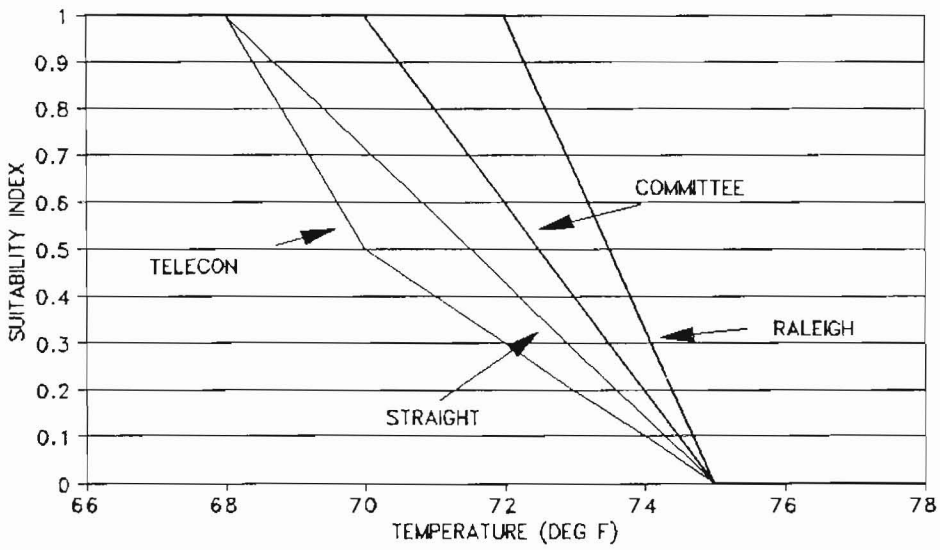


Figure 6.7. Alternative Temperature Suitability Index Relations for Adult Trout in the Dolores River

COMMITTEE is from the Dolores River Biological Advisory Committee. The RALEIGH line is from Raleigh et al. (1986). The line labeled TELECON was discussed in a conference call with biologists from the Forest Service, Division of Wildlife, and Bureau of Reclamation. The line labeled STRAIGHT was added to indicate that the uncertainty in defining where inflections in the curve might occur may not be significant. There is some difference in the temperature for the onset of reduced suitability. However, there is agreement in the general shape and location of the point of

zero suitability. Particularly, all suitability relations show temperatures above 75 Degrees Fahrenheit render the habitat totally unusable.

The committee's temperature suitability relation was used to derive temperature suitability factors for trout adults for the entire 12 miles of river. The Raleigh et al. curves were selected as the best estimate of the temperature effects for non-adult life stages.

Total temperature conditioned habitat was calculated by fitting curves to the mean and maximum temperatures for one extreme day at 20 cfs and one at 50 cfs. Those days were June 8, 1990 and July 2, 1990. The resulting profiles are the smooth lines shown in Figure 6.6. The smooth profiles were sampled to obtain the water temperature for each mile below the dam. These samples yielded the temperature suitability for each mile and an average suitability for the entire 12 miles. The composite sample yielded a total tailwater temperature suitability for each life stage for 20 cfs and 50 cfs. The temperature record did not indicate significant temperature problems had occurred when the discharge was 78 cfs or greater so suitability factors were calculated for the two low discharges only.

Any summer month was assumed to have a risk of sufficiently warm weather conditions to raise water

temperatures into the ranges observed on these two days. High temperatures can exert the reduced suitability effects shown in Figure 6.5 in only two hours. Thus, any one day in a month that is hot enough will cause the habitat suitability for that month to be similarly reduced. High temperature effects on habitat suitability were considered for the months of June to August. All other months did not have temperature suitability problems.

The calculated temperatures and composite temperature suitability factors are shown in Table 6.2. The temperature record did not indicate significant temperature problems occurred when the discharge was 78 cfs or greater so suitability factors were calculated for the two low discharges only. The Raleigh et al. (1982 and 1986) references indicate temperature suitability values for juveniles were based on sketchy data. Since the juvenile values were much higher than fry or adult values, an average of the fry and adult values was used to approximate the juvenile factors. These temperature suitability factors are used to derive the final habitat - discharge relations used in the Dolores River Analysis.

Table 6.2. Calculation of Composite Temperature Suitability Factors

June 8, 1990 Discharge = 20 cfs

Mile	Observed Temperature Mean	Observed Temperature Max.	Calculated Temperature Mean	Calculated Temperature Max.	Temperature Suitability Factors Brown Trout Adult	Brown Trout Juv.	Brown Trout Fry	Rainbow Trout Adult	Rainbow Trout Juv.	Rainbow Trout Fry
0	43.9	44.7	43.1	44.7	1.	1.	1.	1.	1.	1.
1			52.1	55.8	1.	1.	1.	1.	1.	1.
2			57.7	63.0	1.	1.	0.69	1.	1.	1.
3			61.4	67.7	1.	1.	0.33	1.	1.	0.59
4			63.9	70.7	0.86	1.	0.10	0.86	1.	0.77
5			65.5	72.7	0.46	1.	0.	0.46	0.94	0.52
6.6	66.8	74.4	67.1	74.5	0.09	1.	0.	0.09	0.79	0.30
7			67.4	74.8	0.03	1.	0.	0.03	0.76	0.26
8			67.9	75.4	0.	0.90	0.	0.	0.72	0.20
9			68.2	75.7	0.	0.82	0.	0.	0.69	0.15
10			68.4	76.0	0.	0.76	0.	0.	0.67	0.13
11			68.6	76.1	0.	0.72	0.	0.	0.66	0.11
12	69.	75.9	68.7	76.2	0.	0.69	0.	0.	0.65	0.09
Composite Factor					0.418	0.915	0.24	0.418	0.836	0.471
Juvenile Composite Used						0.329			0.445	

July 2, 1990 Discharge = 50 cfs

Mile	Observed Temperature Mean	Observed Temperature Max.	Calculated Temperature Mean	Calculated Temperature Max.	Temperature Suitability Factors Brown Trout Adult	Brown Trout Juv.	Brown Trout Fry	Rainbow Trout Adult	Rainbow Trout Juv.	Rainbow Trout Fry
0	44.6	44.6	44.6	44.6	1.	1.	1.	1.	1.	1.
1			48.2	52.8	1.	1.	1.	1.	1.	1.
2			51.4	58.8	1.	1.	1.	1.	1.	1.
3			54.3	63.3	1.	1.	0.67	1.	1.	1.
4			56.8	66.6	1.	1.	0.41	1.	1.	0.89
5			59.0	69.1	1.	1.	0.23	1.	1.	0.20
6.6	62.	71.8	62.1	71.8	0.65	1.	0.02	0.65	1.	0.64
7			62.8	72.2	0.55	1.	0.	0.55	0.98	0.58
8			64.4	73.2	0.35	1.	0.	0.35	0.90	0.46
9			65.7	74.0	0.20	1.	0.	0.20	0.84	0.37
10			67.0	74.5	0.09	1.	0.	0.09	0.79	0.30
11			68.1	74.9	0.01	1.	0.	0.01	0.76	0.25
12	69.3	75.	69.2	75.3	0.	0.93	0.	0.	0.73	0.21
Composite Factor					0.605	0.994	0.333	0.605	0.922	0.607
Juvenile Composite Used						0.469			0.606	

FISH POPULATIONS IN THE DOLORES RIVER

At closure there was no significant population of trout in this section of the river. The Colorado Division of Wildlife (DOW) introduced brown trout, rainbow trout and greenback cutthroat trout by stocking. Since closure and filling of McPhee Reservoir, trout populations in the tailwater have been maintained by a combination of natural reproduction and stocking.

Brown and rainbow trout numbers biomass increased until 1990. In 1990 however, the brown and rainbow trout biomass decreased as much as 76% to 89% (Nehring, 1991). Table 6.3. summarizes the biomass and numbers of the two species in the river since 1984. Biomass reflects both the size and numbers of fish.

The greenback cutthroat were not found after summer of 1990. Also, reliable SI curves for this species were not available. Considering these factors, the species was omitted from this analysis.

The DOW management objective for this portion of the Dolores River is to produce a trophy fishery. The current fishing regulations for the area allow catch and release fishing. Thus the emphasis is on a stable population of larger fish that are a challenge to the angler.

Table 6.3. Dolores River (below McPhee Dam) Seber-LeCren Two Pass Removal Trout Population and Biomass Estimates for All Trout ≥ 20 cm (Two Size Classes), 1987 - 1991 *

Species (size cm)	Oct. 1988		Sept. 1989		Oct. 1990	
N/Ha	Kg/Ha	N/Ha	Kg/Ha	N/Ha	Kg/Ha	
IFIM Site (3B-20 - River Mile 0.5)						
Brown ≥40	0	0.0	2	0.9	9	5.8
Brown ≥20 & ≤40	52	12.1	28	7.1	47	11.8
Rainbow ≥40	5	5.5	22	20.2	34	32.8
Rbw. ≥20 & ≤40	21	7.3	33	14.3	17	3.9
Ferris Canyon Site (3B-15 - River Mile 6)						
Brown ≥40	11	8.1	29	20.6	29	20.9
Brown ≥20 & ≤40	90	25.2	96	24.9	58	12.8
Rainbow ≥40	13	10.8	21	14.7	20	16.1
Rbw. ≥20 & ≤40	44	15.9	53	13.9	30	6.8
Rock Stockpile Site (3B-10 - River Mile 10)						
Brown ≥40	7	4.3	4	1.9	0	0.0
Brown ≥20 & ≤40	144	31.3	88	14.4	78	12.7
Rainbow ≥40	6	5.1	4	3.4	2	2.0
Rbw. ≥20 & ≤40	12	4.6	58	10.0	49	5.9

Species (size cm)	April 1991		Oct. 1991	
N/Ha	Kg/Ha	N/Ha	Kg/Ha	
IFIM Site (3B-20 - River Mile 0.5)				
Brown ≥40	7	4.6	0	0
Brown ≥20 & ≤40	14	1.9	12	1.8
Rainbow ≥40	22	17.2	15	12.9
Rbw. ≥20 & ≤40	16	3.4	20	4.8
Ferris Canyon Site (3B-15 - River Mile 6)				
Brown ≥40	18	14.7	5	3.1
Brown ≥20 & ≤40	23	4.0	66	12.6
Rainbow ≥40	5	4.2	7	5.3
Rbw. ≥20 & ≤40	5	1.7	17	5.4
Rock Stockpile Site (3B-10 - River Mile 10)				
Brown ≥40	2	1.6	2	1.5
Brown ≥20 & ≤40	25	3.5	51	6.2
Rainbow ≥40	10	8.4	2	1.4
Rbw. ≥20 & ≤40	15	1.7	14	3.2

* Reproduced from Nehring (1991)

DISCUSSION

Technical Contribution

Two example applications of the existing IFIM models are developed in this chapter and Appendix 2. They deal with data difficulties or unique situations that may be encountered when using IFIM. The procedures used to deal with these situations documented here can serve as guidance for IFIM practitioners. Milhous et al. (1989) discuss the effects of using different hydraulic model options. Milhous (personal communication, 1992) believes no comparison of the sensitivity of hydraulic modeling choices and SI index choices such as given in Appendix 2 has been published. The approach to developing composite temperature suitability factors for a river segment presented in this chapter is also new. It expands the range of approaches given by Bartholow (1989). In large river systems with a variety of data density and quality. This approach could be applied over homogenous segments to simplify the task of describing habitat quality. This example suggests approaches to temperature measurement and monitoring that can be adapted to other studies.

Possibly Avoided Conflicts

The Dolores Project was selected as the test case because it contained several important elements. It had most of the basic data needed to drive the models developed here. There was a high level of interest in resolving a conflict over instream flow issues. These factors provided fertile ground for developing and testing the concepts of this thesis because the absence of an analytical method in the planning phase led to a problematic instream flow regime. The tools developed here could have contributed to a better understanding of fish population needs and possibly resulted in different instream flow rules.

If fish population and instream flow management models such as the suite of models developed here had been available in 1970's the current instream flow conflict may not have arisen. When the Definite Plan Report was written, the tools used and developed in this thesis did not exist. The Instream Flow Incremental Methodology team was being assembled and the PHABSIM tools were just being developed. In the absence of these analytical techniques, instream flow values were determined from simpler techniques and professional judgement. In a political climate that demanded strong factual support for any non-agricultural use of water, lack of an easily understood analytical approach made it difficult for instream advocates to present a strong case.

Had the method developed here been available, both the amount and timing of instream flows could have been negotiated on the basis analytical results.

The current dialog between Reclamation, Trout Unlimited, the Colorado Division of Wildlife, and others is revisiting the instream flow management issue for the Dolores River. The IFIM tools are being used to support those discussions. As of this writing, negotiations are proceeding toward establishing an instream storage account in the range of 34,500 to 36,500 AF (Carder, personal communication, 1992). The analytical method developed here will be used to look at management strategies for that account.

Chapter 7

HABITAT MODEL RESULTS

This chapter presents habitat model results, an alternative approach for selecting SI curves for the PHABSIM model, effective habitat time series parameters and calibration steps taken for the Dolores River. The small number of fish population observations (five) and recent stocking of both brown and rainbow trout made it necessary to modify the effective habitat model procedures. The effective habitat model was extended to accommodate stocking effects. The effective habitat model calibration and its performance for a natural flow time series are also presented.

HABITAT - DISCHARGE RELATIONS

Habitat - discharge relations are a critical part of the overall method developed in this study. The habitat - discharge relations for the Dolores River were presented in Chapter 6. The process used to derive them is covered in Appendix 2. In that derivation, the habitat available to juvenile and adult trout at high discharges was assumed to be

greater than that available at very low discharges. This assumption was used to select the juvenile and adult suitability of use index (SI) curves reported in Appendix 2.

The interplay of the habitat - discharge relation and the effective habitat time series allows an added means of selecting SI curves. Using the effective habitat time series with parameters approximated from the literature or derived from knowledge of specific systems it is possible to perform a bounding analysis that can further support or reject use of particular SI curves. The procedure for doing so is summarized in the following section.

USE OF THE EFFECTIVE HABITAT TIME SERIES TO SELECT SI CURVES

This example begins with habitat - discharge relations derived from the Raleigh, et al. (1986) SI curves. The habitat multipliers derived for the S. Platte River example in Chapter 4 were assumed to be an acceptable approximation for the Dolores River. The discharge time series from the Definite Plan Report (U.S. Bureau of Reclamation, 1977b) was used as the flow time series. The effective habitat time series was calculated from those flows. The steps in this process and the conclusion reached are described below.

The effective habitat calibration procedure for the S. Platte River uses four life stages. DOW research biologist R. B. Nehring advised subdividing the fry life stage into two size groups based on susceptibility to velocity. These are the fry and fingerling life stages. Nehring provided SI curves for both size groups.

As described in Chapter 4, habitat multipliers between life stages depend on density of habitat use and mortality between life stages. Since the "fry" life stage was subdivided into two groups, it was necessary to allocate mortality effects between the two life stages. Sixty percent (60%) of the mortality was assigned to the smaller fry and 40% to the larger fingerlings. There is no empirical data to support this division. The smaller fish are more susceptible to high velocities so they were assumed to have higher mortality.

Fifty-four years of simulated stream flows were provided by Reclamation based on the minimum flow criteria used in the Definite plan Report (Powers, 1991). The limiting available habitat (LAH) was calculated for the period 1928 to 1981. Initial conditions for the effective habitat time series were set to one-half of the average LAH for each life stage. The effective habitat time series for the period 1948 - 1967 was then calculated to evaluate the habitat - discharge relations derived from different SI curves.

The adult LAH and effective habitat (EH) for brown trout are shown in Figure 7.1. Note the effective habitat values are limited in some years that have high spring releases (identified by arrows). Effective habitat rises above those

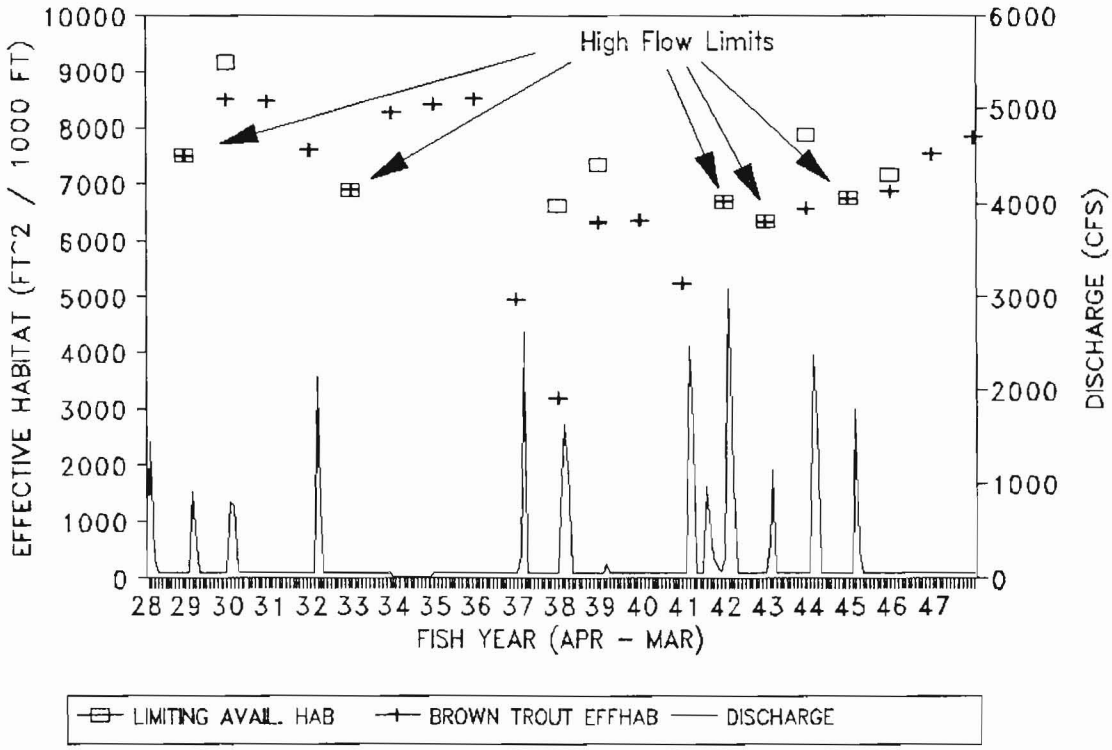


Figure 7.1. Effective Habitat: Original Habitat-Discharge Relation

low limiting values in years of constant low discharge. This is contrary to the experience reported by Nehring (1991) where the populations of brown and rainbow trout adults declined during a low flow year. The difficulty is due to the shape of the habitat - discharge relation. This observation was the initial motivation for evaluating the Raleigh SI curves.

That evaluation led to the analysis of the habitat - discharge relations reported in Appendix 2. That appendix concludes that use of newer SI curves results in a more realistic habitat - discharge relation for the larger life stages of brown and rainbow trout.

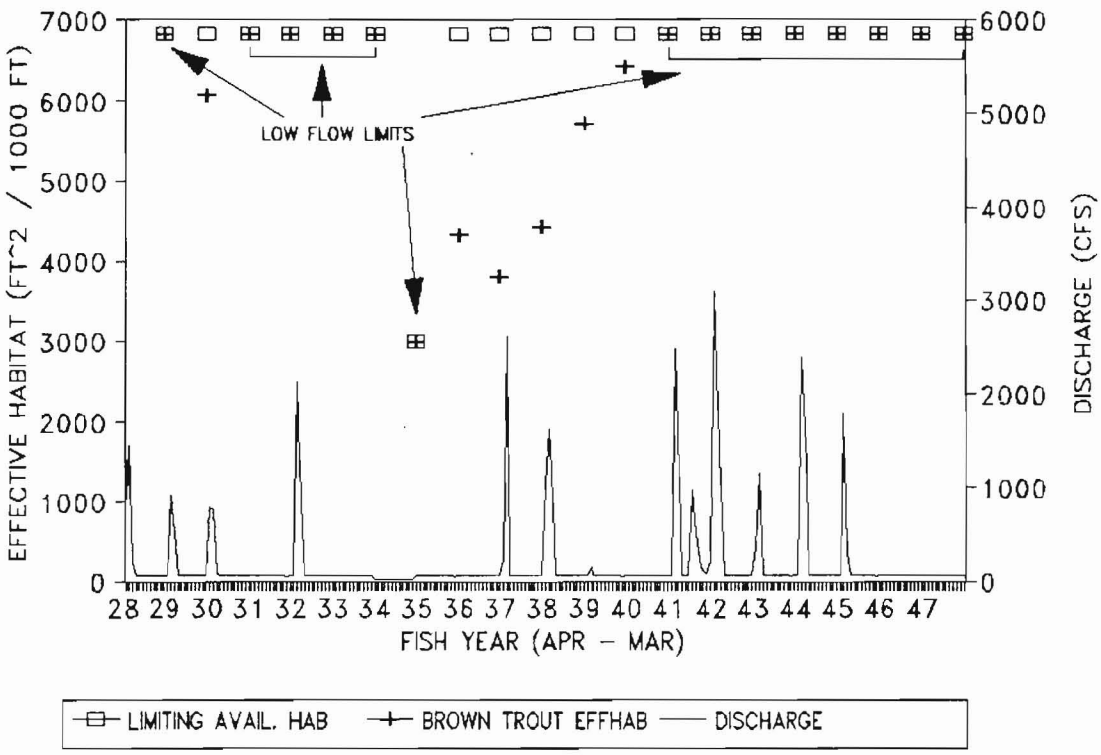


Figure 7.2. Effective Habitat: With New Habitat Discharge Relation

Figure 7.2. shows the EH and LAH traces for brown trout adults when the newer South Platte SI curves are used to generate the habitat - discharge relations. With the S. Platte criteria the yearly limiting available adult habitat is nearly constant. This is due to lower WUA at discharges ranging from 50 to 100 cfs and a fixed minimum discharge

rule. Adult LAH at 50 cfs limits adult EH in several years. The most severe limit is in fish year 1935 when the discharge is restricted to 20 cfs. These low flow year limits are more consistent with Nehring's observations. This example suggests that the effective habitat time series can show possible problems with habitat - discharge relations. It can help test the validity of alternative SI curves in each stream to be studied.

THE EFFECTIVE HABITAT TIME SERIES FOR THE DOLORES RIVER

The effective habitat model calibration technique introduced in Chapter 4 assumes a stable population and flow regime. Unfortunately neither of these conditions were met in the Dolores River. Little data regarding the pre-project trout population in the reach below McPhee Dam is available. However, it is unlikely that there was a naturally sustained population of either brown or rainbow trout because of extensive diversion of the river to agriculture.

The post-project flows represent a newly introduced, managed regime that is a marked change from pre-project conditions. While stocking of the trout species was necessary to initiate the respective populations, the stocking program produced unnatural changes in the population. The calibration technique assumes the fish

population is in a dynamic equilibrium with its environment. In the absence of the needed equilibrium conditions, a judgmental calibration was performed. The habitat multipliers from the South Platte River were used to initiate the process. Adjustments to the multipliers were made to cause the adult effective habitat to mimic the pattern of observed numbers for both trout species.

Adapting the Model and Calibration Procedure for Stocking

The calibration procedure developed in Chapter 4 is based on Bovee's (1982) original homeostatic assumption. Since that was not the situation in the Dolores River stocking was added to the model as follows. The habitat for fingerlings was assumed to support that life stage at approximately the same density as was calculated for fry in the S. Platte River. Knowing the number of stocked fingerlings, this allows the habitat demand (HD) for the stocked fish to be compared with the available habitat. Thus the total habitat demand for resident and stocked fingerlings can be calculated as shown in Equation 7.1 and compared with the LAH as in Equation 4.8.

$$HD_{Total} = HD_{Resident} + HD_{Stocked} \qquad (7.1$$

This extension has the additional advantage of providing a way to start the effective habitat time series when no fish were initially present.

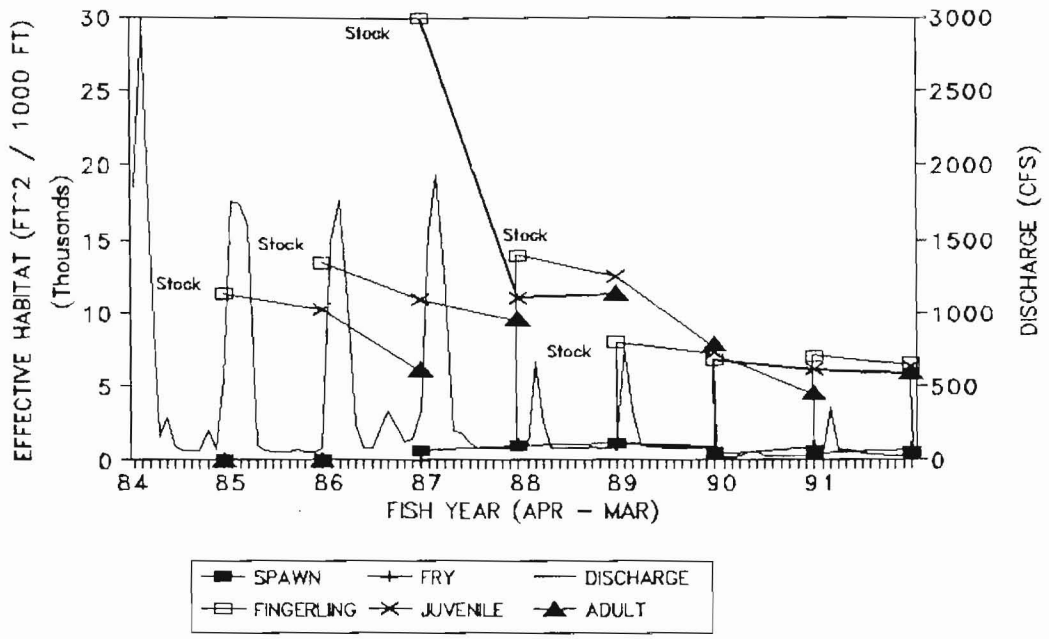


Figure 7.3. Post Dam Discharge and Brown Trout Population Events

Figure 7.3 illustrates the post-dam life history and stocking sequence for brown trout. The near vertical lines between fry (plus) and fingerling (box) indicate those two life stages occur within the same year. This figure also serves to illustrate the simplified once per year calculations of the effective habitat model. Effective habitat for all life stages is calculated at the end of the year. Thus the values appear near the next year's label.

The overall temperature suitability factors from Chapter 6 were applied to the habitat - discharge relations for the river. This produced a temperature-conditioned habitat - discharge relation for the summer period. In this modified relation the habitat suitability is reduced at 20 and 50 cfs.

As a result, there are two habitat - discharge relationships, one for the summer (June - August) and one for the rest of the year. These habitat - discharge relations were then used in calibrating the effective habitat model to the post dam period.

Simulating effective habitat for the period since construction of McPhee Dam requires the same data as the curve evaluation approach described in the previous section. The recorded discharge data, temperature conditioned habitat -discharge relations and assumed habitat multipliers were used as discussed above. The habitat multipliers were manipulated using a trial and error approach within a range of ±50% of the S. Platte values. The final multipliers produce adult effective habitat traces for brown and rainbow trout that show the same trends as the observed population data from Nehring (1991). The resulting post-dam effective habitat time series and observed numbers of brown and rainbow trout are shown in Figures 7.4 and 7.5. The final effective habitat multipliers used in the analysis are shown in Table 7.1.

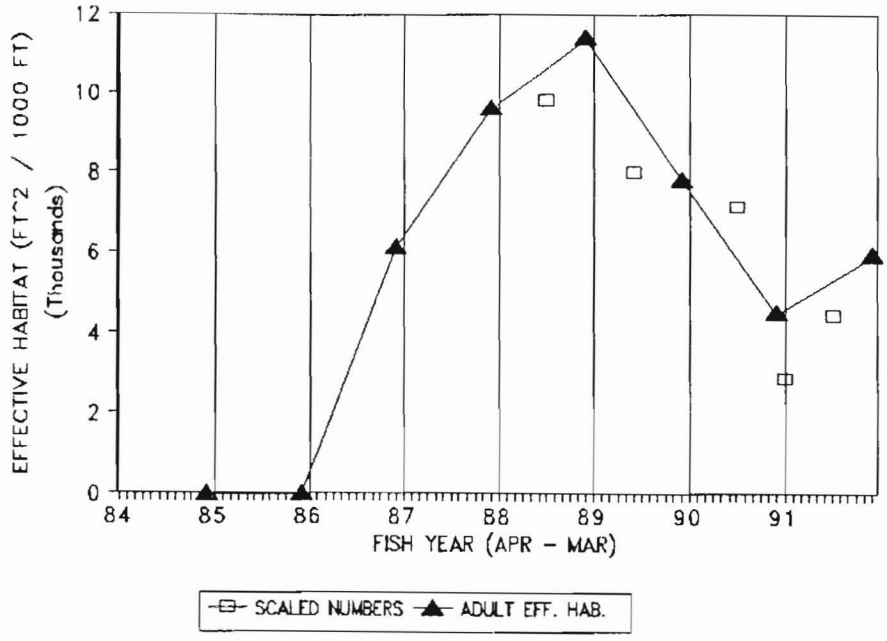


Figure 7.4. Brown Trout Effective Habitat and Density Scaled Numbers Below McPhee Dam

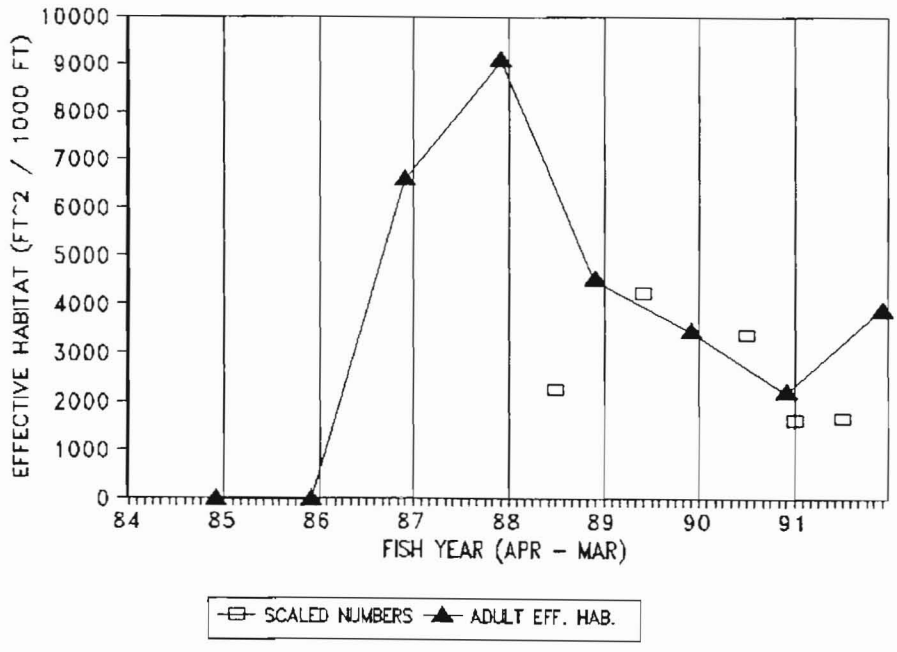


Figure 7.5. Rainbow Trout Effective Habitat and Density Scaled Numbers Below McPhee Dam

Table 7.1. Habitat Multipliers for the Dolores River Below McPhee Dam.

Multiplier Life Stages	Brown Trout	Rainbow Trout
Adult : Spawning	0.1	0.15
Spawning : Fry	5.0	2.00
Fry : Fingerling	8.0	6.0
Fingerling : Juvenile	0.9	0.8
Juvenile : Adult	0.6	0.6

While this is not a systematic approach, it must suffice. The assumptions of a stable, self-reproducing population required for the calibration technique from Chapter 4 were not satisfied. The period of population records is quite short and the populations are known to have been augmented by repeated stocking since McPhee Dam began operations. Nevertheless, the model proved able to approximately match the observed population trends.

Since the effective habitat model calculates the adult effective habitat as of the end of the fish year it does not exactly match the observed population numbers. The population samples were not taken at the end of the fish year so a direct comparison is difficult. As noted in Waddle (1990), the effective habitat time series model is useful as a management tool because matching of the population trends captures the memory effect.

DISCUSSION

Technical Contributions

The extension of the effective habitat time series model to include stocking is a new contribution to the modeling process. It broadens the applicability of that model to include many streams that are managed by stocking. It makes it possible for the effective habitat model to be used in streams where natural reproduction is severely limited.

A second contribution from this chapter is the concept of using the effective habitat time series model to choose SI criteria. In most applications of IFIM the choice of SI criteria is largely a judgmental process. The approach demonstrated here brings an analytical tool to bear on the problem. While the selection of the SI curves will continue to require judgement, this technique supports that judgement by considering long term population responses.

Findings

Though the available data is sparse, and several assumptions have been made, the effective habitat time series captures the adult population trends observed in the Dolores River. As shown in Figure 7.3 the model indicates that stocking of brown trout was sufficient to initialize that

population. It also indicates that the brown trout population had the potential to survive the low flows of 1990. Nehring (1991) concludes the brown trout population did survive that period and can reproduce successfully in the Dolores River. His conclusions corroborate these model results.

Similar to Nehring's findings, the model indicates rainbow trout are less successful at reproduction or survival through low flow periods. This may be due to several factors. Stocking was halted in 1986 and 1987 and resumed in 1988. As a result there is a gap in the age classes of spawning adults. The timing of managed flows and rainbow trout life stage events may have a higher degree of conflict than for brown trout. This is particularly true since rainbow trout eggs incubate and hatch during May and June when high releases are likely to occur.

The effective habitat time series model indicates that brown trout habitat provides more survival potential than rainbow trout habitat. This is further illustrated by Figure 7.6. There the brown trout effective habitat derived from a "natural flow" scenario is clearly greater than that for rainbow trout.

As calibrated, the brown trout time series has about twice the magnitude of the rainbow trout time series. It

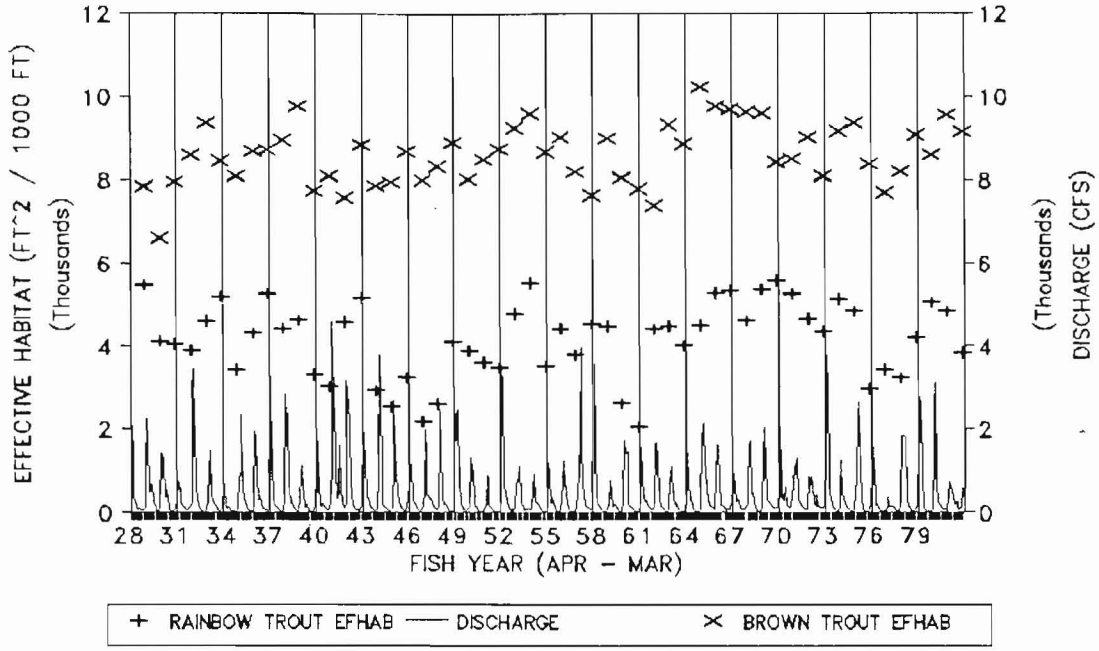


Figure 7.6. Effective Habitat for Brown and Rainbow Trout Based on Flows Recorded Upstream of McPhee Damsite

also has a smaller degree of variation, showing it is less sensitive to adverse flow events. If the assumptions made to derive these model parameters hold, it appears that the Dolores River brown trout population may be more robust than its rainbow trout population. Additional information needs required to reach a reliable conclusion regarding species success in the Dolores River are presented in the final chapter of this thesis.

Chapter 8

SIMULATION MODEL SETUP AND RESULTS

In this chapter the results from applying the various models outlined earlier are reported. The results demonstrate how this modeling approach can address the areas of instream storage account magnitude and efficiency of use. The results represent possible management options for the Dolores River system. They illustrate how the storage account concept ties together decision information needs and operational issues over a range of alternatives.

The water right model used here is highly generalized in the sense that any configuration of water rights and locations can be simulated. This generality is accomplished by using a very literal and inflexible interpretation of the "first in time, first in right" concept. The literal behavior of the model was considered sufficient for the purposes of this study. However, local applications of the model may require additional refinements to allow exceptions to this rule.

In simulation modeling there often is a trade off between generality and accuracy. Here, the generality gained

by having a simple set of rules is offset by a loss of accuracy in handling specific cases. Many water resource systems implement exceptions to the strict appropriation doctrine. Some examples are exchange agreements and storing water out of priority when senior users are not ready to divert. This model does not recognize these kinds of arrangements. As a result it cannot exploit system runoff as efficiently as some tightly managed systems can.

DOLORES SYSTEM SETUP

The U.S. Bureau of Reclamation operates the Dolores Project to satisfy the conditions in the contract they have with the Dolores Water Conservancy District. In their operation, they do not subdivide the storage in the reservoir among various water users was done here. Any departures from Reclamation's operations result from the form of system model chosen. The water use setup and results presented here represent my adaptation of Reclamation's water use data for this study.

Representation of Water Rights

Using the water system simulation data from the Definite Plan Report (DPR) (U.S. Bureau of Reclamation, 1977a), the water deliveries were abstracted into eight aggregate water

rights. The inflows are from the data base Reclamation currently uses in its Dolores Project model (Powers, 1991). The assigned priorities represent the approximate order of deliveries used in Reclamation's model. An example structure for the eight rights are summarized in Tables 8.1 to 8.3. The reasons for structuring each right are elaborated below.

Table 8.1. Water Right Representation of Dolores Project Storage Allocation

Right No.	Name	Type	Account Capacity*	Initial Contents
1	Instream Flow	Storage	30,100	20,067
2	M&I + const.	Storage	11,100	7,333
3	MVIC 6W Lands	Direct		
4	MVIC Other Land	Direct		
5	MVIC Project	Storage	76,000	50,667
6	Dove Cr. Proj.	Storage	82,000	54,667
7	Towaoc Project	Storage	30,000	20,000
8	Narraguinnep	Direct		
Active Storage Capacity			229,200	152,734

* Units: Acre Ft.

Table 8.2. Natural Flow Rights Delivered to Storage or Diversion

Month	1 Instream Flow to Storage	2 M&I + Constant Storage	3 MVIC 6W Lands Direct	4 MVIC Other Direct
Apr.	3000	4000	600	1300
May	15000	5000	7600	17900
June	12100	5000	13200	31000
July	0	5000	12200	28700
Aug.	0	0	5900	14000
Sep.	0	0	4200	9700
Oct.	0	0	3200	2900
Nov.	0	0	0	0
Dec.	0	0	0	0
Jan.	0	0	0	0
Feb.	0	0	200	0
Mar.	0	0	800	0

Month	5 MVIC Project Storage	6 Dove Cr. Project Storage	7 Towaoc Project Storage	8 Narraguinnep Fill Direct
Apr.	40000	45000	28000	12000
May	40000	42725	28000	0
June	31000	25000	28000	0
July	15000	18900	5000	0
Aug.	10000	5000	5000	0
Sep.	10000	10000	10000	0
Oct.	30000	3000	10000	0
Nov.	500	500	3000	0
Dec.	500	500	3000	0
Jan.	500	500	3000	0
Feb.	500	500	3000	0
Mar.	500	11025	12420	6000

* Units: Acre Ft.

In actual project operations, instream flow is a project requirement that is met as part of the Dolores Project operating rules. Here, it was assigned the first priority for ease of gaming with the size of the instream storage

Table 8.3. Storage Right Demand Distributions

Month	1 Instream Flow to Storage	2 M&I + Constant Storage	5 MVIC Project Supplement	6 Dove Cr. Full Project	7 Towaoc Full Project
Apr.	3000	4000	600	1300	500
May	15000	5000	7600	17900	3500
June	12100	5000	13200	31000	5900
July	0	5000	12200	28700	6500
Aug.	0	0	5900	14000	3800
Sep.	0	0	4200	9700	2300
Oct.	0	0	3200	2900	800
Nov.	0	0	0	0	0
Dec.	0	0	0	0	0
Jan.	0	0	0	0	0
Feb.	0	0	200	0	0
Mar.	0	0	800	0	0

* Units: Acre Ft.

account. In each simulation run, the size of the account and the amount of inflow allocated to it is constrained to explicitly limit the effects on the other water uses. That is, a maximum of 30100 AF per year of inflow is allowed when the storage account size was 30100 AF. For different instream storage account sizes, the sizes of all accounts were adjusted so the active storage capacity remained at 229,200 AF and maximum reservoir capacity remained at 381,100 AF.

Municipal and Industrial (M&I) water is always delivered in the DPR model scenario. Thus, priority 2 was assigned to this use.

A portion of the land within the Montezuma Valley Irrigation Company's (MVIC) service area is ineligible to receive Reclamation project water. Runoff from these lands (referred to as 6W lands in the DPR) has a high concentration of dissolved solids. The land is not eligible for project water because it would contribute to the overall salinity problem in the Colorado River Basin. Pre-existing water rights to irrigate this land must be honored. Those rights were represented as the priority 3 right.

The lands in MVIC that are eligible for project water are represented as the priority 4 right. These lands also were served by rights that pre-dated the project. When sufficient streamflow is available to satisfy this demand, it is satisfied directly from the reservoir inflow.

When sufficient water is not available to satisfy right 4, the model provides a supplement from a storage account. The storage account assigned to this supplementing function is right 5. The model represents deliveries to MVIC by the aggregate of rights 3, 4, and 5.

Rights 6 and 7 represent the full service areas near the towns of Dove Creek and Towaoc. These areas are called "full service" areas because they do not have significant pre-existing rights in the Dolores River. Thus they are fully served by the project.

Right 8 represents the occasional filling of Narraguinnep Reservoir in very wet years. This reservoir is represented in the model as a water demand based on the Definite Plan Report study. Operation of this reservoir was not evaluated beyond structuring this low priority delivery.

The system configuration used is shown in Figure 8.1. Since all diversion and project deliveries are made in the San Juan River basin, no return flows accrue to the river.

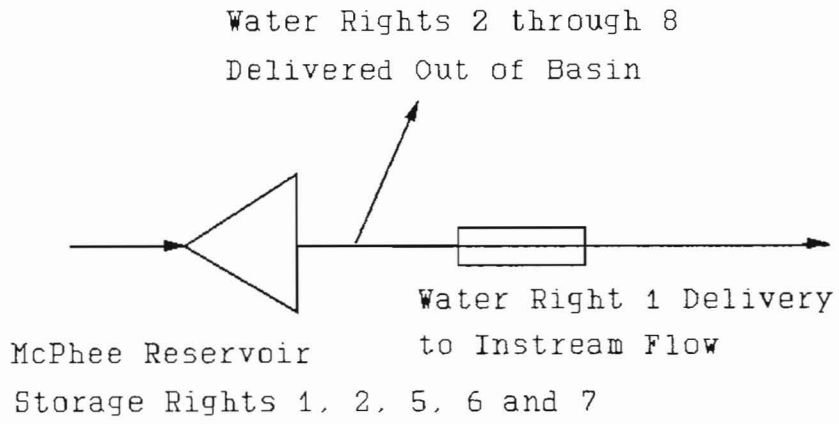


Figure 8.1. Model Schematic for the Dolores River.

EFFECTIVE HABITAT RESPONSE TO WATER MANAGEMENT

The water management model developed here does not produce the same river flows as Reclamation's operation study model. In the interest of establishing a common base for comparison of the various instream water management alternatives proposed here, the model was configured to

closely approximate the Reclamation DPR study. This is accomplished using a 50 cfs constant target flow for all years. The effective habitat time series from this model run is the baseline for comparison of all operating scenarios. The discharge pattern and effective habitat generated for brown trout by the baseline discharge time series is shown in Figure 8.2.

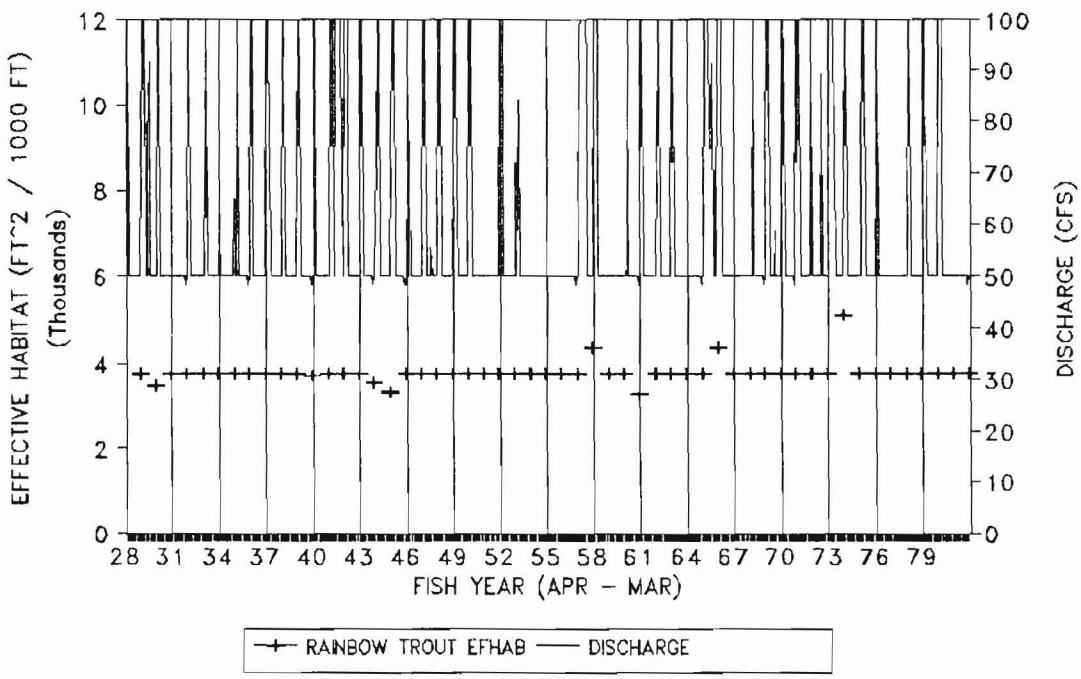


Figure 8.2. Rainbow Trout Effective Habitat Response to Baseline Discharge Scenario

In this configuration, the instream right limited to a maximum of 36000 AF of inflow per year. This is enough to supply a constant 50 cfs for 12 months. In most years, the summer 50 cfs discharge constrains habitat due to the temperature limitation described in Chapter 6. In 1929 the

adult life stage was constrained by low fingerling effective habitat in the initial conditions. The excursion below the constant effective habitat level in fish years 1944 and 1945 is caused by high flows in 1942 and 1943. During those years, spawning, fry and fingerling habitats were constrained by high discharges so there was less recruitment to the adult population in subsequent years.

The few rainbow trout effective habitat values that exceed the constant level happen because high releases occurred later in the year than normal. These releases were high enough to remove the temperature limitation in those years so the population was able to rise.

Response to DPR Instream Flow Scenario

It is illustrative to examine the behavior of the effective habitat model in response to the original DPR flow scenario. Figure 8.3 shows that dropping the discharge to 20 cfs for an entire year can have both immediate and long term effects.

This figure illustrates the immediate and time lagged effects of adverse environmental events. In fish year 1934 the discharge is reduced to 20 cfs for the entire year. The immediate effect is to constrain the adult effective habit to slightly less than 4000 units. Over the next 16 years, the

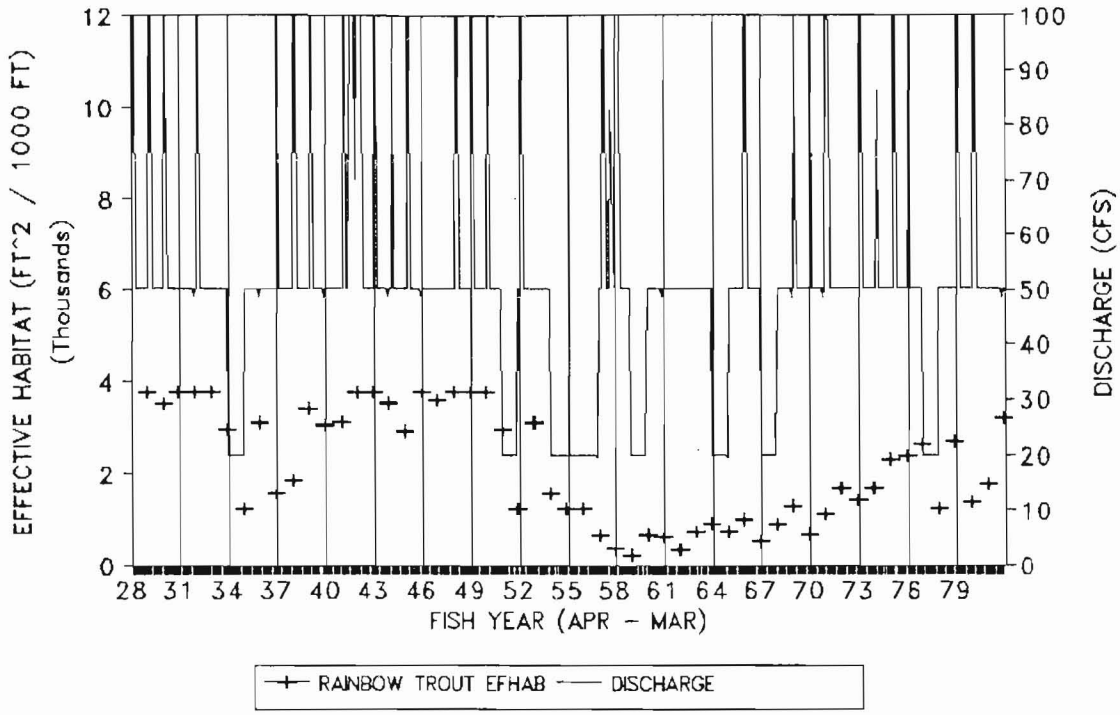


Figure 8.3. Rainbow Trout Effective Habitat Response to the DPR Flow Scenario

flows do not fall to that level. Yet, there is a pronounced drop in effective habitat in 1936 to about 1700 units and another drop to about 3200 units in 1940. The last two events reflect the system memory. How is this so?

In 1934 the adult life stage was constrained by the low flows in a similar manner to the decline observed in 1990 (cf. Chapter 6). Since the 20 cfs discharge continued for all of 1934, the spawning period was also constrained. In the Dolores River, the general rainbow trout population structure has spawning, fry and fingerlings occurring within a single fish year y. They in turn produce juveniles in year

y+1. The juveniles are recruited to the adult population in year y+2. Thus, a constraint on any of those life stages in 1934 can result in fewer new adults to replace natural mortality in 1936. There is a similar reduction in 1937 due to reduced effective spawning in 1935.

During the 9 years from 1935 through 1943 the minimum discharge remains at or above 50 cfs. This allows the effective habitat to recover back to the level of the summer limit. If the streamflow pattern for this period were to continue, the effective habitat would eventually reach the limiting available habitat (LAH) constraints seen when the 50 cfs minimum was maintained for all years. However, this is not the case in this scenario.

Low releases of 20 cfs in 1951, 1954 through 1956, 1965, 1967, and 1977 constrain the population. The lagged effects of reduced spawning in 1951 are exacerbated in 1954 by a series of low flow years. The combined effect of repeated low flow events is to hamper recovery over the entire period from 1954 to 1981.

Use of Stocking to Speed Recovery

If one assumes there is insufficient water to allow more than the 20 cfs minimum flows in those years, an alternative management strategy would be to re-stock the stream after bad

years. A stocking program was simulated by adding 2000 and 10000 fingerlings per year from 1958 through 1964. The resulting effective habitat traces (see Figure 8.4) suggest

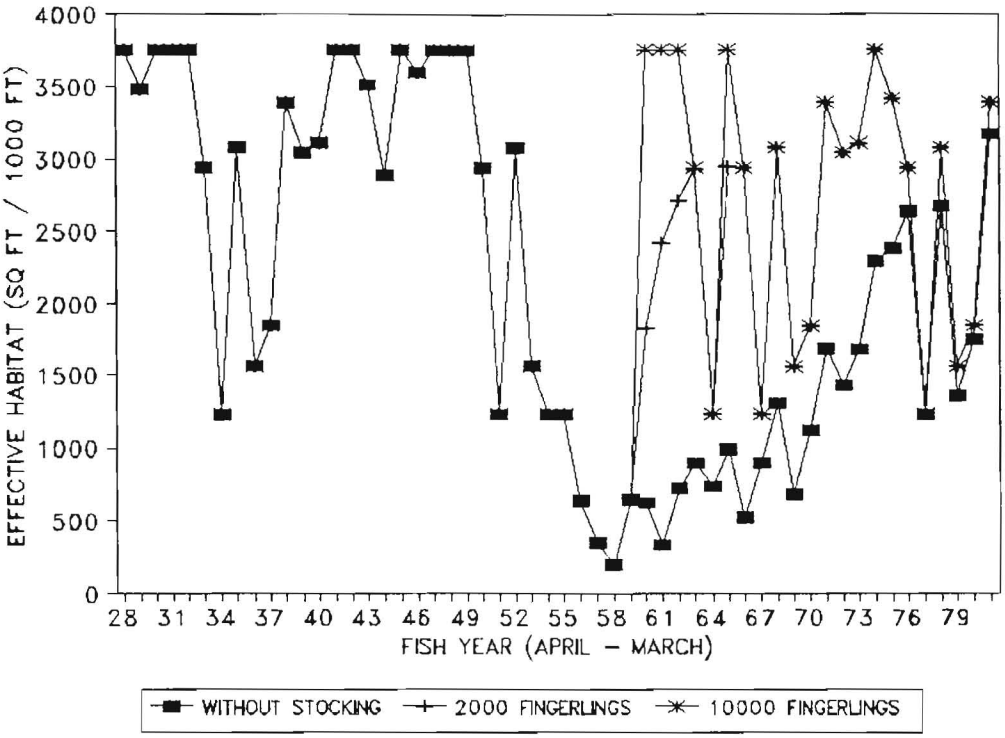


Figure 8.4. DPR Scenario With Two Levels of Stocking from 1958 to 1964.

that stocking can be used to speed recovery of the rainbow trout population levels. Either level of stocking produces a substantially faster recovery than the unstocked scenario. It should be noted that severe limiting conditions, such as occur in 1954 - 1956 or in 1965, may require repeated years of stocking after each adverse year. If the fingerling density assumptions of the effective habitat model hold, a small continuous stocking program may suffice to recover from adverse events. However, stocking cannot overcome the

effects of limiting flow events sufficiently to raise the maximum attainable effective habitat.

DECISION ALGORITHM BEHAVIOR

The habitat demand based decision algorithm acts in two ways. It identifies the amount of habitat for each life stage needed to avoid population limitations due to physical habitat. This allows water to be conserved when habitat demands are low. To avoid setting instream flow targets that exceed the available supply, the algorithm adjusts the targets by reducing habitat for all time steps equally. The result of these processes is to produce habitat values that lie between the worst and best habitat provided by a constant flow regime. This phenomena is illustrated in Figure 8.5.

Since this figure shows only adult habitat the reason for higher value of adult habitat in the first two months of 1931 is not immediately apparent. In most years high releases (controlled spills) produce one of two situations. Either enough rainbow trout spawning habitat is provided that the algorithm does no need to change flows or the flow is so high that adding releases from the storage account will only degrade habitat. In 1931 all inflow is captured so the algorithm releases enough flow to provide spawning habitat in proportion to the spawning habitat demand for that period.

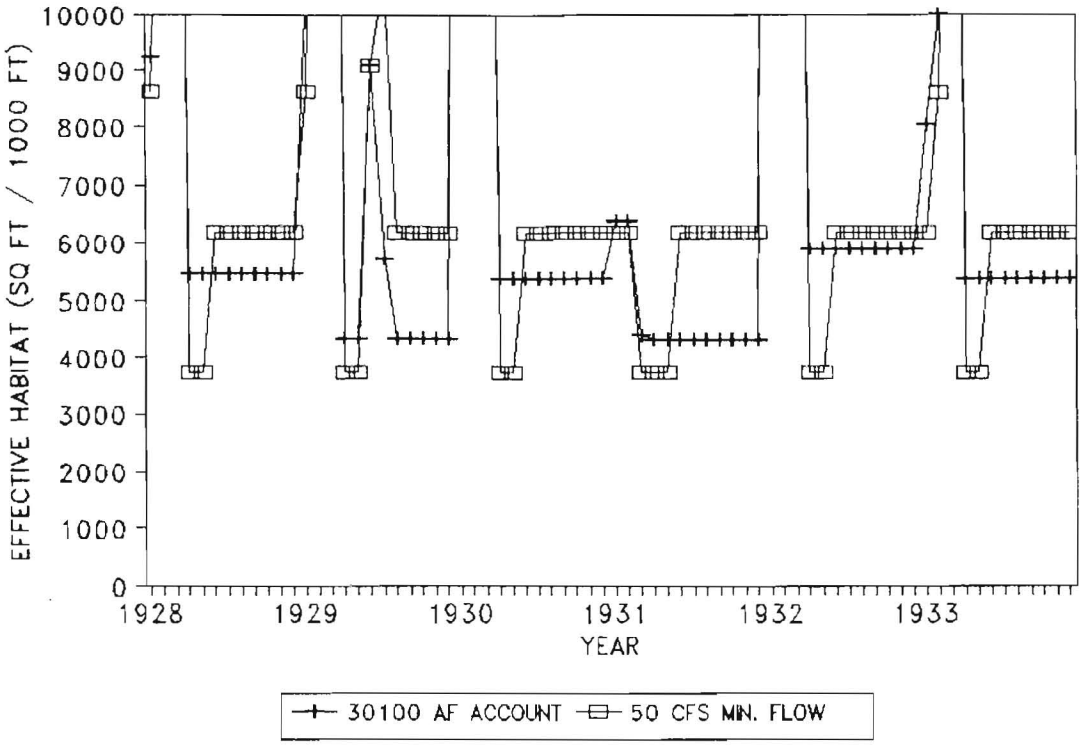


Figure 8.5. Effective Habitat Produced by Decision Algorithm and 50 cfs Constant Flow.

This release has the additional effect of generating a higher amount of gross adult habitat (GAH). 1931 is a dry year so the amount of instream flow water is constrained. This produces the lower value of adult habitat in months 3 to 12. That lower limit is the limiting available habitat (LAH) for that year. Though low, this is an improvement when compared to the constant discharge approach.

Figure 8.5 also illustrates differences among years in the amount of habitat delivered. These differences are caused by either limitations on available water or by year to year changes in habitat demand. Over time, the resulting

annual flow regimes vary noticeably. Figure 8.6 shows the kind of instream flow variation produced by the algorithm in response to water availability. In this alternative, the storage account is 34,500 acre ft. Note that instream flows are constrained by water availability in 1931, 1934, and 1939. In all other years habitat demand dictates the instream flow release volume.

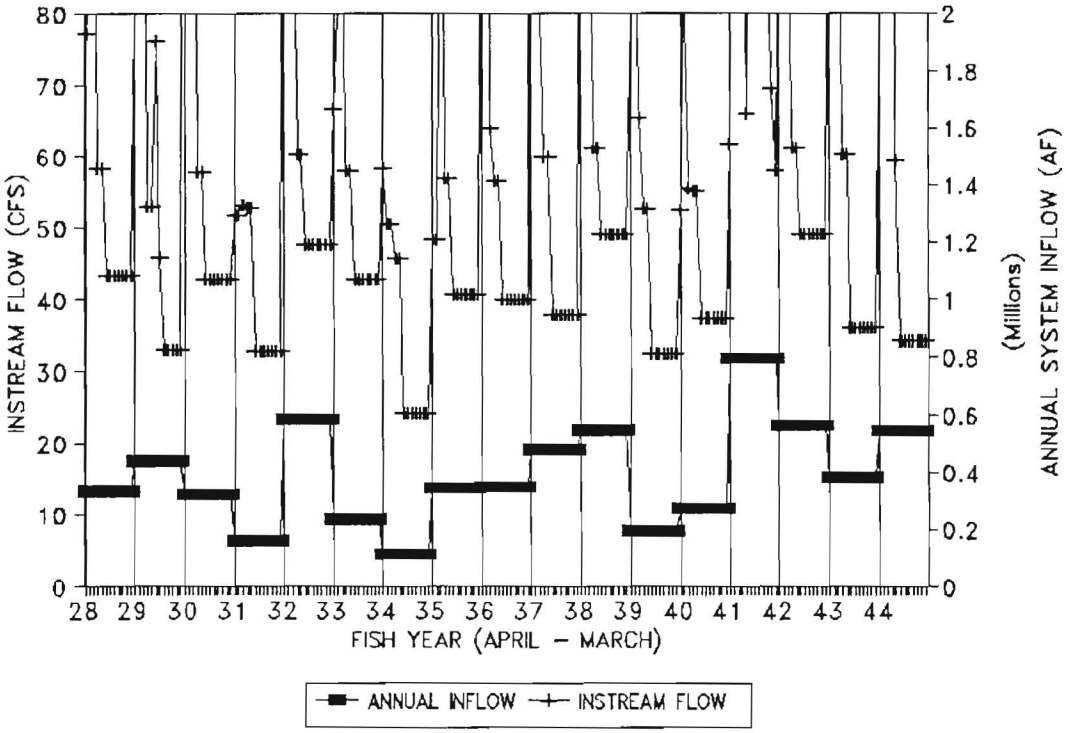


Figure 8.6. Instream Flows Produced by Decision Algorithm

The algorithm begins with calculation seed targets set to user defined minimum flow values. For all alternatives reported here, the target seed is 20 cfs. The algorithm does not release water from the instream account when other releases produce sufficient instream flow.

INSTREAM STORAGE ACCOUNT MODEL RESULTS

Option 1. Population State Decision Strategy

The habitat demand algorithm was applied to the Dolores River using a range of storage account sizes to find an approximate instream benefit relation in terms of effective habitat. Three of these account sizes, 24500 AF, 30100 AF and 34500 AF, are being discussed as possible instream account sizes for the Dolores Project. This range was extended to 55000 AF to explore the possible existence of a diminishing return relation. The rainbow trout effective habitat trace and discharge scenario for a storage account of 30100 AF is shown in Figure 8.7. The population (effective habitat) values for two extreme storage account sizes are compared to the constant instream flow scenario in Figure 8.8. Note the effective habitat values using the storage account are higher in most years than those using a constant minimum discharge.

The benefit to the fish population of increased storage account size is shown in Figures 8.9 and 8.10 and summarized in Table 8.4. Throughout this analysis rainbow trout have appeared to be more sensitive to low discharges than brown trout. The mean and maximum rainbow trout effective habitat values show a greater rate of improvement with increased storage account size than the comparable brown trout values.

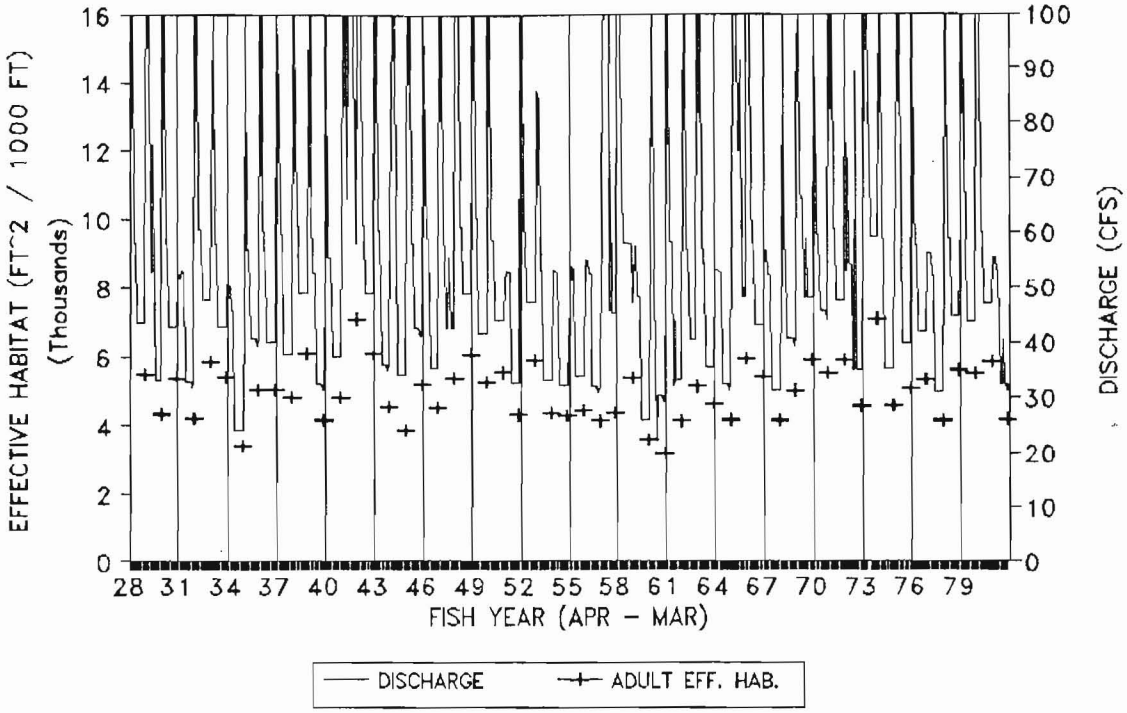


Figure 8.7. Rainbow Trout Effective Habitat and Discharge Scenario for an Instream Storage Account of 30100 AF

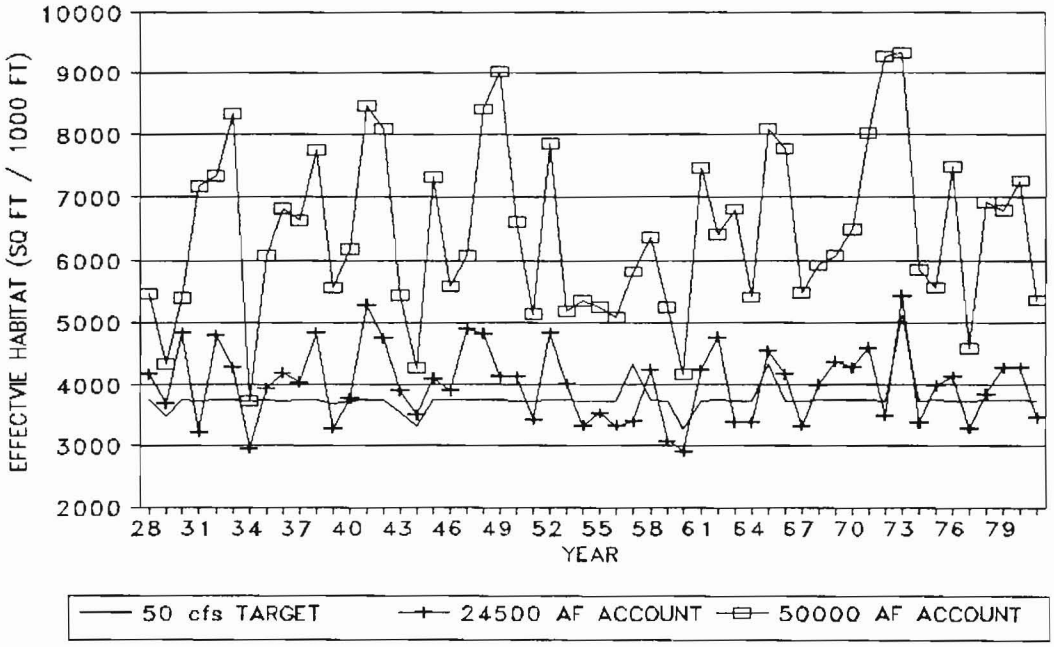


Figure 8.8. Rainbow Trout Effective Habitat Time Series for Constant Minimum Flow and Two Storage Account Sizes

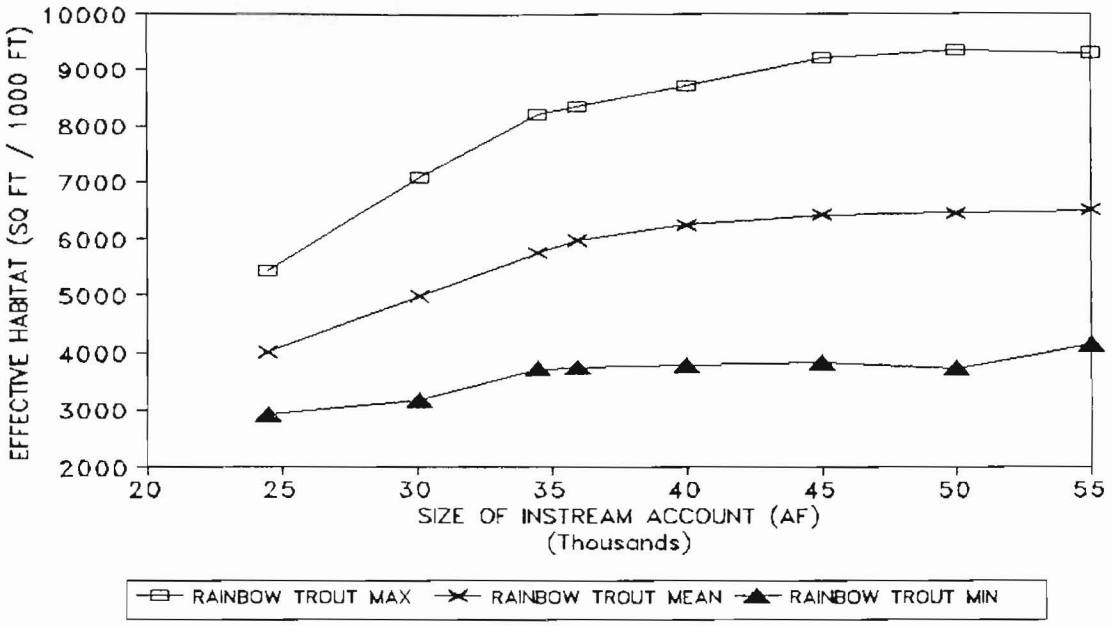


Figure 8.9. Rainbow Trout Effective Habitat and Storage Account Size

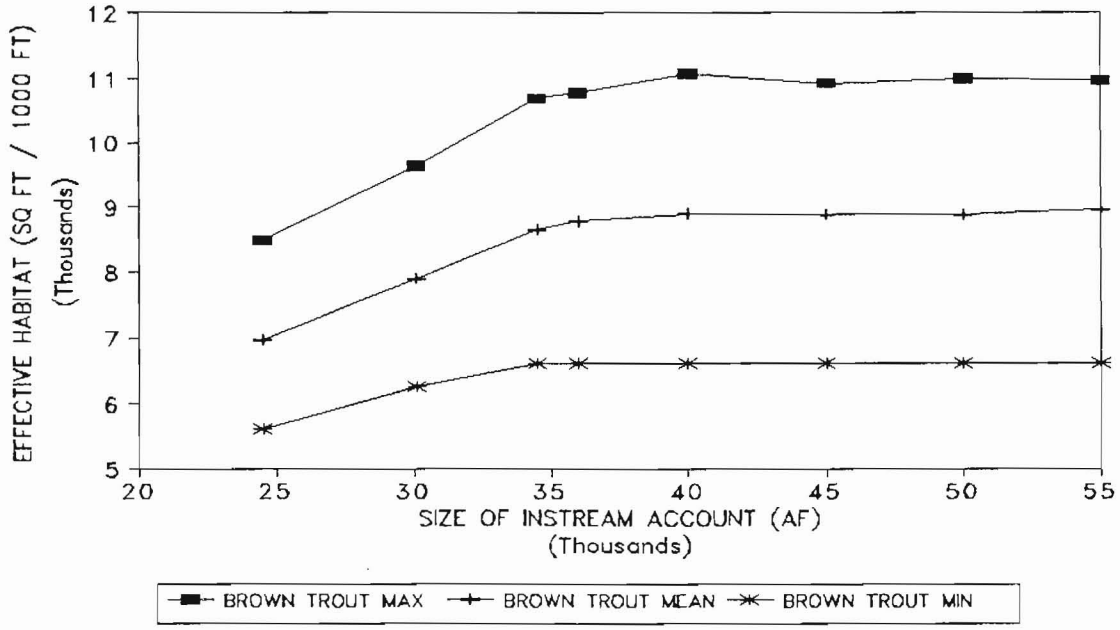


Figure 8.10. Brown Trout Effective Habitat and Storage Account Size

Table 8.4. Effective Habitat Results Using Different Account Sizes for 54 Year Simulations

Account Size	Brown Trout Maximum	Brown Trout Mean	Brown Trout Minimum	Rainbow Trout Maximum	Rainbow Trout Mean	Rainbow Trout Minimum
24500	8483.3	6956.5	5609.3	5436.4	4000.9	2908.1
30100	9631.6	7885.8	6252.1	7078.4	4976.5	3166.4
34500	10683.1	8632.5	6610.2	8211.9	5762.3	3729.4
36000	10765.7	8774.2	6610.2	8349.1	5975.8	3742.3
40000	11069.1	8889.1	6610.2	8705.7	6241.7	3778.8
45000	10922.2	8876.9	6610.2	9200.1	6411.2	3824.2
50000	10990.7	8880.0	6610.2	9331.6	6439.4	3727.2
55000	10969.0	8951.3	6610.2	9306.9	6496.1	4147.5
50 cfs	7078.5	6821.1	6064.5	5115.2	3770.3	3270.3

Units: Account Size (AF),
Fish Population (Effective Habitat WUA ft^2 / 1000 ft)

The gain in effective habitat with increasing storage account size shows a diminishing return relation. This is due to the interaction of two factors. First as the amount of water available for instream use increases, the number of years in which habitat demand can be satisfied increases. However, as more storage is dedicated to instream flows, fewer additional years of habitat demand satisfaction occur. Second, effective habitat state and thus habitat demand is constrained by uncontrolled high flow events as well as low flow events. Thus, a point is reached when additional augmentation of low flows does not remove population limiting habitat events. This is further illustrated by Figure 8.11 which shows that average annual instream deliveries do not increase as fast as the account size that provides them.

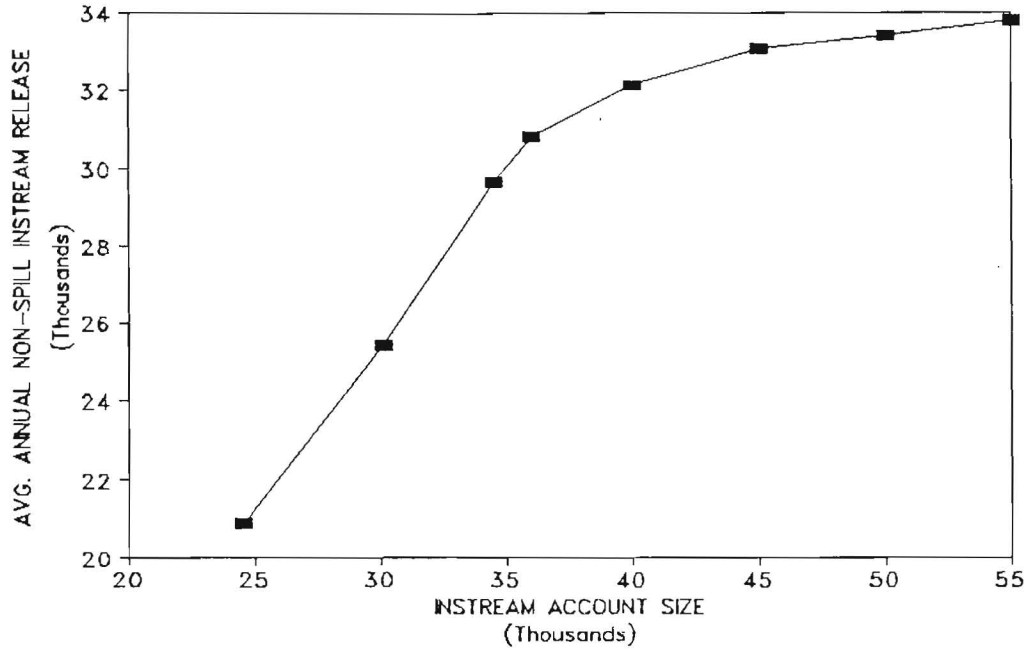


Figure 8.11. Water Deliveries For Various Instream Account Sizes

Examination of the effective habitat scenarios for various storage account sizes shows that some minimum values produced by the management algorithm are lower than those from the fixed flow scenario. That is, the decision algorithm may produce populations that exhibit greater variation than those produced by a fixed flow regime. This phenomenon is illustrated in Figure 8.8, above.

The model also provides information on the trade off of instream flow deliveries and other uses of stored water. One would expect that dedicating increasing amounts of storage to instream flow would reduce the yield to other project deliveries. Table 8.5 and Figure 8.12 show this to be the

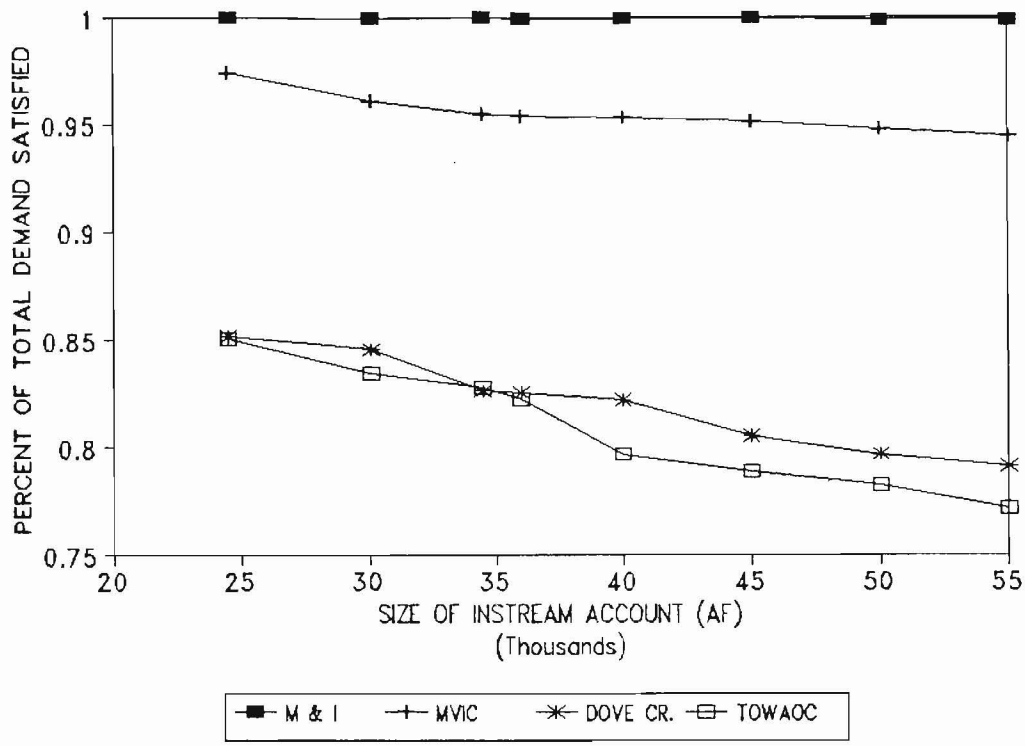


Figure 8.12. Influence of Storage Account Size on Satisfaction of Diverted Water Uses

Table 8.5. Water Delivery Results Using Different Account Sizes for 54 Year Simulations

Account Size	Total Instream Releases	Average Annual Release	Average Delivery of M&I Water	Average Delivery to MVIC	Average Delivery to Dove Creek	Average Delivery to Towaoc
24500	1128256	20894	100.0%	97.4%	85.2%	85.1%
30100	1373378	25433	100.0%	96.1%	84.6%	83.5%
34500	1602726	29680	100.0%	95.5%	82.7%	82.8%
36000	1664693	30828	99.9%	95.4%	82.6%	82.3%
40000	1734560	32121	99.9%	95.3%	82.2%	79.7%
45000	1785664	33068	99.9%	95.1%	80.6%	78.9%
50000	1803943	33406	99.8%	94.7%	79.7%	78.3%
55000	1824141	33780	99.8%	94.4%	79.1%	77.2%
50 cfs	1492164	27633	99.9%	95.4%	82.4%	81.7%

* Units: Acre Ft.

case. In looking at Table 8.5, note that on average, the constant 50 cfs delivery is roughly comparable to the average delivery that would be obtained from an instream account of about 32000 acre ft. To maintain 50 cfs during dry years requires an account of approximately 36000 acre ft. Simply evaluating these options in terms of storage account volume alone shows that water may be saved if the habitat management algorithm is followed. From the total instream release standpoint, it can also be seen that over a multi-year planning horizon approximately the same amount of effective habitat can be provided with less water using the habitat demand based decision algorithm.

Option 2. Fixed instream pattern strategy

To evaluate the effect of trying to gain the maximum habitat for each year without considering the population state, the instream flow target pattern shown in Table 8.6 was simulated as a fixed pattern rule. A storage account size of 36000 AF was used to match the constant discharge case. Since the same amount of storage was dedicated to instream flow as the constant 50 cfs example, the yield impacts on other water uses were the same. The effective habitat results of this strategy are summarized in Table 8.7.

By structuring the annual instream pattern to provide needed habitat for important life stages and to avoid

Table 8.6. Instream Flow Targets and Rationale for Non-State Based Scenario

Month	Flow Target	Reason for Target
April	63 cfs	Rainbow Spawning
May	63 cfs	Rainbow Spawning
June	63 cfs	Temperature Control
July	63 cfs	Temperature Control
August	63 cfs	Temperature Control
September	40 cfs	Maintain constant
October	40 cfs	habitat for brown
November	40 cfs	trout spawning and
December	40 cfs	incubation.
January	40 cfs	"
February	40 cfs	"
March	40 cfs	"

Table 8.7. Comparison of Effective Habitat Results for Three Strategies That Use a 33000 AF Storage Account

Species	Constant 50 cfs	Non-State Decision	Population State Algorithm
Brown Trout			
Maximum	7028.5	9890.9	10765.7
Mean	6820.0	9055.1	8774.2
Minimum	6064.5	6610.2	6610.2
Rainbow Trout			
Maximum	5115.2	5104.4	8349.1
Mean	3771.0	4954.2	5975.8
Minimum	3283.7	3625.6	3747.3

Units: Effective Habitat WUA (ft^2/1000 ft)

temperature limitations, the non-state based decision approach does improve effective habitat. The improvement in

effective habitat for both species over the fixed 50 cfs strategy is more than 30%. This change suggests that in the absence of sufficient data to develop the complete habitat demand based decision model, a seasonal pattern strategy may be a reasonable fall back position.

The advantage of considering population state can be seen by comparing the two fixed patterns with the storage account algorithmic approach. The fixed pattern delivers an improvement in both rainbow and brown trout population over the constant 50 cfs strategy. However, there is further improvement in the rainbow trout population by using the population state algorithm and a 36000 AF storage account. Rainbow trout are given the highest priority due to their relative population weakness in this system (cf. Chapter 6). Since the algorithm favors rainbow trout, the brown trout do not fare as well as with the fixed pattern.

EFFECT OF WATER RIGHT LOCATION ON INSTREAM ACCOUNT SIZE

When water rights are located downstream of an area of instream flow interest, instream benefits accrue as water is routed to those uses. The model was configured to locate Dove Cr. and Towaoc diversions downstream of the fishery maintenance reach. While this is not realistic for the Dolores River, it illustrates the point that instream

benefits increase when complementary uses of instream flow can be obtained. Using a storage account of 24500 AF effective habitat values approaching those of the 30100 AF account were obtained. As show in Table 8.8 this increase in habitat was accompanied by a marked increase in satisfaction of the Dove Creek and Towaoc demands. As with the previous example of multiple storage account sizes, a relation between storage account size and various project benefits for this system geometry can be constructed by solving the system with a range of account sizes.

Table 8.8. Effective Habitat and Water Delivery Results With Dove Cr. and Towaoc Demands Located Downstream of Instream Reach

Account	Brown Trout			Rainbow Trout		
Size	Maximum	Mean	Minimum	Maximum	Mean	Minimum
24500	10004.4	8163.8	6610.2	6862.0	4610.0	3107.8

Account Size	Total Instream Releases	Average Annual Instream Release	Average Delivery of M&I Water	Average Delivery to MVIC	Average Delivery to Dove Creek	Average Delivery to Towaoc
24500	702111	13002	100.0%	97.3%	94.2%	95.5%

Units: Account size and release volumes (AF)
Trout Populations (Effective habitat WUA ft^2/1000 ft)

DISCUSSION

Technical Contributions

This chapter demonstrates the utility of the models developed in this thesis to develop and display the effects of various instream management alternatives. The method successfully delivers a higher average population of both rainbow and brown trout with less water actually released to satisfy instream flows. Table 8.4 shows that the habitat based rule can deliver essentially as much effective habitat with a 24,500 AF storage account as can the constant 50 cfs release rule. This is accomplished using nearly 7000 AF less water per year on average. Larger storage accounts with greater average instream releases show continued improvement in populations of both species.

Improving Communication

The modeling approach demonstrated here supplies information important to both instream flow advocates and project operators. It allows water use trade-offs to be clearly identified as shown in Table 8.5 Using this technique system performance can be condensed to a few easily compared summary values At the same time the concerns of parties on different sides of the issue can be incorporated.

Summary Observations

The results presented here were generated using rainbow trout as the first priority species. That species was selected because it appears to be the least robust of the two trout species considered. This is true in the model and in the Dolores River.

As noted in Chapter 7 the results of the fish population modeling approach used here are sensitive to the habitat-discharge relations. In the Dolores River, the results are particularly sensitive to the spawning habitat-discharge relation at low flows. A different shape of this function may lead to different effective habitat results. The flow regime generated by the decision algorithm would also be affected.

The results are also sensitive to water system geometry. The Dolores River system represents a situation where there is direct and absolute conflict between irrigation diversions and instream flow. When instream uses and diversion points are interwoven along a river system this model can represent the degree to which complementary uses of that water can be obtained. It allows solution for the storage account size needed to maintain a particular effective habitat level given the system geometry. The illustrative example presented

above shows that such complementary uses can improve the satisfaction rate for downstream water demands.

The examples presented in this chapter show the ability of this modeling approach to increase mean fish population. The results depend on a number of assumptions. The technical limits of this approach, extensions to overcome those limits, and future work to further improve communications among those interested in instream decisions are discussed in Chapter 9.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

IMPORTANCE OF THE RESULTS

The results obtained in Chapter 8 demonstrate two important capabilities of the method put forward here. The first is the ability to define and obtain efficient use of instream flow water. That is, the decision approach developed here can produce the same or greater fish population using less water. The ability to identify the timing and magnitude of instream flow needed to satisfy habitat and population objectives is an important advance.

Coupled with this capability is the capability of quantifying trade-offs of instream flow population benefits (measured by effective habitat) and water deliveries for other purposes. The duty of water for various crops, climate conditions and soil types is known. This method now provides an analogous measure of the long term mean amount of instream flow needed to sustain various levels of a fish population.

SENSITIVITY OF METHOD RESULTS

The method is sensitive to its driving components. As shown in Chapter 7, the selection of suitability of use indices (SI) can lead to different conclusions about the magnitude of flow that produces limiting habitat events. Those results are particularly significant when the analysis concludes the limiting events are either well within or beyond the capability of a project's physical control.

In a related finding, the habitat - discharge relations were shown to be more sensitive to selection of SI curves than to alternative analyses of hydraulic data. This indicates that minor errors in hydraulic data collection may not influence the outcome of a population analysis using this method. This is particularly important considering the greater degree of uncertainty of SI curves compared to hydraulic data, assumptions and models (Bovee and Thomas, 1992).

The results are also sensitive to the system configuration. A hypothetical rearrangement of the Dolores River system showed that both population and deliveries to the lower priority rights could be increased. The method is able to identify and exploit complementary benefits between instream and traditional water uses.

The method was also shown to be sensitive to the storage account size. In the case study, the feasible instream flows for fish maintenance were all on the ascending limbs of the habitat - discharge relations. As expected, increasing the storage account size led to greater instream deliveries. This in turn led to increases in both the brown and rainbow trout populations. There were diminishing return effects at the higher storage account sizes because the storage account did not fill during critically dry years. Thus the additional population benefit of the larger account could be realized in only a few years.

HYPOTHESIS SUPPORTED

The general hypotheses behind this work was stated in the introduction. It was: Rules can be developed for water resource system operations that eliminate or reduce the occurrence of critical habitat shortages while avoiding adverse impacts on other (senior) water uses.

The results presented in Chapter 8 show that the decision algorithm developed here can allocate a fixed amount of instream water to improve population potential. The improvements in population potential are accomplished by managing to satisfy habitat demand when sufficient water is available and to reduce or avoid severe habitat shortages

when there is less water. This satisfies the first part of the stated hypothesis.

The second part of the hypothesis, avoidance of adverse impacts on senior water uses, must be identified by judicious use of the model. That is, several alternative water budget account sizes can be simulated to arrive at acceptable deliveries to senior uses. The model was shown to be useful developing such trade off relations.

TECHNICAL CONTRIBUTIONS

Clarification and Expansion of Effective Habitat Model

The original effective habitat model concept was put forward as a group of numerical examples. In this thesis the terms and equations needed to represent the original model relations are defined. Of particular importance is articulation of the concept of habitat demand.

A calibration technique for that model was developed that allows it to be applied to specific stream systems. The calibration uses data that are routinely collected on several rivers by the Colorado Division of Wildlife. The calibration approach accommodates the significant uncertainty in sampling fish populations through long term averaging. The

calibration technique was developed as part of this thesis and first reported in Waddle (1990).

The importance of stocking to the fish populations in the Dolores River led to the expanding effective habitat model to include a stocking component. The stocking procedure translates numbers of stocked fish into habitat values using the average density of the stocked life stage. The procedure allows the model to be applied to streams where the fishery is managed by augmentation (stocking). The density values are derived as part of the calibration procedure.

Screening of Suitability of Use Indices

The effective habitat model was shown to provide an additional tool to select SI curves. A technique for comparing the effective habitat time series derived from different SI curve sets was demonstrated. Those SI curves that yield effective habitat performance similar to known population responses are likely to be better candidates for the analysis.

Major Technical Contribution: Habitat Demand Forecast

The major technical development of this thesis is the use of habitat demand as the mechanism to select efficient

instream flow targets. The population (effective habitat) state and habitat multipliers provide the information needed to forecast the amount of habitat and thus instream flow needed during the current decision year. This allows water to be held in the instream account for later use considering population needs. This ability to respond to population needs is an advance over the use of fixed instream flow regimes.

The second important part of this contribution is the algorithm for managing instream flow when there is insufficient water to meet all habitat demands. It allocates shortages by reducing habitat equally across the year. Thus, it avoids a fractional reduction in discharge which may lead to more severe habitat limits at some times of the year than others.

Support for Instream Decision Making

The method assembled in this thesis provides an analysis framework that points toward treating fish population as an objective. The approach allows the effects of different instream flow management alternatives on both fish population and traditional out-of-stream water uses to be quantified. Whether used as a decision variable or as an index, the effective habitat time series representation of fish population shows the relative amount of change per increment

of instream storage account size. In doing so, information needs of biologists, water users, project planners and operators are addressed. This has the potential to lead to greater communication among them.

ENHANCING COMMUNICATION

The results also show that the model can be used to aid the instream flow decision process by presenting information in a succinct format. This is accomplished by arraying alternatives in a trade-off table and a few easily interpreted graphics. Figures 9.1 and 9.2 show the ability of the suite of models to generate water and instream benefit trade-off displays in a simple and clear format. The 50 cfs scenario is the baseline scenario for comparing alternatives using the models developed here. When questions arise, more detailed displays, such as Figures 8.5 through 8.9 can be obtained from the model.

From comparing these figures it is immediately clear that increasing the size of the instream storage account leads to reduced reliability of irrigation deliveries. This is to be expected in a situation like the Dolores Project where there are no complementary use opportunities. In other river systems the trade-offs may not be as severe and the

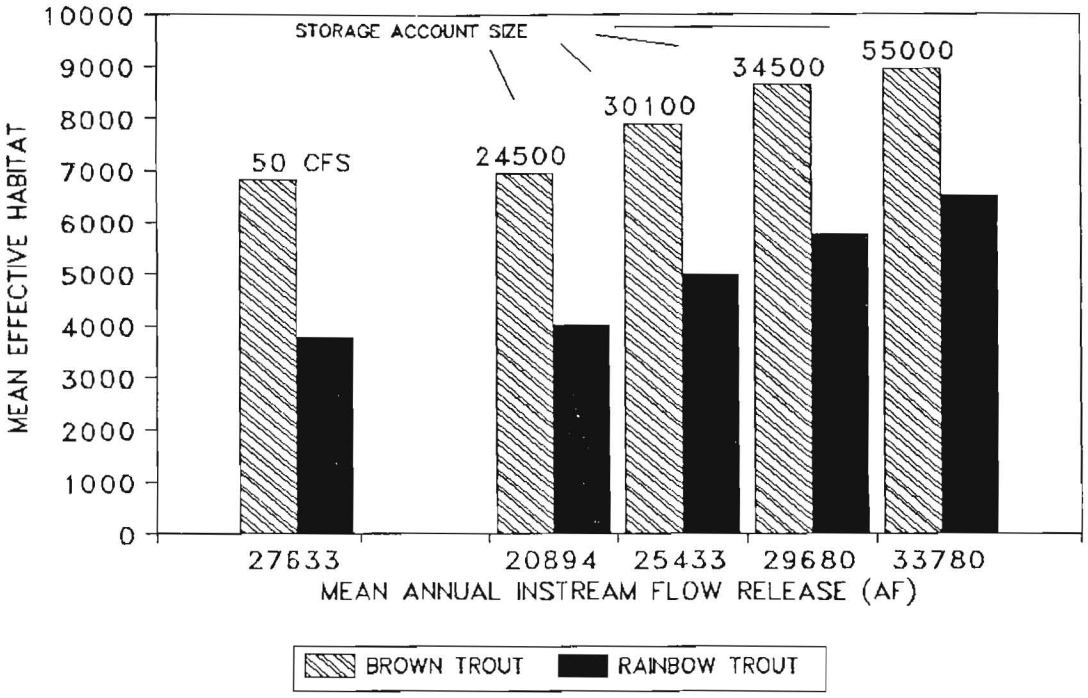


Figure 9.1. Benefits of Effective Habitat Alternatives

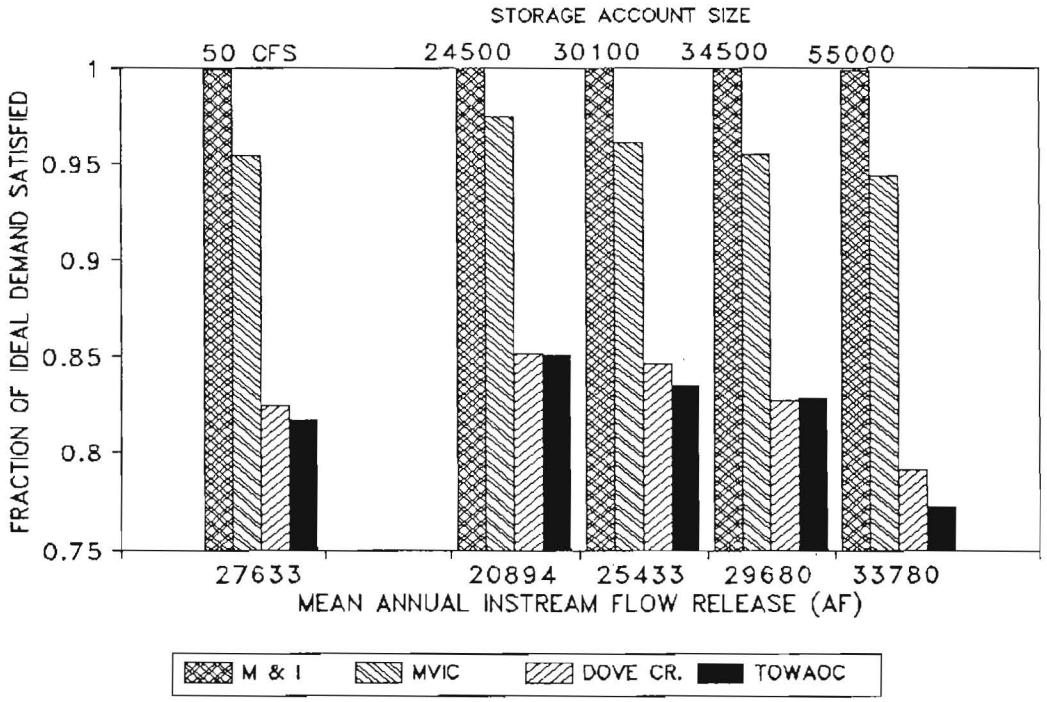


Figure 9.2. Diversion Deliveries for Different Storage Account Sizes

fraction delivered to various uses may be related to their relative positions along the river.

The advantage this modeling approach brings to the decision arena is integration of previously unavailable information. Prior to this thesis an general model for efficiently managing stored water to support fish populations did not exist. The model results allow fish population and traditional water use trade-offs to be simply displayed. Users of this method must interpret the importance of changes in mean effective habitat and changes in deliveries to out-of-stream uses. The method provides a quantitative description of the trade-offs, but it does not make decisions.

UNRESOLVED ISSUES

The Effective Habitat Model

The effective habitat time series model is not well known in the biological community. Until work on this thesis, there was no published calibration technique. Since it abstracts population numbers into an unfamiliar measure (effective habitat) it may be difficult for practicing biologists apply.

The effective habitat representation captures a few characteristics of fish populations and omits others. The memory effect is demonstrated by the lagged effective habitat decline due to restricted spawning in the Dolores River. However, many aspects of causation in population response are not addressed. In particular, density dependent mortality and compensatory survival are not modeled. A better representation of fish population dynamics would be achieved if the model recognized these phenomena.

The model uses critical time periods to determine limiting conditions. As such it cannot deal with chronic phenomena. Nehring (1991) reports weakening of Dolores River trout over winter after the low flow summer of 1990. To the extent the weakening was caused by the low flow and high temperature the effective habitat model can capture the trend if not the exact timing of population response. However, such cause and effect relations are not explicitly discernable in this lumped parameter model.

These concerns can be avoided if the effective habitat values are treated as an index of population robustness. This approach allows comparative management goals to be arrived at by bounding exercises using the model. The spreadsheet version of the model speaks directly to this need in two ways. It allows hands-on experience with the effective habitat model and it provides an opportunity to

experiment with management approaches that are not in the Fortran model.

Other Issues

The fixed timing of life stage events used in this model may be a handicap to its general application. Condition driven events are common. For example, spawning may be initiated earlier or later in a given year depending on runoff volume and water temperature. The representation of temperature conditions and temperature response may need to be expanded beyond that used here.

A model of temperature needs to be added as an explicit component of the model. The assumption that at least one hot day will occur in any month should be replaced with a dynamic calculation of temperature. This would allow calculation of a temperature SI value for each time step.

DOLORES RIVER CONCLUSIONS

This study was conducted using the available data. These data were not collected with knowledge of the models used and developed here. The text contains several notes about data limitations and assumptions made to overcome them. The following comments and conclusions are presented with the

understanding that there are unresolved questions about the biological responses in the Dolores River.

Data Considerations

The PHABSIM data needs to be evaluated and extended. If possible the study site used in the analysis should be resurveyed to incorporate the modified channel. Other sites should be surveyed at a wide enough range of flows to allow meaningful extrapolation. Those sites should reflect the range of habitat conditions in the river. The low flow sites already studied by Reclamation are good candidates for this effort.

Further evaluation of the SI curves the be used is also needed. Biologists need to evaluate if the Raleigh et al. (1986) or Bovee and Thomas (1992) curves can be transferred to the Dolores River. The issue of offsetting effects between high flow and low behavior should be explicitly addressed. If other curves are not transferrable, river-specific curves should be developed by observing the fish in the Dolores River at a wide range of discharge conditions.

Temperature responses need to be refined. Seasonally changing temperature SI curves for each life stage should be developed. In the absence of data from the Dolores River,

literature values can be used and translated to the Dolores by professional judgement.

Continued sampling of the fish populations data is needed. It would be especially useful if the populations can be maintained without stocking. The population sustaining flow regimes identified in Chapter 8 could be used as a starting point.

Validating the Model

Two tests could be conducted simultaneously. A test of the model's ability to predict the trend in fish population would validate the model's use for management. Secondly, several years of population data without stocking would help to calibrate the model and to find the river's true potential.

There appears to be potential for immediate improvement in managing temperature in the Dolores River. Temperature monitoring could be telemetered back to daily operations. This would allow best use of the multi-level outlet and variation of the flow needed to maintain desired temperature conditions. Essentially water could be saved for the hottest days.

Increasing the size of the instream storage account allows increasing delivery of instream flow at critical times. As shown in Figure 9.1 larger account sizes can lead to improved trout populations. Increasing populations were produced for the full range of instream account sizes and instream flow deliveries being considered for the Dolores River.

Temperature Management

The evidence indicates that the combination of high water temperature and low discharge that occurred in the Dolores River in 1990 led to reductions in trout numbers and biomass. McPhee Dam has a small multi-level outlet and a bottom release. It may be possible to immediately implement a water temperature management scheme by installing a telemetered thermograph at the lower end of the instream management segment. This would allow adjusting discharge and release level to maintain desired temperatures. Such adjustments could be treated as variance around other instream flow target flows. Such a scheme would allow saving water until it was needed for temperature reduction.

GENERAL MODEL APPLICATION GUIDELINES

No aspect of the combined group of models used and developed herein is exact. Each model has inherent assumptions and limitations. This combined tool is best used as a decision and communication tool. In this use, parties on all sides of instream flow decisions can supply and receive information. The model provides discharge, diversion, storage, habitat, and an index of fish population so tradeoffs can be discussed and refined. Such an interchange should help to supply the information needs identified in Chapter 3.

The water right, reservoir, and routing algorithms developed are highly generalized and can be applied to many streams by merely changing input data. This generality comes at the expense of being able to precisely describe any specific system. When a storage account is considered as a management alternative for a specific water system, the decision and effective habitat algorithms used here may be best "grafted" on to an existing water system model. This approach would allow more accurate representation of the local system while introducing the new instream decision concepts.

In the discussion of the Dolores River application above, several data items were mentioned. When applying this

model framework, it is imperative that the biological representations be validated for each particular system. That includes reviewing the PHABSIM sites, SI curves, temperature responses and population samples for representativeness. The data supporting these variables must also capture the range and timing of critical events.

As noted in the introduction, the success of any application of this suite of models depends on the will of users to seek solutions to this class of problems. Model users from many groups must openly participate, bringing their best information to the analysis. When results are unclear or trade-offs difficult, thoughtful interpretation will still be needed.

FUTURE RESEARCH

All of the caveats presented in this thesis regarding the effective habitat time series model point to one conclusion. A reliable model of fish population that relates streamflow to population is sorely needed. The decision algorithm developed here could be modified to incorporate such a model in lieu of the effective habitat time series. The efforts to develop such models noted in Chapter 2 are ongoing. Given their success this work could be extended to a direct population representation.

Since the Dolores River and McPhee Dam are relatively isolated from other water resource systems and fish populations, this would be an excellent location for controlled tests. The management concepts developed here could be tested and refined with fewer intervening variables than many other locations with tailwater fisheries.

The effective habitat model and the method of application developed here need further exploration as management tools. Further work to learn when the effective habitat model can be used as a general predictor of fish populations is needed. Specific life stages in some trout populations may be more sensitive to habitat limitations than the model indicates. Further work to identify a "safety factor" to be added to habitat demand should be investigated. Starting from the base provided by this thesis, other management algorithms can be developed to deal with this and a wide variety of fish population management issues.

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Appendix 1

STATE INSTREAM FLOW LAWS: COLORADO AND WYOMING

COLORADO

The prior appropriation doctrine of water rights has been in place in Colorado since statehood. Article XVI of the Colorado Constitution, adopted in 1876, declares all water of every stream to be public property and gives rights to divert it as follows:

> Section 5. Water of streams public property. The Water of every natural stream, not heretofore appropriated, within the state of Colorado, is hereby declared to be the property of the public, and the same is dedicated to the use of the people of the state, subject to appropriation as hereinafter provided.
>
> Section 6. Diverting unappropriated water - priority preferred uses. The right to divert the unappropriated waters of nay natural stream to beneficial uses shall never be denied. Priority of appropriation shall give the better right as between those using the water for the same purpose; but when the waters of any natural stream are not sufficient for the service of all those desiring the use of the same, those using the water for domestic purposes shall have the preference over those claiming for any other purpose, and those using the water for agricultural purposes shall have preference over those using the same for manufacturing purposes.

In a subsequent case, the Colorado Supreme Court rejected the riparian water right doctrine for Colorado. It held that the appropriation doctrine was the law in Colorado since before the constitution was adopted [Coffin v. Left Hand Ditch Co., 6 Colo. 443 (1882)].

Colorado is unique among western states using the appropriative doctrine in that its water rights are granted through a special water court. Most states use some form of permit system with the permits issued by an entity within the administrative branch of the state government. The Colorado system requires a water right applicant to file with the water court for his area. After a notice period, a referee rules on the application. Applications approved by the referee are forwarded to the water court judge. The judge's ruling may be protested and appealed. After the appeal process is satisfied the water right is decreed with conditions appropriate to the situation (Trembly, 1987).

The primary test of a water right in Colorado has been the application of the water to a beneficial use. In 1973 the Colorado Legislature passed a statute that recognized instream flow as a beneficial use. It authorized the Colorado Water Conservation Board to appropriate streamflows for preservation of the "natural environment to a reasonable degree" (CRS ss 37-92-102). These changes were enacted as Senate Bill 97. It contains the following items:

Section 1. 148-21-3 (6), (7) and (10), Colorado Revised Statutes 1963 (1969 Supp.), are amended to read:

148-21-3. Definition. (6) "Appropriation" means [the diversion of a certain portion of the waters of the state and] the application of [the same] A CERTAIN PORTION OF THE WATERS OF THE STATE to a beneficial use.

(7) "Beneficial use" is the use of that amount of water that is reasonable and appropriate under reasonably efficient practices to accomplish without waste the purpose for which the [diversion] APPROPRIATION is lawfully made and, without limiting the generality of the foregoing, shall include the impoundment of water for recreational purposes, including fishery of wildlife. FOR THE BENEFIT AND ENJOYMENT OF PRESENT AND FUTURE GENERATIONS, "BENEFICIAL USE" SHALL ALSO INCLUDE THE APPROPRIATION BY THE STATE OF COLORADO IN THE MANNER PRESCRIBED BY LAW OF SUCH MINIMUM FLOWS BETWEEN SPECIFIC POINTS OR LEVELS FOR AND ON NATURAL STREAMS AND LAKES AS ARE REQUIRED TO PRESERVE THE NATURAL ENVIRONMENT TO A REASONABLE DEGREE.

In 1981 the Colorado Legislature added some clarifications to CRS ss 37-92-102 in Senate Bill 414. S.B. 414 stated that instream water rights would not restrict the use of water imported from another watershed. It also stated that they would be subject to existing exchange agreements and that condemnations of easements on private land for access to streams that have instream rights was not authorized (Trembly, 1987).

Further clarifications were added by S.B. 91 in 1986. The Colorado Water Conservation Board was required to request recommendations from the U.S. Department of Agriculture and the U. S. Department of the Interior regarding appropriation of water for "preservation of the environment to a reasonable degree". Before S.B. 91, the CWCB relied on the Colorado

Division of Wildlife to provide the supporting information regarding the amount of streamflow needed to preserve the environment. S.B. 91 was intended to be an invitation to the Federal Government to cooperate with the state in establishing instream flows on Federally administered lands. The legislature hoped that this cooperation in quantifying instream flow needs would avoid application of the Federal reserved rights doctrine and reduce uncertainty about water rights on Federal lands (Trembly, 1987).

The CWCB has obtained instream water rights on numerous streams. By the end of 1986, nearly 930 streams had instream water rights in place. These rights hold the priority date of the time filed, that is, they all have dates later than 1973. The stream segments with instream rights comprise nearly 5550 stream miles (Trembly, 1987). It should be noted; however, the instream water rights were filed primarily in headwater areas where there was little competition for water. As the typical instream filing comprises less than 2 cfs, it can be seen that the CWCB has been striving to avoid controversy both in the location and volume of instream water rights (Meyer, 1987).

WYOMING

Like Colorado, Wyoming is an appropriative doctrine state. The Wyoming Constitution states in Article 8-001:

"The water of all natural streams, springs, lakes or other collections of still water, within the boundaries of the State, are hereby declared to be the property of the State." In contrast to Colorado the supervision of water matters is placed under the State Engineer and the Board of Control (Wyoming Constitution Art. 8-002). The Board of control consists of the State Engineer and the superintendents of four geographical water divisions. The Board meets quarterly to adjudicate or finalize water rights. They also consider other matters pertaining to water rights, such as changes in points of diversion or other amendments or corrections of water rights [WS ss 41-4-201 et. seq.].

To acquire a water right, a water user must obtain a permit from the State Engineer. Water rights cannot be obtained by historic use or by adverse possession. The water user must state his intention and act as follows:

(1) state the intent to appropriate water,

(2) provide public notice of the appropriation,

(3) comply with state permit application requirements,

(4) divert the water, and

(5) put the water to a beneficial use (Trembly, 1987).

In 1986, Wyoming enacted a law recognizing appropriation of water for instream flows. Enrolled Act No. 53 became WS ss 41-3-1001 to 10014. It provides that unappropriated water

may be appropriated for instream flows to maintain or improve fisheries. The State Engineer determines when such instream flows constitute a beneficial use, "if the use does not impair or diminish the rights of any other appropriator in Wyoming" [WS ss 41-3-1001(a)]. The law stipulates that instream flows shall be the minimum flow necessary to establish, improve or maintain fisheries [WS ss 41-3-1001(c)].

There are some important differences and similarities between the Wyoming and Colorado laws. They would appear to make Wyoming ripe for a method for managing water storage for instream flows. The first is recognition of storage of water for providing a recreational pool or for instream flows as a beneficial use [WS ss 41-3-1001(c)]. In a second important distinction from Colorado, the Wyoming law allows acquisition of existing water rights for instream flow purposes. The State may acquire existing water rights in streams by transfer or gift for the purpose of providing instream flows as stated in WS ss 41-3-1004. Such rights are limited to a specified stream segment and retain their original priority date [WS ss 41-3-1007(b)].

The Wyoming Game and Fish Commission is the agency providing support for instream flow water right claims and regulation of such rights. They must provide the technical information from which the State Engineer will make the

determination of beneficial instream use. Further, they must originate the "call" on the river when the instream right may be injured by other water users. This request for regulation of the river can come only if present or future injury to the fishery can be shown. The call cannot be a futile call, and the call cannot impair senior water rights [WS ss 41-3-1008].

There are other means of maintaining instream flows under Wyoming law. The State Engineer can deny new permits or changes in old permits that may adversely influence the public interest. In addition, permits for major energy or industrial projects may have instream flow mitigation requirements (Trembly, 1987).

The approach proposed here has potential use under existing Wyoming statutes. Colorado law does not currently recognize storage for instream flow as a beneficial use. That change to Colorado law would be required to obtain a similar level of general applicability.

Appendix 2

HYDRAULIC MODEL CALIBRATION AND CALCULATION OF WEIGHTED USABLE AREA FOR THE DOLORES RIVER

The feasibility of managing stored water to provide instream flows is influenced by the relationship between the instream benefit gained and discharge. The models developed in this study use the habitat - discharge relation generated by the U.S. Fish and Wildlife Service's Physical Habitat Simulation System (PHABSIM) (Milhous, et al., 1989). The study conclusions are sensitive to the form of the habitat - discharge relation. This appendix presents the process used to develop that relation for the Dolores River. The topics covered below include the steps in a typical PHABSIM application, the problems encountered with the Dolores River data, selection of suitability of use index (SI) curves, and a sensitivity analysis that led to resolution of those problems. The appendix concludes with the habitat simulation data for the Dolores River.

STEPS IN PHABSIM HYDRAULIC AND HABITAT SIMULATION

The underlying concepts of the physical habitat simulation model are described in Chapter 4. This appendix contains a summary of a normal PHABSIM application. The reader is referred to Milhous, et al. (1989) for a detailed description of the models in PHABSIM.

The general process for calibrating open channel hydraulic data sets in the PHABSIM system consists of the following steps. First, the step-backwater model WSP is calibrated to the observed water surface profile by selecting Manning's n values for each measured transect. When more than one discharge has been measured, the changes in n as a function of discharge are included in this calibration. These changes are used to fit an exponential function of n and discharge allowing the n values for all discharges of interest to be identified.

The second step in the process is to simulate the water surface elevations for all discharges of interest using the backwater model. The discharge related changes in Manning's n are incorporated in this process to assure maximum accuracy of the backwater curves. This step ensures a longitudinal energy balance for the entire study area for all simulated discharges.

The next step is simulation of the lateral velocity distribution at each cross section. The PHABSIM model IFG4 is used to distribute velocities across the channel by applying Manning's equation to each cell and relying on the observed velocity measurement set(s) to provide the local n value. Thus the n values for each cell are used as velocity distribution devices. In this process, each cross section is treated independently. This application of IFG4 uses the water surface elevations from the backwater model to ensure that conservation of energy is preserved.

The hydraulic simulation process produces a mosaic of depth and velocity values for each discharge for each cell in the study area. This depth and velocity information is passed to the habitat simulation where the habitat suitability of each combination is evaluated.

The models in PHABSIM were developed at the Fish and Wildlife Service's National Ecology Research Center (NERC). NERC advises users to verify the applicability of suitability of use index (SI) criteria prior to each application. It is possible for an aquatic species to respond differently to particular depth, velocity, and channel conditions depending on the mix of conditions available in each stream. Thus it is important that the SI criteria be checked before each new use.

Once the SI criteria have been checked, the next step is to simulate the habitat in the stream at various discharges. The result of this process is a relation between habitat, called Weighted Usable Area (WUA), and discharge.

When this relation has been derived, the final step in PHABSIM use is to evaluate the occurrence of habitat for each life stage of each species of interest over time. NERC provides a set of computer programs in the Time Series Library (TSLIB) for this purpose. They interpolate habitat values from the WUA relations for a discharge time series and allow various frequency of occurrence analyses to be performed.

HYDRAULIC CALIBRATION OF THE DOLORES RIVER PHABSIM DATA SET

I received a PHABSIM data set from the Colorado Division of Wildlife (DOW) (Nehring, 1990) for a study site 1/2 mile below McPhee Dam. The data were collected by DOW in 1986 and analyzed by a consultant. I received the data as several hydraulic and habitat model input files, and the suitability of use criteria used in the original analysis. Those data are contained in the tables at the end of this appendix. No field notes were available. The data contained lateral and longitudinal profiles, water surface elevations for one discharge (405 cfs), and the Manning's n values the

consultant used to fit the observed backwater curve. The channel has since been modified so it was not possible to obtain additional measurements to verify or improve the data.

The data contained only one discharge. Thus there were no other data against which to verify the hydraulic simulations. A simple sensitivity analysis approach to selecting the best hydraulic simulation was chosen. The backwater model was calibrated using two methods of selecting n values. Combined with the n values in the original data set these allowed comparison of the resulting differences in the habitat simulation.

The following table and figure summarize the study site backwater information in the original data set.

Table A2.1. Original PHABSIM Study Site Data for 405 cfs. **

Cross Section	Thalweg Elevation	Water Surface Elevation	Manning's n
0	89.8	92.44	0.032
62	88.7	92.50	0.030
232	90.2	93.17	0.092
287	89.3	93.17	0.010
453	91.3	93.38	0.040
910	91.5	94.38	0.064
1434	94.1	95.82	0.032

** Units: Cross section distances as ft from downstream control, Elevations as ft above an arbitrary datum

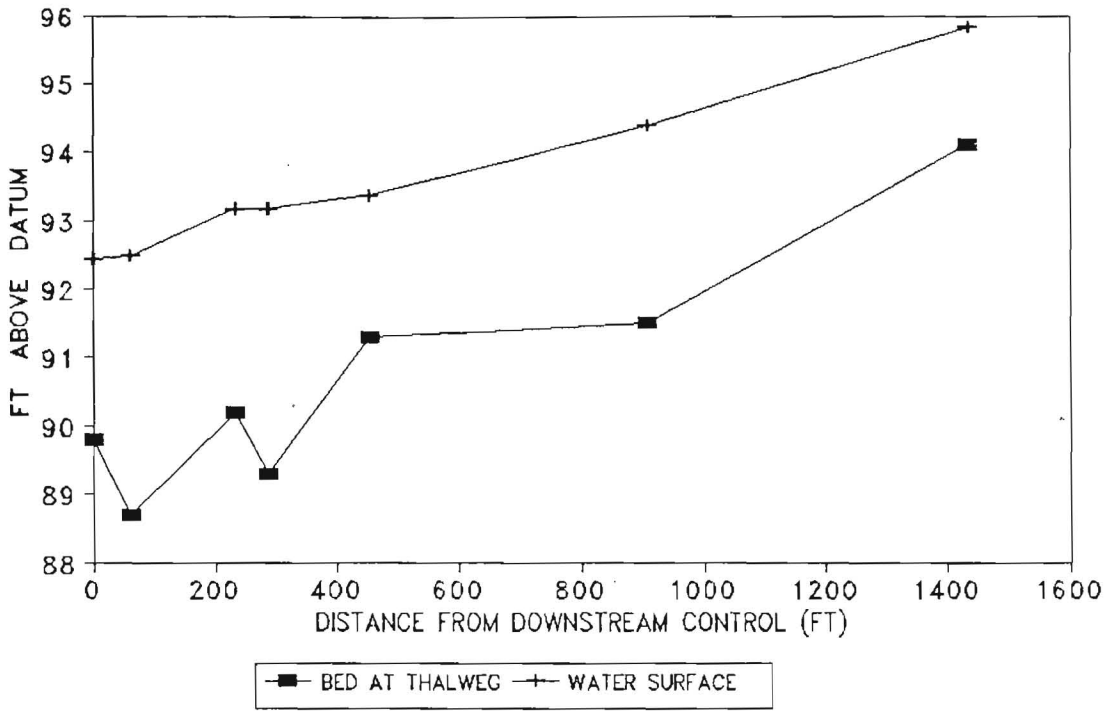

Figure A2.1. PHABSIM Site Water Surface and Bed Profile

A problem with n values was discovered while evaluating the backwater calibration. Though there was no significant change in bedform or substrate type, n varied nearly an order of magnitude w/in a distance of 50 ft between cross sections 232 and 287. The original calibration traded overall accuracy of representation for precision of calibration to the observed water surface profile. Experience with backwater models suggests that significant extrapolation errors may occur when wide variations in modeled channel resistance (n values) do not correspond to dramatic changes in the stream bed (Milhous, 1991). For this reason, the data set was recalibrated.

When using the backwater model, NERC experience suggests that using n values in the approximate range indicated by the substrate material is a good place to begin. Since there were no apparent reasons in the data (constrictions in the channel, sharp changes in channel profile, or expansions) to believe otherwise two approaches were chosen. First, n was confined to the range $0.030 < n < 0.055$ based on the coarse gravel -cobble bed material. The intent was to improve accuracy of representation by using n values more closely related to sediment size and still achieve as much precision in calibration as possible. The second approach was to use a constant Manning's n of 0.050 for all cross sections. In doing so, some precision of calibration was sacrificed for accuracy of simulation.

The backwater model WSP could not project the measured water surface profile from transect 62 to transect 232. Personal communication with Nehring (1990) indicated there was a diagonal gravel bar in that area. Since the cross section data only intersected the bar at one location, there was insufficient information to model the transition from transect 62 to transect 232. Transect 232 appears to be a control, so the backwater calculation was broken between the two pools.

Considerable difficulty was experienced fitting a realistic water surface profile at the upper transect. There

may have been a measurement error, an undetected change in discharge while measurements were being made or a change in the channel that was not described. The measured water surface elevation is too low to provide both mass balance and velocities that are consistent with the other transects. To resolve this problem, n values consistent with the bed material were selected. The last water surface elevation was allowed to be simulated higher than the observed water surface.

Table A2.2 shows the calibration and measured water surface elevations. The calibrations are constrained by possible measurement errors, possible omissions of needed transects, restricting the range of n values to those believed to represent the channel conditions and avoiding unusual variation of n over short distances.

Table A2.2. Calibrated Water Surface Elevations (WSL).

Cross Section	Measured WSL	Original Calibration	Varied n WSL	Fixed n WSL
0	92.44	92.44	92.44	92.44
62	92.51	92.51	92.51	92.59
232	93.17	93.15	93.12	93.12
287	93.17	93.19	93.18	93.22
453	93.38	93.37	93.44	93.49
910	94.38	94.38	94.37	94.32
1434	95.82	95.82	95.92	96.05

Units: (ft.), cross section distances as ft. from downstream control, elevations as ft. above an arbitrary datum

The starting water surface elevations for all simulated discharges were established using the MANSQ model from PHABSIM. In that model there are several options for adjusting Manning's n as a function of discharge. Since only one discharge measurement was available and the approximate size of the bed material was known, the Griffith equation option was chosen (see Milhous, et al., 1989). The Griffith equation is used to adjust Manning's n as follows:

$$\frac{n}{n_c} = \left(\frac{R_c}{R}\right)^{1/6} * \left(\frac{\log\left(2.42\left(\frac{R}{D_{50}}\right)\right)}{\log\left(2.42\left(\frac{R_c}{D_{50}}\right)\right)}\right) \qquad \text{(A2.1}$$

where: n = Manning's n for each simulated discharge,

n_c = Manning's n for the calibration discharge,

R = hydraulic radius for simulated discharge (ft),

R_c = calibration discharge hydraulic radius (ft), and

D_{50} = median bed material size (ft).

An estimated D50 of 0.33 ft was used based on the substrate codes in the data set and based on my own observations of the river bed made in June 1991. The resulting initial water surface elevations for each discharge at the two control sections (stations 0 and 232) and the multipliers for adjusting Manning's n are given in Table A2.3. At the calibration discharge there is no adjustment of n, ie. the multiplier is 1.0.

Table A2.3. N Multipliers and Control Water Surface Elevations (WSL) Used in Backwater Model.

Simulated Discharge	Cross Section 0 n Multiplier	Cross Section 0 WSL	Cross Section 232 n Multiplier	Cross Section 232 WSL
20	1.53	90.75	1.74	91.48
50	1.29	91.07	1.40	91.77
75	1.22	91.26	1.30	91.95
100	1.19	91.44	1.24	92.09
150	1.11	91.66	1.15	92.31
200	1.09	91.90	1.10	92.50
250	1.06	92.06	1.07	92.67
300	1.03	92.19	1.04	92.83
405	1.00	92.44	1.00	93.12
500	0.97	92.63	0.98	93.37
750	0.94	93.08	0.94	93.92
1000	0.92	93.52	0.92	94.44
1500	0.91	94.39	0.89	95.15
2000	0.89	94.83	0.87	95.75
4000	0.85	96.31	0.83	97.69

Units: cross section (XSEC) distances as ft. from downstream control, elevations as ft. above an arbitrary datum, discharges in cfs, n multipliers: dimensionless

IFG4 was used to distribute velocities across each transect by supplying water surface elevations from the respective backwater simulations for each discharge at each cross section. The IFG4 model adjusts Manning's n for each cell as a function of depth. In three cases the minimum n for each cell was restricted to 0.050 using options in the IFG4 model. The purpose was to prevent the model from passing a disproportionate share of the discharge through any cell due to an unrealistically low n value producing high velocities. When this occurs, the model may simulate unrealistically low velocities in several other cells on a transect due to preserving mass balance. If several cells

have low velocities, the simulated habitat values may be too high.

A total of eight hydraulic simulations were performed. Two of them are omitted here. One representation of the original data set produced highly unrealistic velocities and the habitat simulation failed. The other omitted simulation was redundant.

Three backwater simulations were performed. The original data set was reprocessed, Manning's n was varied among cross sections and a constant Manning's n was used. For each of these backwater simulations, two lateral velocity distribution approaches were used; limiting and not limiting the minimum Manning's n value in IFG4. These six different hydraulic representations were used to calculate habitat. The habitat simulations were conducted using the depth and velocity values produced by IFG4.

HABITAT SIMULATION AND SENSITIVITY RESULTS

Habitat simulation in the PHABSIM system depends on two kinds of information. They are depth, velocity and channel index for each cell from the hydraulic simulations and suitability of use data describing the responses of stream biota to those variables. The sensitivity analysis includes

the six alternative hydraulic simulations described above and two choices in suitability of use data.

The data provided by DOW included suitability of use (SI) curves for brown and rainbow trout. The DOW SI curves contain an almagum of data from Raleigh, et al. (1984 and 1986) and locally derived curves for some life stages.

Comparisons of the hydraulic simulation alternatives were made using the suitability of use data for Adult Brown Trout (Salmo trutta). Figure A2.2 shows that there is some

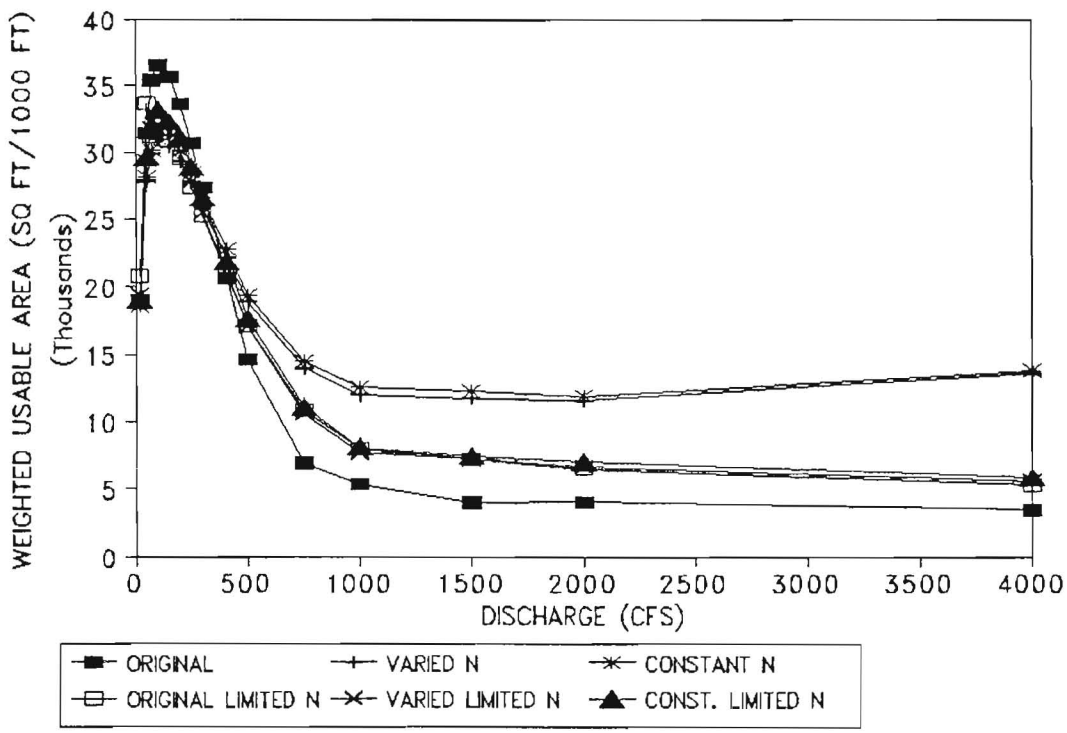

Figure A2.2. Habitat - Discharge Relations with Different Hydraulic Simulations

variation among the habitat - discharge relations. However, they all have the same basic form, including similar maxima and similar response to increasing discharge. Five of the relations were regressed against the last (constant Manning's n with n limited during lateral velocity simulation). The regression coefficients (R squared) ranged from 0.9808 to 0.9989. Similar results were obtained for the other life stages. From these results, I concluded that the habitat - discharge relation is relatively insensitive to possible errors in the hydraulic simulation.

The habitat - discharge relations shown in Figure A2.2 have a significant problem. They all indicate that the habitat suitability for adult brown trout in the Dolores River at 20 cfs is greater than the suitability for any discharge above about 450 cfs. Discussions with the biologists familiar with the stream indicate this is highly unlikely. If this were true, the high flows in this stream would be more limiting to the population than extremely low flows. Since Mcphee Dam begin controlling the flow in this river there have been at least three high spring releases with a duration of one week or more. Samples of the fish population indicate a decline in fish numbers and biomass was not associated with those high flows (Nehring, 1991).

The low habitat values at high discharge in the WUA relations may be attributable to several causes. These

include error in sampling the stream environment (treated above), insufficient number of transects to describe the stream, extrapolation errors in the hydraulic simulations, or inadequate SI curve representation of the fish species' behavior. The evidence suggests that the SI curves need evaluation as recommended for a typical PHABSIM application.

Recent research at NERC suggests that the velocity and depth preferences of brown and rainbow trout differ from those reported in Raleigh, et al. (1984 and 1986). This research uses a snorkel diving technique to observe the fish in a wide variety of habitats. Bovee and Thomas (1992) provided preliminary SI curves for adults and juveniles of the two species used in this study. The habitat - discharge relations produced by these curves are much more consistent with the expectations of the field biologists. This information was not available to DOW at the time of the original study.

Figure A2.3 compares the adult brown trout habitat - discharge relations described by use of the newer SI curves. The R squared obtained by regressing the relation derived from the DOW SI curves on the newer Bovee and Thomas derived relation is 0.0088. From the unmistakable differences in R squared values, I concluded that the habitat description for the Dolores River is more sensitive to selection of SI curves than to alternative hydraulic simulations.

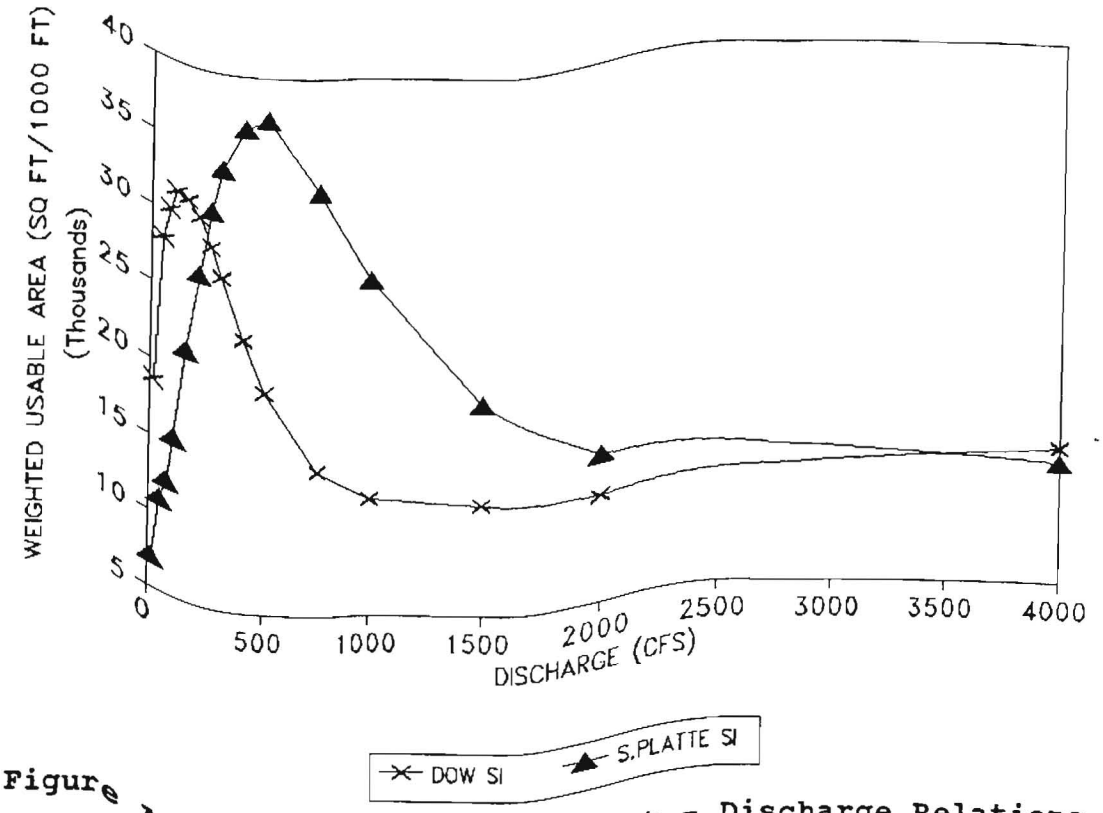

Figure A2.3. Dolores River Habitat - Discharge Relations for Adult Brown Trout Using Two SI Criteria

The newer habitat - discharge functions for adult trout appear to better represent the conditions in the Dolores River. That is, the habitat suitability at low discharges is less than it is at very high discharges. There are few empirical data describing the response of trout adults to depth and velocity during high flow conditions. However, Nehring (1991) concludes the trout populations survived the high flows that occurred since 1984 better than the low flow conditions of 1990. This suggests the newer SI curves should be used in the Dolores River.

The habitat - discharge relations for each life stage of the two trout species used in this study were evaluated. The combination of hydraulic simulation, SI curve and habitat simulation option for each life stage that appeared to best represent the phenomena occurring in the Dolores River was selected. These choices were reviewed by R. Barry Nehring, DOW research biologist (Nehring, 1992). Table A2.4. lists the SI criteria used for each species and life stage. Table A2.5 contains a tabulation of the SI criteria and table A2.6 contains the habitat - discharge relations for each life stage of the two species. Tables A2.7 through A2.9 contain the original data received from DOW.

Table A2.4. Suitability of Use Index (SI) Criteria and Simulation Option Used

Species and Life Stage	SI Criteria Source	Simulation Option
Brown Trout		
Spawning	DOW/Raleigh	Mean Column Velocity
Fry	DOW 2-4 Week	Nose Velocity **
Fingerling	DOW	Nose Velocity
Juvenile	Bovee and Thomas	Mean Column Velocity
Adult	Bovee and Thomas	Mean Column Velocity
Rainbow Trout		
Spawning	DOW/Raleigh	Mean Column Velocity
Fry	DOW 2-4 Week	Nose Velocity
Fingerling	DOW	Nose Velocity
Juvenile	Bovee and Thomas	Mean Column Velocity
Adult	Bovee and Thomas	Mean Column Velocity

** Nose Velocity is a habitat simulation option that uses velocities at a specified distance above the stream bed rather than the mean column velocity.

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves

H 11110 6 4 11 0 BROWN TROUT SPAWNING

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	0.00	0.00	0.00	0.00	0.00
0.30	0.00	0.20	0.00	1.00	0.00
0.70	1.00	0.80	1.00	2.00	1.00
1.70	1.00	10.00	1.00	3.00	1.00
3.90	0.00	100.00	1.00	4.00	1.00
100.00	0.00	0.00	0.00	5.00	0.10
0.00	0.00	0.00	0.00	6.00	0.00
0.00	0.00	0.00	0.00	7.00	0.00
0.00	0.00	0.00	0.00	8.00	0.00
0.00	0.00	0.00	0.00	9.00	0.00
0.00	0.00	0.00	0.00	100.00	0.00

H 11112 12 10 11 0 BROWN TROUT 2-4WEEKS

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	1.00	0.00	0.00	0.00	0.00
0.10	0.45	0.10	0.40	1.00	1.00
0.20	0.37	0.20	1.00	2.00	1.00
0.30	0.28	0.50	1.00	3.00	1.00
0.40	0.10	0.60	0.30	4.00	1.00
0.50	0.04	0.70	0.20	5.00	1.00
0.60	0.03	0.80	0.14	6.00	0.50
0.70	0.02	0.90	0.04	7.00	0.40
0.80	0.01	1.00	0.00	8.00	0.10
0.90	0.00	100.00	0.00	9.00	0.05
1.00	0.00	0.00	0.00	100.00	0.00
100.00	0.00	0.00	0.00	0.00	0.00

H 11113 7 7 11 0 BROWN TROUT FNGRLING

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.38	0.66	0.19	1.00	1.00
0.60	1.00	1.31	1.00	2.00	1.00
0.90	0.94	1.61	1.00	3.00	1.00
1.20	0.47	2.30	0.82	4.00	1.00
2.90	0.00	4.60	0.00	5.00	1.00
100.00	0.00	100.00	0.00	6.00	1.00
0.00	0.00	0.00	0.00	7.00	1.00
0.00	0.00	0.00	0.00	8.00	0.05
0.00	0.00	0.00	0.00	9.00	0.05
0.00	0.00	0.00	0.00	100.00	0.00

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves (Continued)

H 11114 9 9 11 0 BROWN TROUT DOW JUVENILE

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.58	0.00	0.00	0.00	0.00
0.10	0.88	0.50	0.12	1.00	0.67
0.50	1.00	1.00	0.61	2.00	0.67
1.00	0.92	2.00	0.84	3.00	0.67
1.50	0.70	3.00	1.00	4.00	0.67
2.00	0.26	4.00	0.27	5.00	1.00
3.50	0.05	7.00	0.24	6.00	1.00
4.30	0.00	8.00	0.08	7.00	1.00
100.00	0.00	100.00	0.08	8.00	0.75
0.00	0.00	0.00	0.00	9.00	0.10
0.00	0.00	0.00	0.00	100.00	0.00

H 11134 12 17 11 0 BROWN TROUT S. PLATTE CONT JUVENILE

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.60	0.00	0.00	0.00	0.00
0.50	0.82	0.40	0.11	1.00	0.67
0.79	0.92	0.57	0.18	2.00	0.67
1.13	1.00	0.75	0.29	3.00	0.67
1.57	1.00	1.05	0.55	4.00	0.67
1.97	0.91	1.31	0.80	5.00	1.00
2.31	0.80	1.48	0.92	6.00	1.00
3.29	0.42	1.66	1.00	7.00	1.00
3.73	0.28	1.83	1.00	8.00	0.75
4.31	0.15	2.05	0.89	9.00	0.10
5.06	0.00	2.35	0.62	100.00	0.00
100.00	0.00	2.65	0.35	0.00	0.00
0.00	0.00	2.87	0.20	0.00	0.00
0.00	0.00	3.13	0.09	0.00	0.00
0.00	0.00	3.22	0.06	0.00	0.00
0.00	0.00	3.82	0.00	0.00	0.00
0.00	0.00	100.00	0.00	0.00	0.00

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves (Continued)

H 11115 10 9 11 0 BROWN TROUT DOW ADULT

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.21	0.00	0.00	0.00	0.00
0.10	0.70	1.60	0.87	1.00	0.50
0.50	1.00	2.00	0.95	2.00	0.50
1.00	0.69	2.60	1.00	3.00	0.70
1.50	0.50	3.60	0.84	4.00	0.80
2.40	0.20	4.00	0.45	5.00	1.00
3.10	0.03	5.00	0.30	6.00	1.00
5.00	0.03	7.00	0.21	7.00	1.00
6.00	0.00	100.00	0.21	8.00	0.80
100.00	0.00	0.00	0.00	9.00	0.10
0.00	0.00	0.00	0.00	100.00	0.00

H 11135 14 15 11 7 BROWN TROUT S. PLATTE CONT ADULT

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.33	0.00	0.00	0.00	0.00
0.82	0.81	0.23	0.10	1.00	0.50
1.07	0.92	0.88	0.25	2.00	0.50
1.32	1.00	1.31	0.40	3.00	0.70
1.63	1.00	2.25	0.80	4.00	0.80
1.94	0.92	2.68	0.94	5.00	1.00
3.00	0.44	2.97	1.00	6.00	1.00
3.49	0.26	3.40	1.00	7.00	1.00
3.74	0.19	3.77	0.92	8.00	0.80
4.18	0.11	4.63	0.58	9.00	0.10
4.68	0.06	5.21	0.34	100.00	0.00
5.55	0.02	5.57	0.22	0.00	0.00
5.80	0.00	6.00	0.12	0.00	0.00
100.00	0.00	6.90	0.00	0.00	0.00
0.00	0.00	100.00	0.00	0.00	0.00

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves (Continued)

H 21110 7 6 11 0 RAINBOW TROUT SPAWNING

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	0.00	0.00	0.00	0.00	0.00
0.50	0.00	0.30	0.00	1.00	0.00
1.30	0.95	0.70	1.00	2.00	1.00
1.40	1.00	2.00	1.00	3.00	1.00
2.00	1.00	3.00	0.00	4.00	1.00
3.20	0.00	100.00	0.00	5.00	0.10
100.00	0.00	0.00	0.00	6.00	0.00
0.00	0.00	0.00	0.00	7.00	0.00
0.00	0.00	0.00	0.00	8.00	0.00
0.00	0.00	0.00	0.00	9.00	0.00
0.00	0.00	0.00	0.00	100.00	0.00

H 21112 12 10 11 0 RAINBOW TROUT 2-4WEEKS

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	1.00	0.00	0.00	0.00	0.00
0.10	0.45	0.10	0.40	1.00	1.00
0.20	0.37	0.20	1.00	2.00	1.00
0.30	0.28	0.50	1.00	3.00	1.00
0.40	0.10	0.60	0.30	4.00	1.00
0.50	0.04	0.70	0.20	5.00	1.00
0.60	0.03	0.80	0.14	6.00	1.00
0.70	0.02	0.90	0.04	7.00	0.50
0.80	0.01	1.00	0.00	8.00	0.10
0.90	0.00	100.00	0.00	9.00	0.01
1.00	0.00	0.00	0.00	100.00	0.00
100.00	0.00	0.00	0.00	0.00	0.00

H 21113 7 10 11 0 RAINBOW TROUT FNGRLING

VELOCITY		DEPTH		CHANNEL	DESCRPT.
0.00	1.00	0.00	0.00	0.00	0.00
0.60	1.00	0.20	0.10	1.00	1.00
1.00	0.70	0.30	0.20	2.00	1.00
1.50	0.50	0.50	1.00	3.00	1.00
2.00	0.20	1.00	1.00	4.00	1.00
2.50	0.00	1.80	0.20	5.00	1.00
100.00	0.00	3.00	0.05	6.00	1.00
0.00	0.00	6.00	0.05	7.00	0.50
0.00	0.00	7.00	0.00	8.00	0.05
0.00	0.00	100.00	0.00	9.00	0.01
0.00	0.00	0.00	0.00	100.00	0.00

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves (Continued)

H 21114 10 11 11 0 RAINBOW TROUT DOW JUVENILE

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.00	0.40	0.00	1.00	1.00
0.30	0.95	0.60	1.00	2.00	1.00
0.60	1.00	1.00	1.00	3.00	1.00
1.40	1.00	1.60	0.40	4.00	1.00
2.00	0.60	2.00	0.30	5.00	1.00
2.50	0.20	3.00	0.20	6.00	1.00
3.00	0.04	4.00	0.10	7.00	1.00
4.00	0.00	6.00	0.10	8.00	0.50
100.00	0.00	7.00	0.00	9.00	0.10
0.00	0.00	100.00	0.00	100.00	0.00

H 21134 13 16 11 0 RAINBOW TROUT S. PLATTE CONT JUVENILE

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.72	0.00	0.00	0.00	0.00
0.52	0.93	0.30	0.08	1.00	0.67
0.80	1.00	0.47	0.16	2.00	0.67
1.18	1.00	0.65	0.29	3.00	0.67
1.50	0.92	1.11	0.77	4.00	0.67
2.02	0.71	1.34	0.90	5.00	1.00
2.67	0.39	1.63	1.00	6.00	1.00
3.04	0.24	1.86	1.00	7.00	1.00
3.42	0.14	2.09	0.93	8.00	0.75
3.74	0.08	2.55	0.66	9.00	0.10
4.12	0.04	3.01	0.36	100.00	0.00
4.28	0.00	3.36	0.19	0.00	0.00
100.00	0.00	3.65	0.10	0.00	0.00
0.00	0.00	4.00	0.04	0.00	0.00
0.00	0.00	4.63	0.00	0.00	0.00
0.00	0.00	100.00	0.00	0.00	0.00

Table A2.5. Suitability of Use Index (SI) Criteria for Each Life Stage of Two Trout Species, Including Division of Wildlife and South Platte Curves (Concluded)

H 21115 6 4 11 0 RAINBOW TROUT DOW ADULTS

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.00	0.00	0.00	0.00	0.00
1.00	1.00	1.00	0.20	1.00	1.00
1.50	1.00	1.60	1.00	2.00	1.00
2.00	0.60	100.00	1.00	3.00	1.00
3.00	0.00	0.00	0.00	4.00	1.00
100.00	0.00	0.00	0.00	5.00	1.00
0.00	0.00	0.00	0.00	6.00	1.00
0.00	0.00	0.00	0.00	7.00	1.00
0.00	0.00	0.00	0.00	8.00	1.00
0.00	0.00	0.00	0.00	9.00	0.10
0.00	0.00	0.00	0.00	100.00	0.00

H 21135 14 16 11 6 RAINBOW TROUT S. PLATTE CONT ADULT

VELOCITY		DEPTH		CHANNEL DESCRPT.	
0.00	0.31	0.00	0.01	0.00	0.00
0.56	0.55	0.78	0.07	1.00	1.00
1.17	0.86	1.29	0.19	2.00	1.00
1.42	0.95	1.93	0.44	3.00	1.00
1.60	1.00	2.69	0.81	4.00	1.00
1.90	1.00	3.33	1.00	5.00	1.00
2.15	0.94	3.72	1.00	6.00	1.00
2.45	0.81	4.10	0.93	7.00	1.00
3.19	0.37	5.12	0.59	8.00	1.00
3.49	0.22	5.76	0.38	9.00	0.10
3.92	0.09	6.40	0.23	100.00	0.00
4.29	0.03	7.29	0.11	0.00	0.00
4.90	0.00	8.32	0.05	0.00	0.00
100.00	0.00	9.34	0.03	0.00	0.00
0.00	0.00	10.00	0.00	0.00	0.00
0.00	0.00	100.00	0.00	0.00	0.00

Table A2.6. Final Simulated Habitat - Discharge Relations For The Dolores River

BROWN TROUT	DISCHARGE	SPAWNING	FRY	FINGERLING	JUVENILE	ADULT
1	20	107.07	4013.82	7988.18	13566.27	7117.42
2	50	1526.53	2273.09	20387.22	25855.93	11270.27
3	75	2378.42	1562.64	28807.84	34282.41	12766.97
4	100	2682.96	1421.06	35926.55	41392.15	15994.34
5	150	3343.57	1184.95	44849.73	49649.32	22631.86
6	200	4018.46	931.91	51979.98	53072.43	28555.50
7	250	4753.34	1009.18	55959.60	52115.50	33622.69
8	300	5123.87	949.18	57546.34	48926.43	37154.57
9	405	5333.71	707.43	55498.44	40139.06	40904.29
10	500	5365.79	726.22	51999.34	32381.12	41610.63
11	750	4972.72	1210.91	41368.32	18076.88	35311.46
12	1000	4103.21	1023.68	31167.02	11947.55	27158.11
13	1500	2615.54	1608.89	22742.47	10901.60	16236.46
14	2000	1647.27	1008.83	21470.84	11760.01	11789.49
15	4000	628.90	711.79	22908.18	11438.45	10171.88

RAINBOW TROUT	DISCHARGE	SPAWNING	FRY	FINGERLING	JUVENILE	ADULT
1	20	3.85	5849.74	28006.22	18383.72	2933.03
2	50	426.96	3065.32	39037.89	34029.09	6184.89
3	75	1052.25	1871.94	38012.26	42031.58	8967.10
4	100	1567.53	1653.12	36914.57	47883.68	12049.23
5	150	2371.40	1310.43	32142.78	52951.65	17971.65
6	200	2801.89	999.87	27575.91	53876.04	23846.93
7	250	3126.98	1075.52	24191.72	50820.86	29039.66
8	300	3501.06	1011.18	21599.68	46444.84	33363.26
9	405	4008.20	801.20	17789.71	36598.48	39574.28
10	500	3881.20	1012.60	14311.52	28599.51	41179.91
11	750	2730.66	1398.12	12798.40	15489.29	37052.83
12	1000	1745.93	1224.42	13718.65	10990.63	28400.06
13	1500	684.48	1817.40	15769.83	10838.83	16264.04
14	2000	354.74	1148.69	16329.75	11843.06	12073.96
15	4000	61.78	712.15	15673.09	11608.68	14633.44

Units: Habitat - Weighted Usable Area (sq. ft. / 1000 ft.),
Discharge - cfs

Table A2.7. Original IFG4 Data Set Received From The Colorado Division of Wildlife

```
DOLORES RIVER
ONE HALF MILE BELOW MCPHEE DAM - JULY 1986
IOC       01100002010000000000
QARD  405.
XSEC    0.       0.0 .50     89.77   0.00000
        0.  0.0 96.4  5.0 95.8 10.0 95.5 15.0 94.6 20.0 94.1 25.0 93.6
        0. 30.0 93.6 35.0 94.0 40.0 93.8 45.0 94.1 50.0 94.1 55.0 94.1
        0. 60.0 93.4 66.2 92.4 70.0 92.0 75.0 91.7 80.0 91.8 85.0 91.7
        0. 85.2 91.6 90.0 91.3 95.0 91.3100.0 91.0105.0 90.8110.0 90.5
        0.115.0 90.6120.0 90.3125.0 90.1130.0 89.8135.0 89.8140.0 90.0
        0.145.0 90.1150.0 90.4155.0 90.7160.0 91.1165.0 91.4165.9 91.6
        0.169.6 92.4170.0 93.1178.0 93.4182.0 94.3185.0 95.4189.0 95.8
        0.193.0 96.5198.0 96.7202.0 96.1209.3 98.1
NS      0.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  5.0
NS      0.0.000  5.00.000  4.00.000  6.00.000  6.00.000  6.00.000  6.0
NS      0.0.000  6.00.000  6.00.000  6.00.000  6.00.000  6.00.000  6.0
NS      0.0.000  6.00.000  4.00.000  5.00.000  4.00.000  5.00.000  7.0
NS      0.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  7.0
NS      0.0.000  7.00.000  8.00.000  7.00.000  8.00.000  7.00.000  7.0
NS      0.0.000  6.00.000  5.00.000  1.00.000  1.00.000  1.00.000  1.0
NS      0.0.000  1.00.000  1.00.000  1.0
CAL1   0.0     92.44    405.00
VEL1   0.0
VEL1   0.0      0.00  .10  .80 1.10 1.60 1.40 1.70 2.20 2.50 2.60 2.80
VEL1   0.0 2.90 3.20 3.20 3.70 3.30 3.20 2.80 2.30 1.90 1.40 1.30  .60
VEL1   0.0
XSEC   62.      62.0 .70     89.77   0.00000
       62.  0.0 95.8 10.0 95.0 15.0 95.2 20.0 95.2 30.0 95.0 38.0 94.7
       62. 45.0 94.5 50.0 94.1 55.0 93.8 60.0 93.3 65.0 93.1 70.0 92.5
       62. 75.0 92.6 80.0 92.5 85.0 92.1 90.0 92.0 95.0 92.0100.0 91.7
       62.104.3 91.7105.0 91.6110.0 91.5115.0 91.2120.0 90.7125.0 90.5
       62.130.0 90.4135.0 89.7140.0 89.4145.0 88.7150.0 87.9155.0 89.2
       62.160.0 89.3165.0 89.8170.0 90.2173.5 91.7174.0 92.1174.4 92.5
       62.180.0 95.2185.0 95.9191.0 96.5196.0 96.8204.0 97.0209.0 98.2
       62.214.0 98.1
NS     62.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS     62.0.000  6.00.000  6.00.000  6.00.000  6.00.000  6.00.000  7.0
NS     62.0.000  6.00.000  6.00.000  4.00.000  5.00.000  4.00.000  5.0
NS     62.0.000  4.00.000  5.00.000  4.00.000  6.00.000  6.00.000  6.0
NS     62.0.000  6.00.000  7.00.000  8.00.000  7.00.000  7.00.000  8.0
NS     62.0.000  8.00.000  8.00.000  7.00.000  4.00.000  4.00.000  4.0
NS     62.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS     62.0.000  1.0
CAL1  62.0     92.50    405.00
VEL1  62.0
VEL1  62.0      0.00  .12  .50 1.05  .86  .96  .97 1.18 2.05 1.94 2.11
VEL1  62.0 3.16 3.55 3.78 3.88 4.20 1.70  .13 -.20 -.27 -.15 -.10 0.00
VEL1  62.0
```

Table A2.7. Original IFG4 Data Set Received From The Colorado Division of Wildlife (Continued)

```
XSEC  232.      170.0 .50      90.15    0.00000
      232.  0.0 96.6  5.0 96.4 10.0 95.9 15.0 94.6 20.0 94.2 25.0 94.1
      232. 30.0 93.3 31.0 93.2 33.4 92.1 35.0 92.0 40.0 91.8 45.0 91.7
      232. 50.0 91.4 55.0 91.2 60.0 91.0 65.0 91.3 70.0 91.1 75.0 91.0
      232. 80.0 91.1 85.0 91.2 90.0 91.1 95.0 91.2100.0 94.3105.0 91.2
      232.110.0 91.1115.0 90.5120.0 90.4125.0 90.2130.0 90.6132.0 92.0
      232.135.0 93.1136.0 93.2141.0 94.7142.0 95.3143.0 96.6148.0 97.3
      232.154.0 99.3158.0 99.6
NS    232.0.000  1.00.000  1.00.000  1.00.000  1.00.000  6.00.000  1.0
NS    232.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS    232.0.000  1.00.000  1.00.000  1.00.000  4.00.000  4.00.000  4.0
NS    232.0.000  4.00.000  5.00.000  4.00.000  5.00.000  4.00.000  5.0
NS    232.0.000  4.00.000  5.00.000  7.00.000  7.00.000  5.00.000  4.0
NS    232.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS    232.0.000  1.00.000  1.0
CAL1 232.0     93.17    405.00
VEL1 232.0                                    0.00  .80 1.00  .90 1.20
VEL1 232.0 1.4 1.60 2.10 2.00 2.18 2.10 2.20 2.30 2.50 2.10 2.00 1.80
VEL1 232.0 2.00 2.30 2.20 2.00  .90  .80  .60 0.00
VEL1 232.0
XSEC  287.       55.0 .75      90.15    0.00000
      287.  0.0 98.3  5.0 98.0 19.0 97.8 15.0 97.6 20.0 97.3 25.0 97.0
      287. 30.0 96.6 35.0 95.0 40.0 94.7 45.0 94.0 45.0 94.0 50.0 93.7
      287. 55.0 93.2 57.0 92.1 60.0 91.8 65.0 91.9 70.0 91.5 75.0 91.2
      287. 80.0 90.7 85.0 90.6 90.0 90.3 95.0 90.4100.0 90.3105.0 90.1
      287.110.0 90.0115.0 89.6120.0 90.0125.0 89.6130.0 89.6135.0 89.3
      287.140.0 89.4144.9 92.1145.0 92.1145.1 93.2150.0 96.7155.0 97.2
      287.160.0 97.4165.0 97.6170.0 98.6175.0 99.6180.0 99.9
NS    287.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS    287.0.000  1.00.000  1.00.000  1.00.000  5.00.000  6.00.000  6.0
NS    287.0.000  6.00.000  6.00.000  4.00.000  5.00.000  7.00.000  7.0
NS    287.0.000  6.00.000  6.00.000  6.00.000  6.00.000  6.00.000  5.0
NS    287.0.000  6.00.000  5.00.000  6.00.000  5.00.000  5.00.000  5.0
NS    287.0.000  5.00.000  4.00.000  4.00.000  1.00.000  1.00.000  1.0
NS    287.0.000  1.00.000  1.00.000  1.00.000  1.0
CAL1 287.0     93.17    405.00
VEL1 287.0                                                        0.00
VEL1 287.0  .50 1.00 1.00 1.00 1.20  .00 1.80 2.00 1.80 2.10 2.30 1.90
VEL1 287.0 2.40 1.90 1.50  .60  .30  .30  .10 0.00
VEL1 287.0
XSEC  453.      166.0 .10      91.29    0.00000
      453.  0.0 99.4  5.0 99.3 10.0 97.9 15.0 96.6 20.0 94.4 23.0 93.4
      453. 25.0 92.7 26.9 92.5 30.0 91.6 35.0 91.4 40.0 91.3 45.0 91.9
      453. 50.0 91.8 55.0 91.7 60.0 91.5 65.0 91.7 70.0 91.8 75.0 91.8
      453. 80.0 91.9 85.0 92.0 90.0 91.9 95.0 91.9100.0 91.9105.0 92.1
      453.110.0 91.9115.0 91.8120.0 91.6121.0 92.2125.0 91.6130.0 93.4
      453.133.0 94.7137.0 96.3143.0 97.7146.0 98.7150.0100.2151.0100.8
NS    453.0.000  1.00.000  1.00.000  1.00.000  6.00.000  6.00.000  7.0
```

Table A2.7. Original IFG4 Data Set Received From The Colorado Division of Wildlife (Concluded)

```
NS    453.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  6.0
NS    453.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  7.0
NS    453.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  7.0
NS    453.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  1.0
NS    453.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
CAL1 453.0     93.38    405.00
VEL1 453.0                          0.00 1.30 1.40 1.50 2.20 2.30 2.50
VEL1 453.0 2.40 3.20 3.00 3.20 2.80 3.10 2.60 3.20 2.90 2.50 2.10 2.00
VEL1 453.0 2.00 2.10  .30  .40  .40 0.00
XSEC  910.     457.0 .20     91.50   0.00000
      910.  0.0100.3  5.0 99.9 10.0 99.1 15.0 99.2 20.0 97.4 25.0 97.6
      910. 30.0 96.6 35.0 95.7 37.0 94.4 37.7 93.3 40.0 91.9 45.0 91.7
      910. 50.0 91.6 55.0 91.6 60.0 91.7 65.0 91.9 70.0 91.7 75.0 91.5
      910. 80.0 91.8 85.0 91.8 90.0 91.8 95.0 91.6100.0 91.7105.0 91.8
      910.110.0 92.0115.0 92.1120.0 92.5120.9 93.3121.0 94.4125.0 95.2
      910.130.0 96.0135.0 96.3140.0100.2148.0101.4
NS    910.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS    910.0.000  1.00.000  1.00.000  5.00.000  5.00.000  5.00.000  6.0
NS    910.0.000  6.00.000  6.00.000  7.00.000  7.00.000  7.00.000  7.0
NS    910.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  6.0
NS    910.0.000  6.00.000  6.00.000  6.00.000  1.00.000  1.00.000  1.0
NS    910.0.000  1.00.000  1.00.000  1.00.000  1.0
CAL1 910.0     94.38    405.00
VEL1 910.0                                          0.00  .30  .70 1.30
VEL1 910.0 1.70 1.80 1.90 2.00 2.00 1.90 2.10 2.10 2.10 2.00 2.20 2.40
VEL1 910.0 2.20 1.60  .20  .10 0.00
XSEC 1434.     524.0 .80     94.20   0.00000
     1434.  0.0101.9  5.0101.5 10.0100.5 15.0 99.3 20.0 98.2 25.0 97.2
     1434. 30.0 96.4 34.0 95.8 35.0 95.6 38.7 95.2 40.0 94.3 45.0 94.1
     1434. 50.0 94.7 55.0 94.9 60.0 94.7 65.0 94.7 70.0 94.1 75.0 94.2
     1434. 80.0 94.2 85.0 94.7 90.0 94.7 95.0 94.5100.0 94.4105.0 94.4
     1434.110.0 94.4115.0 94.4120.0 94.8125.0 95.0125.8 95.2130.0 95.9
     1434.135.0 97.1140.0 97.7145.0 99.2150.0 99.9155.0101.2160.0102.6
     1434.172.0102.9
NS   1434.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS   1434.0.000  1.00.000  6.00.000  7.00.000  7.00.000  7.00.000  7.0
NS   1434.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  7.0
NS   1434.0.000  8.00.000  7.00.000  5.00.000  5.00.000  5.00.000  7.0
NS   1434.0.000  7.00.000  7.00.000  7.00.000  7.00.000  7.00.000  5.0
NS   1434.0.000  1.00.000  1.00.000  1.00.000  1.00.000  1.00.000  1.0
NS   1434.0.000  1.0
CAL11434.0     95.82    405.00
VEL11434.0                                      0.00  .70 1.00 1.46 1.50
VEL11434.0 1.20 3.00 3.50 4.10 3.90 3.90 4.20 3.10 3.40 3.40 4.00 3.60
VEL11434.0 2.90 2.40 3.10 2.70 1.00 0.00
VEL11434.0
ENDJ
```

Table A2.8. Original WSP Data Set Received From The Colorado Division of Wildlife

```
DOLORES RIVER WSP INPUT DATA
HALF MILE BELOW MCPHEE DAM
PARD     1      1.00            1.000
QARD  405.    92.440                1.00      1.00
FFFFT                                                                    **
        0.  0.0 96.4  5.0 95.8 10.0 95.5 15.0 94.6 20.0 94.1 25.0 93.6
        0. 30.0 93.6 35.0 93.9 40.0 93.8 45.0 94.1 50.0 94.1 55.0 94.1
        0. 60.0 93.4 66.2 92.4 70.0 92.0 75.0 91.7 80.0 91.8 85.0 91.7
        0. 85.2 91.6 90.0 91.3 95.0 91.3100.0 91.0105.0 90.8110.0 90.5
        0.115.0 90.6120.0 90.3125.0 90.1130.0 89.8135.0 89.8140.0 90.0
        0.145.0 90.1150.0 90.4155.0 90.7160.0 91.1165.0 91.4165.9 91.6
        0.169.6 92.4170.0 93.1178.0 93.4182.0 94.3185.0 95.4189.0 95.8
        0.193.0 96.5198.0 96.7202.0 96.1209.0 98.1
       0.0 .032  5.0   0. .032 10.0   0. .032 15.0   0. .032 20.0   0.        *
       0.0 .032 25.0   0. .032 30.0   0. .032 35.0   0. .032 40.0   0.        *
       0.0 .032 45.0   0. .032 50.0   0. .032 55.0   0. .032 60.0   0.        *
       0.0 .032 66.2   0. .032 70.0   0. .032 75.0   0. .032 80.0   0.        *
       0.0 .032 85.0   0. .032 85.2   0. .032 90.0   0. .032 95.0   0.        *
       0.0 .032100.0   0. .032105.0   0. .032110.0   0. .032115.0   0.        *
       0.0 .032120.0   0. .032125.0   0.-.032130.0   0. .032135.0   0.        *
       0.0 .032140.0   0. .032145.0   0. .032150.0   0. .032155.0   0.        *
       0.0 .032160.0   0. .032165.0   0. .032165.9   0. .032169.6   0.        *
       0.0 .032170.0   0. .032178.0   0. .032182.0   0. .032185.0   0.        *
       0.0 .032189.0   0. .032193.0   0. .032198.0   0. .032202.0   0.        *
       0.0 .032209.3   0.                                                     *
       62.  0.0 95.8 10.0 95.0 15.0 95.2 20.0 95.2 30.0 95.0 38.0 94.8
       62. 45.0 94.5 50.0 94.1 55.0 93.8 60.0 93.3 65.0 93.1 70.0 92.5
       62. 75.0 92.6 80.0 92.5 85.0 92.0 90.0 92.0 95.0 92.0100.0 91.7
       62.104.3 91.7105.0 91.6110.0 91.5115.0 91.2120.0 90.7125.0 90.5
       62.130.0 90.4135.0 89.7140.0 89.4145.0 88.7150.0 87.9155.0 89.2
       62.160.0 89.3165.0 89.8170.0 90.2173.5 91.7174.0 92.1174.4 92.5
       62.180.0 95.2185.0 95.9191.0 96.5196.0 96.8204.0 97.0209.0 98.2
       62.214.0 98.1
      62.0 .030 10.0   0. .030 15.0   0. .030 20.0   0. .030 30.0   0.        *
      62.0 .030 38.0   0. .030 45.0   0. .030 50.0   0. .030 55.0   0.        *
      62.0 .030 60.0   0. .030 65.0   0. .030 70.0   0. .030 75.0   0.        *
      62.0 .030 80.0   0. .030 85.0   0. .030 90.0   0. .030 95.0   0.        *
      62.0 .030100.0   0. .030104.3   0. .030105.0   0. .030110.0   0.        *
      62.0 .030115.0   0. .030120.0   0. .030125.0   0. .030130.0   0.        *
      62.0 .030135.0   0. .030140.0   0. .030145.0   0.-.030150.0   0.        *
      62.0 .030155.0   0. .030160.0   0. .030165.0   0. .030170.0   0.        *
      62.0 .030173.5   0. .030174.0   0. .030174.4   0. .030180.0   0.        *
      62.0 .030185.0   0. .030191.0   0. .030196.0   0. .030204.0   0.        *
      62.0 .030209.0   0. .030214.0   0.                                      *
      232.  0.0 96.6  5.0 96.4 10.0 95.9 15.0 94.6 20.0 94.2 25.0 94.1
      232. 30.0 93.3 31.0 93.2 33.4 92.1 35.0 92.0 40.0 91.8 45.0 91.7
      232. 50.0 91.4 55.0 91.2 60.0 91.0 65.0 91.3 70.0 91.1 75.0 91.0
      232. 80.0 91.2 85.0 91.2 90.0 91.1 95.0 91.2100.0 94.3105.0 91.2
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Table A2.8. Original WSP Data Set Received From The Colorado Division of Wildlife (Continued)

```
 232.110.0 91.1115.0 90.5120.0 90.4125.0 90.2130.0 90.6132.0 92.0
 232.135.0 93.1136.0 93.2141.0 94.7142.0 95.3143.0 96.6148.0 97.3
 232.154.0 99.3158.0 99.6
232.0 .092  5.0   0. .092 10.0   0. .092 15.0   0. .092 20.0   0.        *
232.0 .092 25.0   0. .092 30.0   0. .092 31.0   0. .092 33.4   0.        *
232.0 .092 35.0   0. .092 40.0   0. .092 45.0   0. .092 50.0   0.        *
232.0 .092 55.0   0. .092 60.0   0. .092 65.0   0. .092 70.0   0.        *
232.0 .092 75.0   0. .092 80.0   0. .092 85.0   0. .092 90.0   0.        *
232.0 .092 95.0   0. .092100.0   0. .092105.0   0. .092110.0   0.        *
232.0 .092115.0   0. .092120.0   0.-.092125.0   0. .092130.0   0.        *
232.0 .092132.0   0. .092135.0   0. .092136.0   0. .092141.0   0.        *
232.0 .092142.0   0. .092143.0   0. .092148.0   0. .092154.0   0.        *
232.0 .092158.0   0.                                                     *
 287.  0.0 98.3  5.0 98.0 10.0 97.8 15.0 97.6 20.0 97.3 25.0 97.0
 287. 30.0 96.6 35.0 95.0 40.0 94.7 45.0 94.0 50.0 93.7 55.0 93.2
 287. 57.3 92.1 60.0 91.8 65.0 91.9 70.0 91.5 75.0 91.2 80.0 90.7
 287. 85.0 90.6 90.0 90.3 95.0 90.4100.0 90.3105.0 90.1110.0 90.0
 287.115.0 89.6120.0 90.0125.0 89.6130.0 89.6135.0 89.3140.0 89.4
 287.144.9 90.6145.0 92.1145.1 93.2150.0 96.7155.0 97.2160.0 97.4
 287.165.0 97.6170.0 98.6175.0 99.6180.0 99.9
287.0 .010  5.0   0. .010 10.0   0. .010 15.0   0. .010 20.0   0.        *
287.0 .010 25.0   0. .010 30.0   0. .010 35.0   0. .010 40.0   0.        *
287.0 .010 45.0   0. .010 50.0   0. .010 55.0   0. .010 57.3   0.        *
287.0 .010 60.0   0. .010 65.0   0. .010 70.0   0. .010 75.0   0.        *
287.0 .010 80.0   0. .010 85.0   0. .010 90.0   0. .010 95.0   0.        *
287.0 .010100.0   0. .010105.0   0. .010110.0   0. .010115.0   0.        *
287.0 .010120.0   0. .010125.0   0. .010130.0   0.-.010135.0   0.        *
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 453.  0.0 99.4  5.0 99.3 10.0 97.9 15.0 96.6 20.0 94.4 23.0 93.4
 453. 25.0 92.7 26.9 92.5 30.0 91.6 35.0 91.4 40.0 91.3 45.0 91.9
 453. 50.0 91.8 55.0 91.7 60.0 91.5 65.0 91.7 70.0 91.8 75.0 91.8
 453. 80.0 91.3 85.0 92.0 90.0 91.9 95.0 91.9100.0 91.9105.0 92.1
 453.110.0 91.9115.0 91.8120.0 91.6121.0 92.2125.0 91.6130.0 93.4
 453.133.0 94.7137.0 96.3143.0 97.7146.0 98.7150.0100.2151.0100.8
453.0 .040  5.0   0. .040 10.0   0. .040 15.0   0. .040 20.0   0.        *
453.0 .040 23.0   0. .040 25.0   0. .040 26.9   0. .040 30.0   0.        *
453.0 .040 35.0   0.-.040 40.0   0. .040 45.0   0. .040 50.0   0.        *
453.0 .040 55.0   0. .040 60.0   0. .040 65.0   0. .040 70.0   0.        *
453.0 .040 75.0   0. .040 80.0   0. .040 85.0   0. .040 90.0   0.        *
453.0 .040 95.0   0. .040100.0   0. .040105.0   0. .040110.0   0.        *
453.0 .040115.0   0. .040120.0   0. .040121.0   0. .040125.0   0.        *
453.0 .040130.0   0. .040133.0   0. .040137.0   0. .040143.0   0.        *
453.0 .040146.0   0. .040150.0   0. .040151.0   0.                       *
 910.  0.0100.1  5.0 99.9 10.0 99.1 15.0 99.2 20.0 97.4 25.0 97.6
 910. 30.0 96.6 35.0 95.7 37.0 94.4 37.7 93.3 40.0 91.9 45.0 91.7
 910. 50.0 91.6 55.0 91.6 60.0 91.7 65.0 91.9 70.0 91.7 75.0 91.5
```

Table A2.8. Original WSP Data Set Received From The Colorado Division of Wildlife (Concluded)

```
     910. 80.0 91.8 85.0 91.8 90.0 91.8 95.0 91.6100.0 91.7105.0 91.8
     910.110.0 92.0115.0 92.1120.0 92.5120.9 93.3121.0 94.4125.0 95.2
     910.130.0 96.0135.0 96.3140.0100.2148.0101.4
    910.0 .064  5.0   0. .064 10.0   0. .064 15.0   0. .064 20.0   0.        *
    910.0 .064 25.0   0. .064 30.0   0. .064 35.0   0. .064 37.0   0.        *
    910.0 .064 37.7   0. .064 40.0   0. .064 45.0   0. .064 50.0   0.        *
    910.0 .064 55.0   0. .064 60.0   0. .064 65.0   0. .064 70.0   0.        *
    910.0-.064 75.0   0. .064 80.0   0. .064 85.0   0. .064 90.0   0.        *
    910.0 .064 95.0   0. .064100.0   0. .064105.0   0. .064110.0   0.        *
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    910.0 .064148.0   0.                                                     *
    1434.  0.0101.9  5.0101.5 10.0100.5 15.0 99.3 20.0 98.2 25.0 97.2
    1434. 30.0 96.4 34.0 95.8 35.0 95.6 38.7 95.2 40.0 94.3 45.0 94.1
    1434. 50.0 94.7 55.0 94.9 60.0 94.7 65.0 94.7 70.0 94.1 75.0 94.2
    1434. 80.0 94.2 85.0 94.7 90.0 94.7 95.0 94.5100.0 94.4105.0 94.4
    1434.110.0 94.4115.0 94.4120.0 94.8125.0 95.0125.8 95.2130.0 95.9
    1434.135.0 97.1140.0 97.7145.0 99.2150.0 99.9155.0101.2160.0102.6
    1434.172.0102.9
   1434.0 .032  5.0   0. .032 10.0   0. .032 15.0   0. .032 20.0   0.        *
   1434.0 .032 25.0   0. .032 30.0   0. .032 34.0   0. .032 35.0   0.        *
   1434.0 .032 38.7   0. .032 40.0   0. .032 45.0   0. .032 50.0   0.        *
   1434.0 .032 55.0   0. .032 60.0   0. .032 65.0   0.-.032 70.0   0.        *
   1434.0 .032 75.0   0. .032 80.0   0. .032 85.0   0. .032 90.0   0.        *
   1434.0 .032 95.0   0. .032100.0   0. .032105.0   0. .032110.0   0.        *
   1434.0 .032115.0   0. .032120.0   0. .032125.0   0. .032125.8   0.        *
   1434.0 .032130.0   0. .032135.0   0. .032140.0   0. .032145.0   0.        *
   1434.0 .032150.0   0. .032155.0   0. .032160.0   0. .032172.0   0.        *
ENDJ
ENDRUN
```

Table A2.9. Original Habitat Input Data File Received From The Colorado Division Of Wildlife

```
IOC       00000001010000
HEADER    10
CURVES     11110   11111   11112   11114   11115   21110   21111   21112   21114
CURVES     21115
```

Appendix 3

WATER RIGHTS IN THE DOLORES RIVER

This appendix reproduces Chapter III of the Dolores River Project Definite Plan Report Appendix B, Water Supply (U.S. Bureau of Reclamation, 1977). It contains a succinct and authoritative summary of the relationship between the Dolores Project and pre-existing Dolores River water rights.

Chapter III

WATER RIGHTS

Existing Water Rights

Water rights in the Dolores Project are based upon the appropriation doctrine: the basic system of first in time, first in right. The project area lies within Colorado Water Division 7, and the water rights are administered by the State Engineer through a Division Engineer. The first general adjudication of water rights was made in 1892. Water is allocated for irrigation through the use of a basic "water duty" scheme, in which a flow of 1 cubic foot per second (c.f.s.) is apportioned to a specific number of acres depending upon the type of irrigation, the location, etc. No specific period of use for irrigation is specified, and no limiting quantity is stated.

The earliest priority rights for using water from the Dolores River are dated May 31, 1879. From that date various users have rights to the flows of the Dolores River. The Montezuma Valley Irrigation Company (MVIC) holds by far the largest water right, with a priority date of November 25, 1885. Based upon a duty of 1 c.f.s. for each 65 acres of land, this right allows 1,300 c.f.s. for the irrigation of nearly 84,500 acres. The first 707.7 c.f.s. are an absolute

right for the irrigation of about 46,000 acres, and the remaining 592.3 c.f.s. are conditional, based upon proof of beneficial use. The MVIC also has a right for 100 c.f.s. for industrial, domestic, stock,and other uses which bring the total rights held by the company to 1,400 c.f.s. A summary of the MVIC diversion and storage rights is given in the following table.

Summary of MVIC diversion and storage rights.

Structure	Appropriation date	Adjudication date	Amount	Unit
Main Canals 1 and 2	11/25/1885	2/1/1892	707.7	c.f.s.
	11/25/1885	2/1/1892	592.3[1]	c.f.s.
	11/25/1885	3/22/1963	100.0	c.f.s.
Narraguinnep Reservoir	3/15/1888	12/18/1933	5,969.0	acre-feet
	10/28/1907	12/18/1933	3,306.0	acre-feet
	8/17/1922	12/18/1933	9,782.0	acre-feet
	5/1/1956	3/22/1963	1,653.0	acre-feet
Groundhog Reservoir	8/1/1905	12/18/1933	10,623.0	acre-feet
	10/24/1929	12/18/1933	11,086.0	acre-feet
Totten Lake	4/25/1907	12/18/1933	400.0	acre-feet
	2/1/1951	3/22/1963	3,000.0	acre-feet

[1]A conditional right.

Several small rights totaling 6.5 c.f.s. are senior to the rights of the MVIC and downstream from the MVIC diversion dam. Additional senior rights totaling 4.2 c.f.s. are owned by the city of Cortez and are diverted through the MVIC's canals. These rights are shown in the following table.

Rights senior to MVIC rights.

Structure	Appropriation date	Adjudication date	Amount (c.f.s.)
House, Summers Ditch	3/1/1881	2/1/1892	1.0
George P. Moore Ditch	4/30/1881	2/1/1892	0.7
Aztec Ditch	5/1/1881	2/1/1892	1.0
D.D. Williams Ditch	5/1/1881	2/1/1892	1.0
Kuhlman Ditch	5/1/1881	2/1/1892	1.8
Long Dome Ditch	2/20/1882	2/1/1892	1.0
Total			6.5
City of Cortez			
Main Canal Nos. 1 and 2	5/31/1879	2/1/1892	1.1
Main Canal No. 1	4/15/1880	2/1/1892	1.1
Main Canal No. 1	5/31/1882	2/1/1892	1.0
Main Canal No. 1	5/31/1883	2/1/1892	1.0
Total			4.2

The water rights that are downstream from McPhee Dam and senior to the project rights total 9.2 c.f.s. These rights are shown in the following table.

Water rights downstream from McPhee Dam and senior to project rights.

Structure	Appropriation date	Adjudication date	Amount (c.f.s.)
George P. Moore Ditch	4/30/1881	2/1/1892	0.7
D.D. Williams Ditch	5/1/1881	2/1/1892	1.0
Lone Dome Ditch	2/20/1882	2/1/1892	1.0
Bradfield Ditch	5/1/1891	12/18/1933	3.0
Lawrence E. Rogers Ditch	4/1/1919	3/8/1937	2.0
Troy Rose Diversion	6/1/1908	6/11/1968	2.0
Total			9.2

The Summit Irrigation Company holds rights to divert 135 c.f.s. from Lost Canyon Creek, a tributary of the Dolores River upstream from the MVIC diversion. Summit and Puett Reservoirs are used to regulate this flow for the irrigation of about 4,600 acres in the San Juan River Basin.

Water rights for Dawson Draw Reservoir would have to be purchased from landowners in Dawson Draw. Four water rights lie within the Dawson Draw Reservoir takeline. Down stream from the dam are two absolute rights and one condition right. All of these rights are summarized in the following table.

Water rights in Dawson Draw.

Structure	Appropriation date	Adjudication date	Amount (c.f.s.)
Retherford	3/15/1908	8/14/1962	2.14
Durand and Durand Ditch	4/17/1910	8/14/1962	2.04
Woods and Woods Ditch	6/1/1935	8/14/1962	4.50
Smith Flat	6/1/1940	8/14/1962	1.30
Total within reservoir			10.28
Arch Rock (Retherford)	7/10/1916	8/14/1962	10.4
Ismay Ditch	Since 1968		5.0
Shumway Perkins	Since 1968		10.0
Total downstream			25.4

Project Water Rights

In July of 1962, the Southwestern Water Conservation District filed for project water rights. Both storage and diversion rights were acquired, with assigned priority dates of September 10, 1940, and an adjudication date of March 22, 1963. On July 8, 1970, these water rights were transferred from the Southwestern Water Conservation District to the Dolores Water Conservancy District. The project rights are listed in the following table.

Project water rights.

Structure	Appropriation date	Adjudication date	Amount
McPhee Reservoir Inlet	9/10/40	3/22/63	585 c.f.s.
McPhee Reservoir	9/10/40	3/22/63	750,000 acre-feet
Cahone Reservoir Inlet[1]	9/10/40	3/22/63	75 c.f.s.
Cahone Reservoir[1]	9/10/40	3/22/63	13,800 acre-feet
Monument Creek Reservoir Inlet[1]	9/10/40	3/22/63	40 c.f.s.
Monument Creek Reservoir	9/10/40	3/22/63	7,800 acre-feet
Ruin Canyon Reservoir Inlet[1]	9/10/40	3/22/63	120 c.f.s.
Ruin Canyon Reservoir[1]	9/10/40	3/22/63	30,000 acre-feet

[1]Part of the plan at the time of authorization but not part of the present plan.

Three water rights are senior to the MVIC rights and within the McPhee Reservoir right-of-way takeline. These rights are listed below.

Water rights within McPhee Reservoir and senior to MVIC rights.

Structure	Appropriation date	Adjudication date	Amount (c.f.s.)
Horse and Summers Ditch	3/1/1881	2/1/1892	1.0
Aztec Ditch	5/1/1881	2/1/1892	1.0
Kuhlman Ditch	5/1/1881	2/1/1892	1.8
Total			3.8

Agreements Affecting Water Rights

The MVIC water rights are senior to all project rights. The Dolores Water Conservancy District and the MVIC are

negotiating an agreement that would limit the volume of water the MVIC would divert and thereby assure an adequate water supply for the project. In exchange for such an agreement the MVIC would receive project water during the late season from present conditions. The agreement would limit the annual irrigation diversions of the MVIC to the demand for 37,500 acres which is computed to be 150,400 acre-feet. The 37,500 acres contain 11,200 acres of class 6W land which is not eligible for supplemental water from the project. The average annual irrigation diversions of nonproject water would be 130,600 acre-feet. In addition, the MVIC would purchase supplemental irrigation water from the project for 26,300 acres, which would average 13,700 acre-feet annually and would divert up to 3,000 acre-feet annually for stock use.

Appendix 4

DOLORES PROJECT FACILITIES

Table A4.1. Main Storage Facility Design Characteristics

McPhee Reservoir

Capacity:	381,100 acre ft
Minimum Pool:	151,900 acre ft
Active Capacity:	229,200 acre ft

Bounded by McPhee Dam and Great Cut Dike

McPhee Dam

Volume:	5,029,000 cubic yd.
Height:	270 ft above stream bed
Crest Length:	1,300 ft
Crest Width:	30 ft
Crest Elevation:	6936 ft

Great Cut Dike

Volume:	189,000 cubic yd.
Height:	64 ft above ground surface
Crest Length:	1900 ft
Crest Width:	30 ft
Crest Elevation:	6939 ft

Table A4.2. Carriage Facilities

Dove Creek Canal

Location: From Great Cut Dike, extends northwest 39.5 mi to Monument Creek Reservoir.
Length: 39.5 mi
Initial Capacity: 380 ft^3/s
Terminal Capacity: 30 ft^3/s

South Canal

Location: Heads on Dove Creek Canal near Pleasant View, extends south and west.
Length: 7.6 mi
Initial Capacity: 150 ft^3/s
Terminal Capacity: 35 ft^3/s

Dolores Tunnel

Location: Through Dolores - San Juan Divide, 2 mi west of the town of Dolores.
Length: 1.3 mi
Diameter 9 ft
Maximum Capacity: 520 ft^3/s

Dolores Canal

Location: Heads at outlet of Dolores Tunnel, extends south and east.
Length 1.3 mi
Initial Capacity: 520 ft^3/s
Terminal Capacity: 475 ft^3/s

Towaoc Canal

Location: Heads on Dolores Canal 1.1 mi. below outlet of Dolores Tunnel, extends south.
Length 45.4 mi
Initial Capacity 135 ft^3/s
Terminal Capacity 86 ft^3/s

Table A4.2. Carriage Facilities (Concluded)

Cortez-Towaoc Pipeline

Location: Heads above terminus of Dolores Canal, extends southward to near Towaoc.

Length 19.5 mi

Maximum Capacity 17.3 ft^3/s

Pumping Plants	Maximum Lift ft	Capacity ft^3/s
Great Cut Pumping Plant At the toe of the Great Cut Dike.		
To Dove Creek Canal	108	380
To U Lateral	29	72
Pumping Plants Along Dove Creek Canal		
Fairview	169	98
Cahone	162	72
Cross Canyon	83	20
Monument Creek	110	23
Pumping Plants Along South Canal		
Pleasant View	147	36
Ruin Canyon	171	85

Appendix 5

SPREADSHEET STORAGE ACCOUNT GAMING MODEL

GETTING STARTED WITH THE SPREADSHEET

The spreadsheet is designed to run under Lotus 123 (tm) or any compatible software that can process Lotus compatible macros. It requires a microcomputer with an Intel (tm) compatible microprocessor. The computer must have 2 Mb of random access memory (RAM), of which the upper 1 Mb must be configured as "expanded" memory.

Users are assumed to be sufficiently familiar with spreadsheet software to invoke the software and load a spreadsheet file. Consult program documentation for use of WK1 type files with specific software packages. Recalculation is time consuming so the spreadsheet is set to manual recalculation. After making any entries to the spreadsheet, the "calc" button (F9 in Lotus) must be pressed to cause the program to act on those values.

To avoid errors that disturb the equations that represent the model, most cells are "protected". The

unprotected cells are displayed as highlighted values. Users may alter any values that are highlighted. The display is divided into an upper and lower window to allow continuous display of column headings while column values are manipulated. The spreadsheet software's window and title features are used to position column captions and dates so they can be viewed at all times. Certain columns have been "hidden" to allow display of pertinent storage account information.

The general pattern for use of this model is to enter water allocation data in the appropriate cells, press the "calc" button, and view various graphs to determine the fish population and water delivery effects of that decision. Several graphs within the spreadsheet illustrate various conditions. The plots show time traces of effective habitat for each life stage of both species, end of month storage, target and delivered water volumes for locations 1 and 2 and target and delivered instream flows. The graphs are viewed by pressing Alt and the letter indicated in Table A5.5 simultaneously.

Figure A5.1 shows the system layout modeled in the spreadsheet. The three demands consist of diversions at locations 1 and 2 and instream flows between them. The location 1 demand is considered higher priority than the location 2 demand.

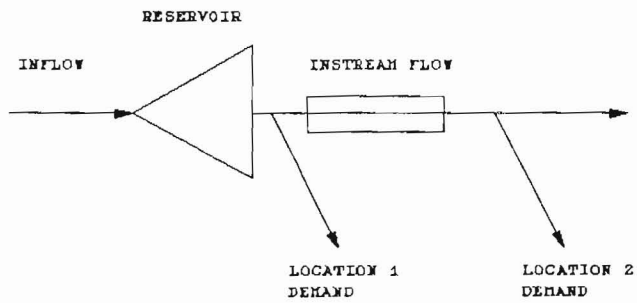

Figure A5.1. Water System Layout Used in Spreadsheet

GAMING WITH THE SPREADSHEET

When invoked, the initial spreadsheet screen looks like the example in Figure A5.2. Note the location 1 and instream flow targets, and their feasible releases. The item ACCOUNT is followed by the amount of water available to be allocated to instream flows in each year. The INSTREAM FLOW SUM gives the acre foot equivalent of the total instream target flows for the year. During spill months, the instream flow is not charged against the account as shown in the second month of 1992. Thus, the feasible instream deliveries may exceed the account in years when spills occur.

The instream account is initialized with 31888 AF in 1993, but the sum of instream targets is 34003 AF. Since there is insufficient water to supply all target flows, the account is exhausted and the flow drops to 1 cfs in the last

month. Figure A5.3 shows the effective habitat consequence for rainbow trout adults.

	B	C	D	F	H	I	K	L	M	N	S
4	SPREADSHEET				Storage Acct		Maximum Instream				
5	STORAGE ACCOUNT				Inflow Fraction		Storage Account Size			Min Storage	
6	GAMING					0.25	33500				151900
7	TOOL					|----------	Instream Flows			----------|	
8			Monthly	LOC 1	Feasible		Sum of		Depletion	Feasible	
9			Demand At	Annual	LOC 1	Target	Target Instream		of	Instream	Storage
10			LOC 1	Demand	Release	Flows	Flows Account		Account	Release	
11	Fish										
12	year	mon	AF	AF	AF	cfs	AF	AF	AF	cfs	AF
	B	C	D	F	H	I	K	L	M	N	S
109		■									300000
110		Apr	64934	3840	3840	45	ACCOUNT:	33500	30824	45	357818
111		■	96838	37320	37320	55			30824	0	381100
112		j	69929	68560	68560	75	INSTREAM		26364	75	377247
113		j	21383	68900	68900	75	ANNUAL		21756	75	324567
114		a	18372	35430	35430	75	SUM		17148	75	302052
115	92	s	10941	22450	22450	55	36243		13877	55	286668
116		o	4670	6790	6790	45			11112	45	281210
117		n	2973	630	630	35			9031	35	280909
118		d	3932	450	450	35			6880	35	281679
119		j	2826	350	350	35			4730	35	281441
120		f	2830	590	590	35			2787	35	281176
121		■	11675	970	970	35			637	35	289168
122		Apr	26075	3840	3840	38	ACCOUNT:	31887.93	29628	38	308565
123		■	38880	37320	37320	45			26863	45	306743
124		j	28080	68560	68560	75	INSTREAM		22404	75	261189
125		j	8590	68900	68900	75	ANNUAL		17795	75	195749
126		a	7380	35430	35430	75	SUM		13187	75	165087
127	93	s	4390	22450	5295	45	34003		10511	45	162411
128		o	1875	6790	1048	35			8360	35	160260
129		n	1195	630	199	35			6279	35	158424
130		d	1580	450	450	35			4129	35	157086
131		j	1135	350	350	35			1978	35	155406
132		f	1135	590	590	35			35	35	153698
133		■	4690	970	970	35			0	1	157075

Figure A5.2. Initial Spreadsheet Screen With Software Menus Removed

As noted in Chapter 5, the model defaults are configured to represent the Dolores Project. The calculations cover a span of seventeen years, beginning in 1984 and include water system operations and effective habitat. The year boundaries run from April to March to represent the approximate fish year for trout in this system.

In particular, note that the default inflow values are median year values for all years but 1993. A severely dry

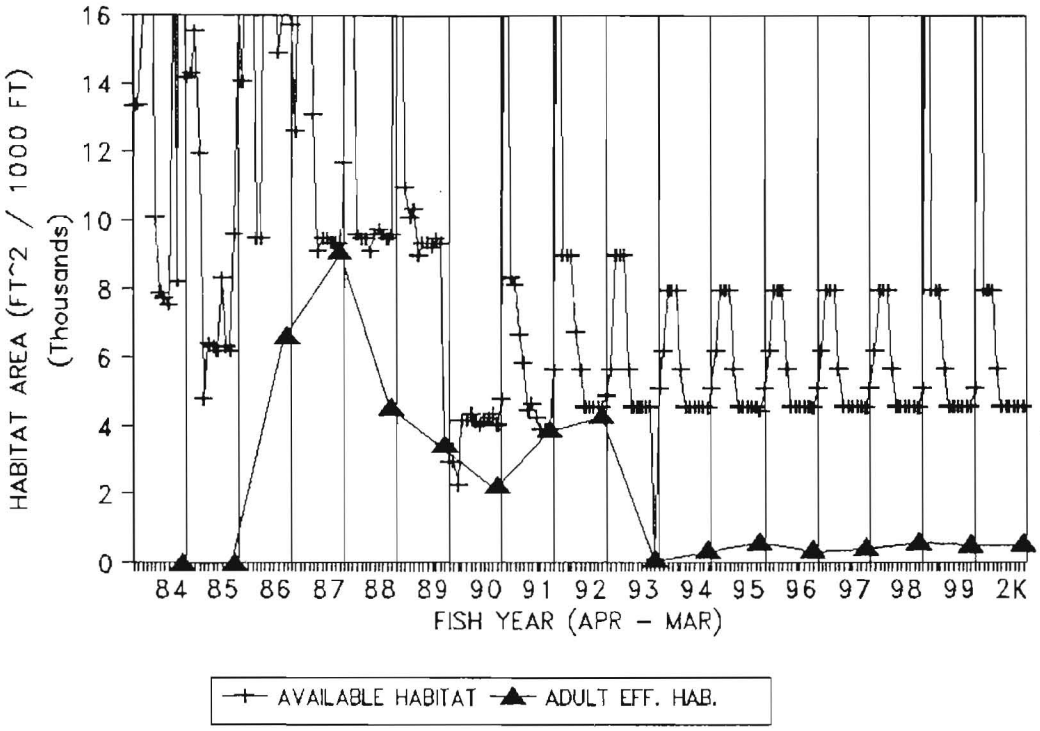

Figure A5.3. Rainbow Trout Effective Habitat for Default Instream Flow Conditions

year (synthesized 96% exceedance based on total annual inflow) is included as year 1993 to illustrate the effects of a dry year on system operations and on the fish population. The inflow values may be changed by entering new numbers in column D.

Before gaming with this model users are strongly urged to evaluate all default values of the user defined parameters (cf. Table A5.2). Users should also review columns D - inflow, F - location 1 target demand, I - instream flow targets, N - location 2 demand, AK - brown trout stocking and

BE - rainbow trout stocking. Descriptions of all entries in the spreadsheet are included in Tables A5.2 through A5.4.

The next section suggests steps to evaluate within-year distribution of instream flows. Then the following section discusses using the model to evaluate different storage account sizes.

USE OF THE SPREADSHEET TO GAME WITH INSTREAM FLOWS

The primary purpose of this model is to allow users to game with alternative instream flow scenarios. Begin by allocating instream flow for each year beginning in 1992. Start with a constant minimum value. Use the plot macros to find the weakest life stage for each year, determine if releasing additional water will remove a life stage limitation. Increase the instream flow target for that month and observe the effect on all life stages using Alt-A through Alt-M. Check that the instream flow target amounts do not exceed the instream storage account for the year. Repeat this process for the current year until the account is exhausted or population goals are achieved.

When all of the instream account is exactly allocated, the items in column K under SUM will equal those to the right of ACCOUNT and the march entry under column L, Depletion of

Account, will be zero. Check column M, Feasible Instream Delivery, to ensure that the last months' streamflow targets are met.

If a proposed instream flow account size and monthly allocation pattern cannot meet fishery management goals, negotiations between fishery managers and project managers may be necessary to relieve population bottlenecks. This model can facilitate such negotiations by helping to identify when and how much water is needed to relieve population limits. Alternatively it can be used to determine when and how much stocking is needed to recover from low flow years when water management cannot relieve population limits.

A Gaming Example

First initialize the model by invoking the spreadsheet software and retrieving file WBGAME.WK1. Press "Calculate" (F9 in Lotus) when the spreadsheet is loaded and after making a set of new entries to force recalculation.

The object of this example game is to arrange the 1992 streamflows to relieve population bottlenecks and provide the greatest habitat safety factors for the limiting life stages within the year's instream account allocation of 33,500 acre ft. The flow patterns attempted are shown in Table A5.1.

The flow pattern shown for step 1 is the default pattern supplied in the spreadsheet.

Table A5.1. Instream Flow Patterns for 1992 Used in Sample Game.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Step 1.	45	55	75	75	75	55	45	35	35	35	35	35
Step 2.	55	55	70	70	70	55	45	35	35	35	35	35
Step 2a.	55	55	65	65	65	50	45	38	38	38	38	38
Step 3.	55	55	60	60	60	55	45	42	42	42	42	42
Step 4.	55	55	60	60	60	50	45	45	45	45	45	45
Step 4a.	55	55	60	60	60	45	45	45	45	45	45	45

Units: cfs.

<u>Step 1</u>. Find the limiting available habitat (LAH) and effective habitat area (EFA) for the default flows.

View the effective habitat effects for both species and note which life stages have EFA values equal to the LAH values for those life stages. For rainbow trout use the plot macros Alt-A for adults, Alt-E for juveniles, Alt-G for fingerling, Alt-J for fry, and Alt-L for spawning. For brown trout use the plot macros Alt-B for adults, Alt-F for juveniles, Alt-H for fingerling, Alt-K for fry, and Alt-M for spawning.

From these plots one finds that in 1992 rainbow trout adult effective habitat area is slightly below its LAH; rainbow juvenile, fingerling and fry EFA are well below their limits; and rainbow spawning habitat is at its limit. The spawning limit occurs in April. The April raw habitat (HA) value is lower than the June value as are the flows for those months. Thus increasing flow in April would increase the habitat and raise the limit. This is accomplished by taking water from high flow, non-limiting months and moving it to April. Note that May is a spill month. Spills are not charged against the instream storage account but water cannot be moved from May to April without a charge against the account.

Step 2. Change the flow pattern to relieve the rainbow trout spawning bottleneck as shown in Table A5.1.

Viewing the plots again, we find that rainbow trout spawning is not limited by available habitat and all other rainbow trout life stages are still below their limiting values. This indicates the population is limited by events in previous years. It is possible to provide a safety factor during the most limiting period.

Step 2a. Add a safety factor for rainbow trout adult habitat as shown in Table A5.1.

There were no changes in the rainbow trout effective habitat values, but there is a greater margin between the LAH and EFA values for adults. Within this model, no further improvements for rainbow trout in 1992 can be achieved by flow redistribution. So next consider brown trout.

From the brown trout plots, we find that effective spawning is limited by winter low flows. It appears that moving more water from summer to winter may help.

Step 3. Change the winter flows to improve brown trout spawning as shown in Table A5.1.

Again, there were no changes in the rainbow trout effective habitat. Brown trout effective spawning was raised from 257.7 to 314.1 sq. ft. per 1000 lineal ft. and all other brown trout life stages were unchanged. Brown trout spawning is still limited by available habitat, so further adjustments to the flow pattern are appropriate.

Step 4. Additional adjustments to instream flow pattern as shown in Table A5.1.

Pattern 4 does not change the rainbow trout effective habitat and improves brown trout spawning from 314.1 to 356.4 sq. ft. per 1000 ft. It leaves only 82 AF for carry over to the next year

Step 4a. Try to leave more storage to carry over while maintaining brown trout spawning as shown in table A6.1.

This caused no effective habitat changes, but it increased the carry over storage to 379 AF. It is not possible to know the next year conditions with certainty so retaining a portion of storage for use in future years is desirable.

EVALUATION OF DIFFERENT STORAGE ACCOUNT SIZES

The amount of water available in the instream account each year is determined by two mechanisms. A maximum account size is entered in cell K6 and a fraction of annual inflow is entered in cell I6. If the product of I6 and the annual inflow sum is greater than the account size, the amount of water in the account at the beginning of the year is capped at the maximum size in cell K6. If the product is less, only

the product plus any carry over from the previous year is available.

To determine the effect of a different account size, change the maximum instream storage account size in cell K6. If you want this amount to be allocated in all years, set the inflow fraction cell I6 to a high value like 0.8. This will cause the maximum cap in K6 to govern at all times. If you want this amount to be fully allocated in wet years and prorated in dry years, successively reduce the inflow fraction (I6) until the desired reduction in the account size under ACCOUNT is achieved in a dry year.

Next, repeat the instream allocation process described above. Compare location 1 and location 2 deliveries and their targets using Alt-O and Alt-P. Note the amount of shortage (if any) that occurs by comparing columns F and H, and M and P. If shortages occur, it may be necessary to reduce the location 1 or location 2 demands for that year to avoid running out of water. Users should consulting the project water managers for the rules one would use to do these reductions. Here again, negotiations may be necessary to allocate water under shortage conditions.

Table A5.2. Parameter Cells Initialized by the User

Cell	Description of Contents
I6	Storage Account Inflow Fraction - The fraction of annual inflow the instream storage account is allowed to capture for exclusive use in instream flows. When the inflow is low enough that the product of this fraction and the annual inflow is less than the maximum account size, the initial storage account for that year is I6 * annual inflow + residual carryover from last year's account. In all other years, this amount is limited by the maximum account size given below.
K6	Maximum Instream Storage Account Size - The maximum size of the instream storage account. This is treated as a once per year account so it acts like a one filling per year storage right under Colorado Water Law.
S6	Min Storage - The minimum storage value for the reservoir being studied. In the Dolores River example, this is 151,900 acre ft. This value is the practical equivalent of dead storage volume and can approach zero in some reservoirs. Entered once for a project.
S109	Initial Reservoir Contents as of March 31, 1992. - The user must supply the initial reservoir condition for valid calculations of the reservoir state.
V6	Reservoir Maximum storage - Entered once for a project. Spills occur when storage attempts to go beyond this value.
R10	Reservoir evaporation rate - This is an approximate value based on reservoir storage. The spreadsheet does not calculate the reservoir surface area and the evaporation rate does not vary during the year. Adjust this value to produce annual average evaporation that approximates actual evaporation losses. This value is a monthly fraction of total storage. Since evaporation is such a small portion of storage, this simplified approach is used.

Table A5.2. Parameter Cells Initialized by the User (Continued)

Cell	Description of Contents
AV1	Brown Trout Fingerling Density (number of fingerlings per unit of fingerling WUA) - to determine how much fingerling habitat is occupied by stocked fish.
BQ1	Rainbow Trout Fingerling Density (number of fingerlings per unit of fingerling WUA) - to determine how much fingerling habitat is occupied by stocked fish.
AI4	Brown Trout Adult : Spawning Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
AK4	Brown Trout Spawning: Fry Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
AN4	Brown Trout Fry : Fingerling Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
AS4	Brown Trout Fingerling : Juvenile Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
AU4	Brown Trout Juvenile: Adult Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
AW4	Brown Trout Adult Survival Rate from other effects beyond habitat limits - This value is derived using the procedures described in Chapters 4 and 6.
BB4	Rainbow Trout Adult : Spawning Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
BE4	Rainbow Trout Spawning: Fry Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
BH4	Rainbow Trout Fry : Fingerling Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.

Table A5.2. Parameter Cells Initialized by the User (Concluded)

Cell	Description of Contents
BM4	Rainbow Trout Fingerling : Juvenile Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
BO4	Rainbow Trout Juvenile: Adult Habitat Multiplier - This value is derived using the procedures described in Chapters 4 and 6.
BQ4	Rainbow Trout Adult Survival Rate from other effects beyond habitat limits - This value is derived using the procedures described in Chapters 4 and 6.
AI8 .. BS8	Initial effective habitat values for the population. Assuming there is no viable trout population when McPhee Dam is constructed these values are all zero in the Dolores River case. The populations are initiated by stocking.
AD110 AD116 AD128 etc.	Brown Trout Stocking - enter number of fingerlings to be stocked in October of each year stocking is planned. Actual stocked numbers are entered for 1984 to 1991.
BJ110 BJ116 BJ128 etc.	Rainbow Trout Stocking - enter number of fingerlings to be stocked in October of each year stocking is planned. Actual stocked numbers are entered for 1984 to 1991.

Table A5.3. Habitat - Discharge Relations

Range	Description of Contents
BV - CB	Habitat - discharge relations for brown and rainbow trout including the original and temperature modified relations. Labels at the top of each table describe their contents.
CD - CI	Interpolation coefficients for each habitat - discharge table. These coefficients allow linear interpolation of each discharge value in column X to the respective GAH values for each life stage.

Table A5.4. Columns Representing Model Processes

Col.	Description of Contents
A	Fish year for use in certain graphs
B	Fish year used as general index and for other graphs
C	Month, April is displayed as Apr to denote start of fish year, all other months identified by their first letter only.
D	Monthly inflow (AF) - The spreadsheet contains default median year inflows in all years from 1992 to 2000, except 1993. 1993 represents a very low inflow year to show the effects of a dry year on succeeding years. The user may revise the inflow values by entering new values for each month in each year. This would allow evaluation of wet and dry year scenarios by changing the future inflow scenario.
E	Annual sum of inflow (AF) - This value is used by the instream account calculation in conjunction with cell I6. The user can compare the annual inflow with hydrologic statistics to see how wet or dry the year is. If the sum of location 1 and 2 demands plus the instream account exceed the inflow, the reservoir will experience a net depletion for the period.
F	Demand at Location 1 (AF) - The user supplies the total out-of-stream demand pattern by entering 12 monthly values for each year in this column. The user may enter the sequence of monthly demands appropriate to each project being evaluated. The default values represent total values estimated from the Dolores River Definite Plan Report (U.S. Bureau of Reclamation, 1977b).
G	Annual sum of Location 1 demands (AF) - Compare this to inflow as noted for column E.
H	Feasible Demand (AF) - When there is insufficient storage + inflow to satisfy Location 1 demands, the demand is shorted to match the supply. A trial mass balance is performed to estimate feasible demand

Table A5.4. Columns Representing Model Processes (Continued)

Col.	Description of Contents
I	Target Instream Flows (cfs) - The user supplies desired instream flows as monthly mean cfs. (The spreadsheet does not consider time periods less than one month.)
J	Target Instream Flows (AF) - The spreadsheet converts the cfs values to acre feet using a conversion table within the spreadsheet.
K	"INSTREAM ANNUAL SUM" entry is the annual sum of Target Instream Flows. (AF) - Compare this to the annual instream account amount (ACCOUNT) to see if more is being demanded than can be delivered. Also compare this to inflow as noted for column E.
L	"ACCOUNT" entry is the annual instream storage account calculated as the minimum of these items: 1) the inflow fraction (cell I6) times the annual inflow plus any carry over storage from the previous year or 2) the maximum storage account size from cell K6. Units are acre ft.
M	Depletion of storage account (AF) - This column shows the amount remaining in the account after the current month's instream flow is released.
N	Feasible Instream Delivery (cfs) - The amount that can be delivered from the instream account. This can be one of four values: - the target amount if there is sufficient water left in the account, - a lesser amount if the account is drained dry in the current month, - zero if the account is empty, or - zero if there is a spill and no water needs to be released from the account to satisfy instream flows.
O	Demand at Location 2 (AF) - Contains user supplied values which are treated the same as for Location 1. The default values are zero for the Dolores River since there are no project diversions downstream of McPhee Dam.
P	Annual sum of Location 1 demands (AF) - Same as for Location 1.

Table A5.4. Columns Representing Model Processes (Continued)

Col.	Description of Contents
Q	Feasible Demand (AF) - When there is insufficient storage + inflow to satisfy Location 1 demands and Location 2 demands, this demand is shorted to match the supply that is not needed for Location 1. The demand target is reduced by the amount of instream flow so instream flow may provide some of this delivery. This demand acts as if it is a lower priority than that at Location 1.
R	Evaporation from the Reservoir (AF) - Evaporation rate (cell Q10) times previous period end of month storage.
S	Reservoir Storage (AF) - The final storage value derived from columns U and V. This storage is trapped at zero. That is, no negative storage is allowed. It is possible for evaporation to draw the reservoir below its stated minimum value, though unlikely.
T	Release (AF) - The actual release made during this period.
U	Spill (AF) - If the reservoir fills, this is the excess. It is delivered to the stream channel and shows up in column X.
V	Upper Bound Storage (AF) - This column is used to trap storage at the reservoir capacity (cell U109).
W	Unbounded Storage (AF) - This column is used to calculate the mass balance on the reservoir. The mass balance is the sum of the inflow, releases and evaporation. The equation is: $$S(t) = S(t-1) + I - R1 - IFQ - R2 - E - S.$$ This reads: Storage at the end of this time period (t) equals the storage at the end of the last period (t-1) plus inflow minus releases for location 1, releases for instream flow, releases for location 2, evaporation and spills.

Table A5.4. Columns Representing Model Processes (Continued)

Col.	Description of Contents
X	Delivery to Location 1 (AF) - This column uses the final mass balance rather than a trial mass balance so it updates the estimated feasible delivery to location 1.
Y	Instream Delivery (cfs) - All water that is not diverted to location 1 is considered stream flow and thus a delivery to instream flow. When spills occur, the flows may be sufficiently high to cause adverse population impacts. The effective habitat results of all flows are calculated in columns AB through BN.
Z	Delivery to Location 2 (AF) - Location 2 tries to take any water that is coming by up to its target delivery. This is calculated as the minimum of the target or what is available in the river so the instream flows can be utilized.
AA	Min. Storage Plot Line (AF) - This is an artifact of displaying a line representing the minimum reservoir storage in the storage graph. The minimum line may be altered by changing cell Z14.
AB	Location 1 shortages (AF) - Used for plotting.
AC	Instream flow shortages (cfs) - Used for plotting.
AD	Location 2 shortages (AF) - Used for plotting.
AE	Number of days per month - Used in unit conversions.
AF	This column is blank.

The next columns calculate the effective habitat time series for Brown Trout. All values have units of WUA (sq ft per ft).

AG	Spawning Gross Available Habitat (GAH) - See Chapter 4.
AH	Spawning Limiting Available Habitat (LAH) - See Chapter 4.
AI	Spawning Effective Habitat (EFA) - See Chapter 4.
AJ	Fry Gross Available Habitat (GAH) - See Chapter 4.

Table A5.4. Columns Representing Model Processes (Continued)

Col.	Description of Contents
AK	Fry Limiting Available Habitat (LAH) - See Chapter 4.
AL	Fry Effective Habitat (EFA) - See Chapter 4.
AM	Fingerling Gross Available Habitat (GAH) - See Chapter 4.
AN	Fingerling Limiting Available Habitat (LAH) - See Chapter 4.
AO	Number of Stocked Fingerlings - See Chapter 6.
AP	Fingerling Revised Limiting Available Habitat (LAH)
AQ	Fingerling Effective Habitat (EFA) - See Chapter 4.
AR	Juvenile Gross Available Habitat (GAH) - See Chapter 4.
AS	Juvenile Limiting Available Habitat (LAH) - See Chapter 4.
AT	Juvenile Effective Habitat (EFA) - See Chapter 4.
AU	Adult Gross Available Habitat (GAH) - See Chapter 4.
AV	Adult Limiting Available Habitat (LAH) - See Chapter 4.
AW	Adult Recruitment from the Juvenile Life stage - See Chapter 4.
AX	Adult Survival from the previous year - See Chapter 4.
AY	Adult Effective Habitat (EFA) - See Chapter 4.
AZ	This Column is Blank.

Table A5.4. Columns Representing Model Processes (Continued)

Col.	Description of Contents
The next columns calculate the effective habitat time series for Rainbow Trout. All values have units of WUA (sq ft per ft).	
BA	Spawning Gross Available Habitat (GAH) - See Chapter 4.
BB	Spawning Limiting Available Habitat (LAH) - See Chapter 4.
BC	Spawning Effective Habitat (EFA) - See Chapter 4.
BD	Fry Gross Available Habitat (GAH) - See Chapter 4.
BE	Fry Limiting Available Habitat (LAH) - See Chapter 4.
BF	Fry Effective Habitat (EFA) - See Chapter 4.
BG	Fingerling Gross Available Habitat (GAH) - See Chapter 4.
BH	Fingerling Limiting Available Habitat (LAH) - See Chapter 4.
BI	Number of Stocked Fingerlings - See Chapter 6.
BJ	Fingerling Revised Limiting Available Habitat (LAH)
BK	Fingerling Effective Habitat (EFA) - See Chapter 4.
BL	Juvenile Gross Available Habitat (GAH) - See Chapter 4.
BM	Juvenile Limiting Available Habitat (LAH) - See Chapter 4.
BN	Juvenile Effective Habitat (EFA) - See Chapter 4.
BO	Adult Gross Available Habitat (GAH) - See Chapter 4.
BP	Adult Limiting Available Habitat (LAH) - See Chapter 4.
BQ	Adult Recruitment from the Juvenile Life stage - See Chapter 4.
BR	Adult Survival from the previous year - See Chapter 4.

Table A5.4. Columns Representing Model Processes (Concluded)

Col.	Description of Contents
BS	Adult Effective Habitat (EFA) - See Chapter 4.
BT	This Column is Blank.

Table A5.5. Plotting Macros

Rainbow Trout	
Alt-A	Adult Effective Habitat
Alt-C	Adult Effective Habitat, Extended Scale
Alt-E	Juvenile Effective Habitat
Alt-G	Fingerling Effective Habitat with Stocking
Alt-J	Fry Effective Habitat
Alt-L	Effective Spawning Habitat
Brown Trout	
Alt-B	Adult Effective Habitat
Alt-D	Adult Effective Habitat, Extended Scale
Alt-F	Juvenile Effective Habitat
Alt-H	Fingerling Effective Habitat with Stocking
Alt-K	Fry Effective Habitat
Alt-M	Effective Spawning Habitat
Water Quantities	
Alt-I	Instream Flow Since 1984
Alt-N	Instream Storage Account and Its Depletion Pattern
Alt-Q	Instream Flow Target and Delivery 1992 forward
Alt-O	Deliveries to Location 1
Alt-P	Deliveries to Location 2
Alt-S	Reservoir Storage
Alt-T	Location 1 Shortages
Alt-U	Instream Shortages
Alt-V	Location 2 Shortages