The simulation programs of the Instream Flow Incremental Methodology

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Abstract. The Instream Flow Incremental Method (IFIM) is a logical guide to the analysis of various issues related to developing an environmental (instream) flow policy that incorporates multiple or variable flow rules to meet the needs of the aquatic ecosystem while considering habitat-flow relationships, timing of flow events, institutional arrangements, and water supply and water allocation. Models of the IFIM include the Physical Habitat Simulation System (PHABSIM), Time Series Analysis Library (TSLIB), two temperature models: Stream Network Temperature Model (SNTEMP) and the Stream Segment Temperature Model (SSTEMP), SALMOD, and the Legal Institutional Analysis Model (LIAM). The various models are designed to give the user information required to select environmental flow needs. The models do not calculate an environmental flow need - selecting an environmental flow need is the responsibility of the user. PHABSIM is a set of programs designed to predict microhabitat conditions in rivers as a function of streamflow and the relative suitability of those microhabitat conditions to aquatic life. TSLIB programs provide data entry, analysis, and display of daily or monthly flow or habitat values. Some programs are useful for integrating microhabitat and macrohabitat, and some are of value in the analysis of water operations systems. SNTEMP predicts the water temperature in streams and rivers from data describing the stream's geometry, meteorology, and hydrology. It handles a dendritic network of streams through time and space. SSTEMP is a scaled down version of SNTEMP suitable for single (to a few) reaches and single (to a few) time periods. SALMOD is a computer model that simulates the dynamics of freshwater salmonid populations. Developed and used for the Trinity River, California, Chinook salmon evaluation, SALMOD has wide applicability for freshwater habitat-limited salmonid populations. LIAM was designed to accomplish three goals: (1) plan for participation in a negotiation, (2) predict organizational behavior, and (3) examine likely negotiation strategies.

Key Words: instream flows, environmental flows, temperature modeling, fish habitat, macrohabitat, microhabitat, legal analysis, institutional analysis, water management.

1. Introduction

The Instream Flow Incremental Methodology (IFIM) is an approach to the analysis of environmental flows as an aspect of water resources management (Stalnaker et al, 1995 and Bovee et al, 1998). The need to protect environmental flows in the United States is now well established (Dixon and Cox, 1985 and Brandes, 1985). The IFIM was developed to assist water and natural resources managers in the quantification of environmental flow requirements. This paper presents an overview of the simulation models developed under the umbrella of the IFIM.

The IFIM is a logical guide to analysis of the various issues related to developing an environmental flow policy that incorporates multiple, or variable, flow rules to meet the needs of the aquatic ecosystem by considering habitat-flow relationships, timing of flow events, institutional arrangements, water supply, and water allocation. Models of the IFIM include the Physical Habitat Simulation System (PHABSIM), Time Series Analysis

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Library (TSLIB), Stream Network Temperature Models (SNTEMP and SSTEMP), SALMOD, and Legal Institutional Analysis Model (LIAM). The various models are designed to give the user information required to select environmental flow needs. The models do not calculate an environmental flow need - selecting an environmental flow need is the responsibility of the user.

Prior to about 1975 an instream (environmental) flow need was simply a "minimum flow requirement" for the minimum flow to be released from a storage project or the minimum flow to remain in a river at a diversion. The minimum flow was viewed as a constraint on operation of a water resources project. Between 1975 and about 1982 the conceptual basis changed to an acceptance of an environmental flow use as equivalent to any other use.

The usual approach to quantifying an environmental flow requirement is to determine alternative environmental flow needs and then determine the final environmental flow needs through negotiation among the various groups with interests in the use of the water. Two basic principles are fundamental to the process; these are: (1) the environmental flow requirement must actually produce an environmental benefit, and (2) the environmental flow needs are related to the water resources actually available. The negotiation process often has an additional requirement: the environmental flow need must be the "best use" of the water. This requirement is rarely stated but often implied. A successful negotiation requires the group or individual proposing a specific environmental flow requirement must show that the use is beneficial and the allocated quantity of water is not wasted. The probability of positive results is enhanced if best use is also demonstrated. The argument against allocating water to environmental flows generally follows a logic that environmental use is a waste compared to what could be obtained from other uses. Demonstration of best use removes this objection. IFIM is designed to assist in the process of determining the environmental flow requirement based on these criteria.

An IFIM analysis can be divided into four components: these are 1) physical habitat analysis, 2) time series analysis, 3) temperature analysis, and 4) legal/institutional analysis. In some situations a fifth component linking physical habitat, flow and temperature to simulate the response of the fishery to streamflows in a river is used during the process. Figure 1 shows how the principle four components are related. Some aspects of analysis in IFIM were given in Cavendish and Duncan (1986), and in Lamb (1989). Each of the four components is described in the following sections along with a presentation of one model that meets the needs of the fifth component.

There are four major components of a stream system that determine the productivity of the fishery (Karr and Dudley, 1978). These are: (1) flow regime, (2) physical habitat structure (channel form, substrate distribution, and riparian vegetation), (3) water quality (including temperature), and (4) energy inputs from the watershed (sediments, nutrients, and organic matter). The complex interaction of these components determines the primary production, secondary production, and fish population of the stream reach. The physical habitat analysis relates to item 2, the time series analysis to item 1, and the temperature analysis to part of item 3. Water quality factors other than temperature and energy inputs are considered in IFIM but not by any specific analytical procedure.

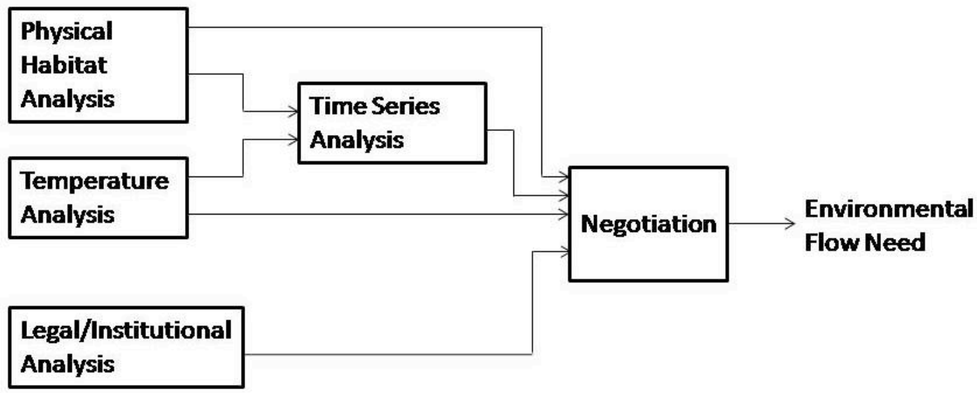

Figure 1. The major components of a typical analysis supporting the application of the Instream Flow Incremental Method (IFIM) to the selection of an environmental flow requirement for management of a water resources system.

2. Physical Habitat Analysis

The basic theory of physical habitat analysis is:

$$WUA(Q) = \int_A f(v,d,ci)dA$$

where WUA(Q) is the physical habitat at the streamflow Q, dA is an incremental area, A is the total stream surface area at the streamflow Q, v is the velocity, d is the depth, ci is an index to the channel characteristics often a combination of a substrate index and a cover index, although other forms of a channel index are possible. Specifics of the model are presented in Nestler et al (1989). The WUA is often called the weighted usable area. The function f() is based on the habitat requirements of a specific life stage and specific species of aquatic animal.

Three alternative weighting functions, f(), are available. These are:
1) $f(v,d,ci) = g(v) * h(d) * k(ci)$, 2) $f(v,d,ci) = \min\{g(v), h(d), k(ci)\}$, and
3) $f(v,d,ci) = \sqrt[3]{g(v) * h(d) * k(ci)}$ where g( ) is some function of the velocity, h( ) is some function of the depth, and k( ) is some function of the stream channel index. The velocity and depth change as the streamflow changes. The channel index does not. The user may also define any type of function desired so long as it uses combinations of velocity, depth, and a channel index. The first function (simple multiplication) assumes each factor has an impact on the combined results no matter whether the other factors are high or low; the second (minimum) assumes only one factor, the one that is a minimum, has an impact on the combined results; the third (geometric mean) assumes the impact on the combined factor to be based on all three, but there are compensatory linkages between the three factors. The user must select between the various forms. Stalnaker (1980) presents information on the nature of the habitat models and the critical assumptions of the models.

An example of the relation between the physical habitat (WUA) and discharge (streamflow) is presented in Figure 2.

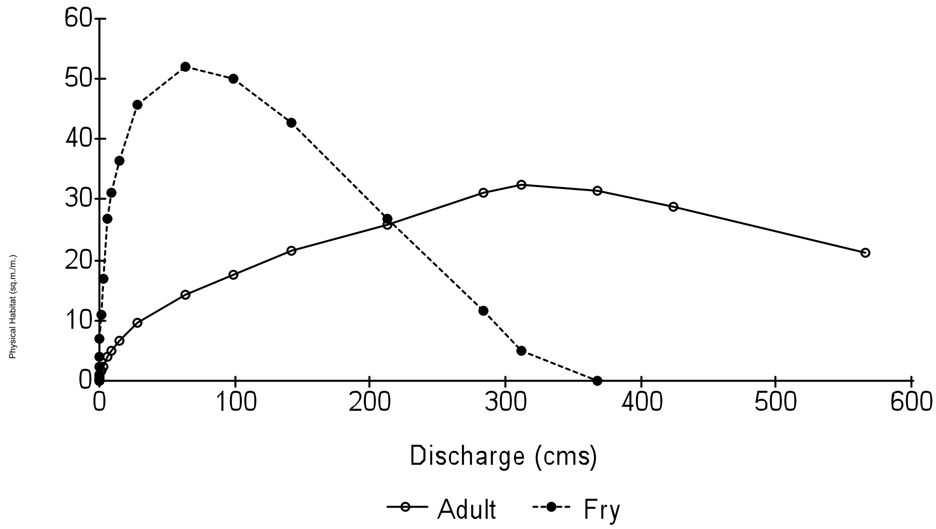

Figure 2. Physical habitat versus discharge relations for channel catfish in the Washita River near Dickson, OK. The velocity and depth data used in the analysis are from the discharge measurement summaries for the USGS gage at the site. The HABVD program in PHABSIM was used to calculate the relations.

A library of programs has been developed to assist in the physical habitat analysis (Milhous et al, 1989). The library is called the Physical Habitat Simulation System (PHABSIM). There are two basic components of PHABSIM: hydraulic simulation and habitat simulation. Hydraulic simulation is used to describe the stream in terms of' depth and velocity combinations over a range of flows. Habitat simulation calculates physical habitat using the velocities and depths from the hydraulic simulation and the channel index. The result is physical habitat as a function of flow. The user of the library must define the habitat worth weighting functions for the various species and life stages of interest in a stream reach. Techniques for developing these species criteria, f(v,d,ci), are given in Bovee (1978) and Bovee and Zuboy (1988).

3. Time Series Analysis

The basic premise of a habitat time series analysis is that the physical habitat in a stream at a given time, HA{t), can be calculated from the streamflow using the equation HA{t) = WUA{Q(t)} where WUA{) is the physical habitat versus streamflow function for a given life stage and species of aquatic organism; Q{t) is the streamflow at time t; and HA(t) is the habitat area at time t.

An example of a time series of the physical habitat is presented in Figure 3.

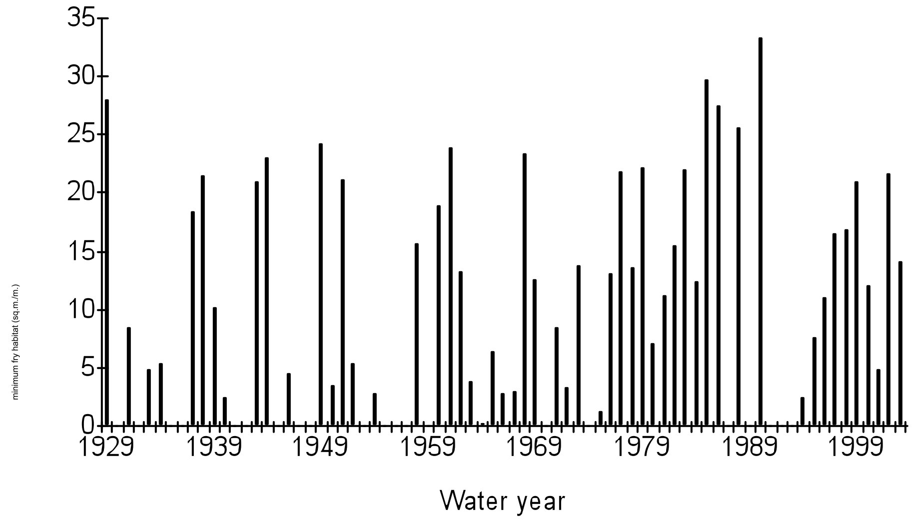

Figure 3. Annual minimum physical habitat for channel catfish fry in the Washita River near Dickson, OK. The annual minimum habitat is the physical habitat at the minimum 10-day average discharge. The streamflow data used was the daily discharge measured by USGS at the gage on the Washita River near Dickson, OK.

Usually the habitat versus streamflow function is calculated using PHABSIM but time series analysis does not require PHABSIM to generate the relation WUA( ); it does require that the WUA( ) function exist and be credible.

The objective of many environmental studies is to compare various water management schemes which may include both structural and non-structural elements. By developing a time series of habitats for various management schemes, knowledge about the impacts on environmental values of the options can be improved.

A library of programs (Milhous et al, 1990) called the Time Series Library (TSLIB), has been developed to assist in the habitat time series analysis. The library contains programs for 1) assembling streamflow data, 2) manipulating the habitat versus streamflow functions, 3) transforming the streamflow data from one location to another, 4) analyzing the water resources system, 5) analyzing monthly habitat, and 6) analyzing annual habitat. The annual habitat analysis includes approaches that consider habitat as a surrogate for population. Programs displaying results of the analysis in both graphical and tabular form are included in the library.

4. Temperature Analysis

Water temperature is considered to be a limiting factor in the quality of habitat for all aquatic animals.

One concept used in environmental flow analysis is that the physical habitat considering temperature can be calculated from the results of PHABSIM using the equation

$$WUAT(Q) = m(T) * WUA(Q)$$

where WUA(Q) is the physical habitat simulated by PHABSIM for the streamflow Q, WUAT(Q) is the physical habitat adjusted for temperature, and m() is the temperature suitability relation for a specific life stage and species. This suitability index approach is usually used when growth of biomass is considered.

The second approach is to consider temperature as a threshold above which the aquatic organism can not exist. In this case the physical habitat modified to account for the water temperature, WUAT(Q), is the same as WUA(Q) if the water temperature is less than or equal to the threshold. If the water temperature is greater that the threshold temperature WUAT(Q) is zero.

Information on performing a temperature study as part an environmental flow analysis is given in Bartholow (1989). The Stream Network Temperature Model (SNTEMP; Theurer et.al. 1984) simulates steady-state water temperatures at specified locations (nodes) in a river network. The SSTEMP program is a scaled down version of SNTEMP. Bartholow (1991) presented an application of the model to assessment of the thermal regime.

The object of the analysis was to determine if the fishery for brown and rainbow trout could be improved by increasing flow from an existing reservoir, a proposed reservoir, and/or by modifying the channel.

5. SALMOD

SALMOD is a computer model that simulates the dynamics of freshwater salmonid populations. The model was developed and used for the evaluation of Chinook salmon in the Trinity River, California (Williamson et al, 1993). The presentation that follows is based on personal communications with John Bartholow. SALMOD has wide applicability for the analysis of environmental flow issues related to freshwater habitat-limited salmonid populations. SALMOD is a dynamic population models that was designed to help understand and predict the effects environmental habitat conditions have on fish production. Figure 4 is one example from SALMOD in which mortality is a function of the time series of water temperatures (affecting in vivo egg, fry, and parr life stages) and streamflow (affecting the probability of redd superimposition, as well as egg incubation and fry habitat quantity). In any given year, it is the combination of one or more of these factors that control salmon production.

A user's manual describing the use and application of SALMOD is available (Bartholow et al, 2001). An example of the use of the model to analysis water management issues is Bartholow and Waddle (1995).

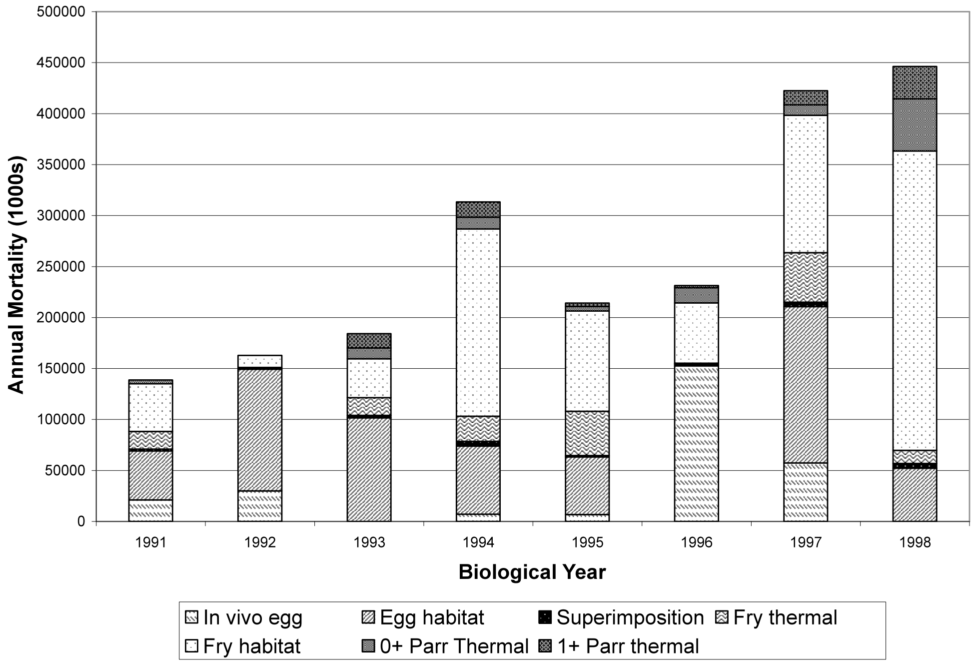

Figure 4. Example illustrating simulated annual variability in mortality for an Atlantic salmon population in the State of Maine. (Adapted from Bartholow et al. 2003).

6. Legal and Institutional Analysis

A key aspect of IFIM is the actual selection of an environmental flow need or requirement thru negotiation. The negotiations are usually between individuals, groups, and institutions with significantly different values. The negotiations are within the framework of an inter-agency setting and are constrained by both legal and institutional factors. The negotiation process is usually considered to be adversarial, with each group attempting to maximize gains in its own values. Almost always the values of any group are a mixture of monitory and non-monitory values. If the values were always monetary; operations research techniques could be used to maximize the overall improvement in welfare. Because of the non-monitory nature of many of the values, negotiation is required. Failure to understand the characteristics of the participants in a negotiation can lead to a less then optimal outcome. The Legal and Institutional Analysis Model (LIAM) was developed to assist in understanding the characteristics of the participants in a negotiation. Application of LIAM has four components (Wilds 1988) and the presentation that follows is strongly based on the work of Leah Wilds. The four components of LIAM are:

1. Survey of organizations and regulations. A survey the laws, court cases, and regulations that govern an environmental flow issue; and determine the most probable organizations to be involved in the negotiation.

2. Description of organizational roles. Each organization is considered in LIAM to have two characteristics describing its role. These characteristics are a goal preference and a decision process preference. The goal preference is said to be guardian or advocate; in-

practice guardian is pro-development and advocate is pro-environment. The decision-process is either a preference for a brokered decision (decision negotiated between interested parties) or for an arbitrated decision (decision imposed by an "arbitrator". The role of an organization is determined in the second component. An example of the results of an organization analysis is presented in Figure 4.

3. Analysis of power relationships. Each organization is considered to have power from three sources; these are 1) control of resources, 2) professional expertise, and 3) public or clientele support.

4. Assessment and Prediction of Organizational Behavior. The fourth component is a compilation of the information obtained in the first three steps into a prediction of organizational behavior.

A computer program has been developed to assist in the analysis required in the LIAM analysis. Uses of the program are described in Lamb (1987), and a validation study of LIAM is described in Wilds (1988).

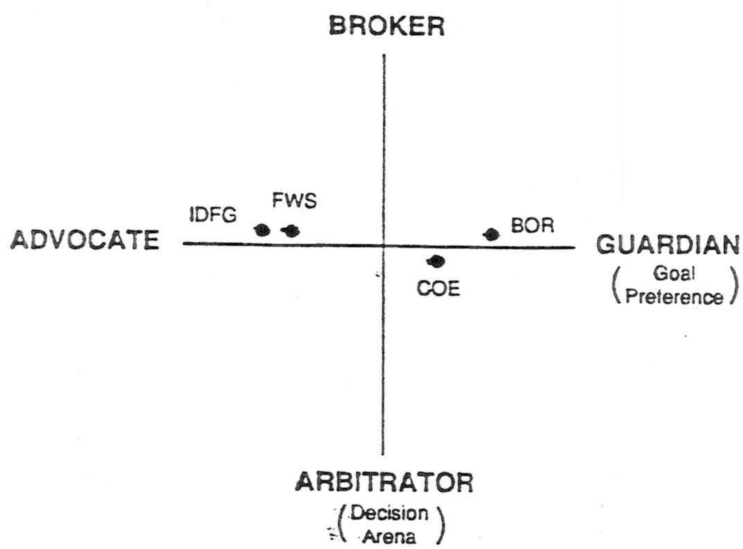

Figure 4: LIAM Roles for the Ririe Project, Idaho. FWS is the U.S. Fish and Wildlife Service; COE is the U.S. Army Corps of Engineers; IDFG is the Idaho Department of Fish and Game; and BOR is the U.S. Bureau of Reclamation. (From Taylor and Lamb 1989)

7. Discussion

The impact of IFIM on water resources management has been significant. The programs have been extensively used in North America; the European countries of France, Great Britain, and Norway; and the South Pacific countries of New Zealand and Australia (for example see Bullock, Gustard, and Grainger 1991; Jowett 1992; and Souchon, Trocherie, Fragnoud, and Lacombe 1989).

Two dimensional models have replaced the hydraulics simulation programs in PHABSIM in some studies. An example of the use of two dimensional models is presented in Bovee et al (2004). The study was an evaluation of the impact of hydropower dams operated for peak-load generation on the physical habitat for freshwater mussels in the Osage River, Missouri. The 2-dimensional hydraulic simulation program RIVER_2D (Ghanem et al. 1996) was used for the hydraulic simulation. Output from the hydraulic simulations were imported to ArcGIS®, and converted to reclassified grids representing suitable habitat for freshwater mussels.

The basic concepts of linking modes have been applied to analysis the riverine ecosystem of the Klamath River in California. SALMOD, along with other models, were linked to form SIAM, a System Impact Assessment Model. "SIAM is an integrated set of models used to address significant interrelationships among selected physical (temperature, microhabitat, and geomorphic features), chemical (dissolved oxygen) and biological variables (young-of-year salmonid production), and stream flow in a river. SIAM has been developed for the Klamath River from Klamath Falls, Oregon, to the river's mouth on the California coast using data and models selected to be appropriate for the riverine portion of that study area." (Bartholow et al. 2005).

Availability of Models

The programs can be found on the web at http://www.fort.usgs.gov/. Documentation for the various programs is also found at the site along with references to papers and reports describing the application of the models. The RIVER_2D program and documentation can be found at http://www.river2d.ualberta.ca.

References

Bartholow, J.M. 1989. Stream temperature investigations: Field and analytic methods. Instream Flow Information Paper No. 13. U. S. Fish and wildlife Service Biological Report 89(17). 139 pp.

Bartholow, J.M. 1991. A Modeling Assessment of the Thermal Regime for an Urban Sport Fishery. Environmental Management. Vol. 15, No.6, pp 833-845.

Bartholow, J.M., and T.J. Waddle. 1995. The search for an optimum flow regime using a salmon population model. in John J. Cassidy,editor. Waterpower '95 (Proceedings of the International Conference on Hydropower) San Francisco, CA: American Society of Civil Engineers. pp 331-339.

Bartholow, J.M., J.G. Trial, J.W. Terrell, K. Beland, and B. Kulik. 2003. Modeling Atlantic Salmon Production on the Narraguagus River, Maine. Presented at Status of Atlantic salmon; populations and habitats. American Fisheries Society 2003. August 10-14, 2003. Quebec City, Quebec.

Bartholow, J.M., J. Heasley, J. Laake, J. Sandelin, B.A.K. Coughlan, A. Moos. 2001. SALMOD: A Population Model For Salmonids. Users Manual. Version W3 Revised September 2001. U.S. Geological Survey. Midcontinent Ecological Science Center. Fort Collin s, Colorado. 76 pages.

Bartholow, J.M, J. Heasley, B. Hanna, J. Sandelin, M. Flug, S. Campbell, J. Henriksen, and A. Douglas. 2005. Evaluating water management strategies with the Systems Impact Assessment

Model: SIAM Version 4 (Revised October 2005). Open-File Report 03-82 [Revised]. Fort Collins, CO: U.S. Geological. Survey, Fort Collins Science Center. 122 pages.
Bovee, K.D. 1978. Probability-of-Use criteria for the Family Salmondidae. Instream Flow Information Paper No.4, U.S. Fish and wildlife Service, FWS/OBS-78/07, 80 pp.
Bovee, K.D., T.J. Waddle, and R.B. Jacobson. 2004. Quantification of habitat patch persistence in rivers affected by hydropeaking. in Lanfear, K.J. and D.R. Maidment, (eds). Proceedings: GIS and Water Resources III. May 17-19, 2004. Nashville, TN (CD). American Water Resources Association. 10 pages.
Bovee, K.D. and J .R. Zuboy. 1988. Proceedings of a Workshop on the Development and Evaluation of Habitat Suitability Criteria. U.S. Fish Wildl. Serv., BioI. Rep. 88 (11) • 407 pp.
Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology. Information and Technology Report USGS/BRD/ITR-1998-0004. Fort Collins, CO: U.S. Geological Survey-BRD. 130 p.
Brandes, K. (ed.). 1985. Opportunities to Protect Instream Flows in Idaho, Oregon, and Washington. U.S. Fish wildl. Serv., BioI. Rep. 85(10). 103 pp.
Bullock, A., A. Gustard, and E.S. Grainger. 1991. Instream Flow Requirements of Aquatic Ecology in Two British Rivers. Report No. 115. Institute of Hydrology. Wallingford, Oxfordshire. 138p.
Cavendish, M.G., and M.I. Duncan. 1986. Use of the Instream Flow Incremental Methodology: A Tool for Negotiation. Environmental Impact Assessment Review 6:347363.
Dixon, W.D., and W.E. Cox. 1985. Minimum Flow Protection in Riparian States. Journal of Water Resources Planning and Management, 111(2) :149-156.
Ghanem, A., P. Steffler, F. Hicks, and C. Katopodis. 1996. Two-dimensional simulation of physical habitat conditions in flowing streams. Regulated Rivers: Research and Management 12:185-200.
Jowett, Ian G. 1992. Models of the Abundance of Large Brown Trout in New Zealand Rivers. North American Journal of Fisheries Management, 12:417-432.
Karr, J .R. and D.R. Dudley 1978. A Primer on the Biological Integrity of Running Waters. Unpublished ms. 12pp.
Lamb, B.L. 1987. Software for Negotiation Planning: Experience with a New Program. Social Science Microcomputer 'Review. Vol 5(2). pp137-148.
Lamb, B.L. 1989. Comprehensive Technologies and Decisionmaking: Reflections on the Instream Flow Incremental Methodology. Fisheries. Vol. 14. No.5. Bethesda,MD. pp 1216.
Milhous, R.T., J.M. Bartholow, M.A. Updike, and A.R. Moos. 1990. Reference Manual for Generation and Analysis of Habitat Time Series version II. Instream Flow Information Paper No. 27. U. S. Fish Wildl. Serv. Biol. Rep. 90(16). 249 pages.
Milhous, R.T., M.A. Updike, and D.M. Schneider. 1989. physical Habitat Simulation system Reference Manual Version II. Instream Flow Information Paper No. 26. U.S. Fish Wildl. Servo BioI. Rep. 89(16). v.p.
Nestler, J.M., R.T. Milhous, and J.B. Layzer. 1989. Instream Habitat Modeling Techniques. in James A. Gore and Geoffrey E. Petts eds. Al ternatives in Regulated River Management. CRC Press. Boca Raton, Florida. pp295-315.
Souchon, Y., F. Trocherie, E. Fragnoud, and C. Lacombe. 1989. Les modeles numeriques des microhabitats des poissons: application et nouveaux developpements. Revue des Sciences de l'Eau. Vol 2(4), pp807-830.
Stalnaker, C.B., B.L. Lamb, J. Henriksen, K. Bovee, and J. Bartholow. 1995. The Instream Flow Incremental Methodology: A Primer for IFIM. Biological Report 29. Washington, DC: U.S. Geological Survey. 45 p.

Stalnaker, Clair B. 1980. The Use of Habitat Structure Preferenda for Establishing Flow Regimes Necessary for Maintenance of Fish Habitat in J.V. War~ and J.A. Stanford (eds.). The Ecology of Regulated Stream. Plenum PUblishing Corp. New York, N.Y. pp321-337.

Taylor, J.G. and B.L. Lamb. 1989. Using Role Analysis for Instream Flow Negotiations. in G.R. Baumli, editor. Legal, Institutional, Financial, and Environmental Aspects of Water Issues. American Society of civil Engineers. New York, NY. pp131-140.

Theurer, F.D., K.D. Voos, and W.J. Miller. 1984. Instream Water Temperature Model. Instream Flow Information Paper No. 16. U.S. Fish and Wildlife Service. FWS/OBS-84/15. v.p. Wilds, Leah J. 1986. A New Perspective in Institutional Analysis: The Legal-Institutional Analysis Model (LIAM). Instream Flow Information Paper No. 23. U. S. Fish and wildlife Service Biological Report 86(9). 143 pages.

Wilds, L.J. 1988. The Legal-Institutional Analysis Model (LIAM): A Validation Study. Instream Flow Information Paper No. 25. U. S. Fish and Wildlife Service Biological Report 88 (33). 73 pages.

Williamson, S.C., J.M. Bartholow, and C.B. Stalnaker. 1993. Conceptual model for quantifying pre-smolt production from flow-dependent physical habitat and water temperature. Regulated Rivers: Research and Management 8(1&2): 15-28.