# Evolution and Application of Instream Flow Methodologies to Small Hydropower Developments: An Overview of the Issues[1]

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Abstract.--Methods for evaluating instream flow needs have evolved over the last 30 years resulting in two categories which are defined as "standard-setting" and "incremental". Standard-setting methodolgies refer to those measurement and interpretative techniques designed to generate a flow value(s) which is intended to maintain the fishery at some acceptable level. Incremental methodologies on the other hand are organized and repeatable processes by which: (1) a fishery habitat/streamflow relationship and the hydrology of the stream are transformed into a baseline habitat time series; (2) proposed water management alternatives are quantified and compared with the baseline; and (3) project operating rules are negotiated. A hierarchial approach to small-hydro instream flow analysis is suggested.

Several techniques exist today which, to varying degrees, are capable of either identifying a base streamflow necessary to maintain instream resources at some acceptable level or quantifying the incremental response of the instream resource to naturally occurring or project-induced changes in streamflow, stream temperature, sediment transport, or water quality. These techniques were developed primarily to resolve conflicts resulting from excessive allocation of streamflow to out-of-stream uses. Central to the evolution of instream flow methodologies are western water law (appropriation doctrine), Federal water policy (e.g., the Carey Act) and environmental concerns (e.g., NEPA). A discussion of the evolution of institutional awareness and the quantification of instream flow needs is found in Stalnaker (1982).

Today we are discussing instream flow methodologies due to yet another institutional stimulus that is particularly applicable to small scale hydropower development. This stimulus is the Public Utility Regulatory Policies Act of 1978 (PURPA). Without the economic incentives provided by this Act--which stimulate small scale hydropower development on steep gradient headwater streams--little interest or need for new or modified instream flow methods would exist.

In this paper, we define methods as specific techniques for measuring or predicting changes in important physical, chemical, or biological variables of the stream environment. Methodologies on the other hand, are collections of methods sequenced in organized repeatable processes which identify the response of specific resources to changes in water, sediment, chemical, and/or nutrient supply. Quantifying these changes leads to either specific limits on streamflow modifications necessary for protecting the existing instream resource or identification of impacts and tradeoffs among the resource uses evaluated. Consequently, neither a fish sampling method nor a hydraulic simulation method constitute an instream flow methodology. They are simply methods for examining important variables.

A brief review of the evolution of instream flow methodologies from early studies to the small-hydro era shows that during the 1950's and 1960's the concentration was on the construction of large federally-funded irrigation and hydropower projects in the West, particularly those of the Bureau of Reclamation and to a lesser extent the Corps of Engineers. Due to the nature of western water law and the fact that most of these projects were predominantly associated with downstream diversions for

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irrigation, fisheries biologists were logically most concerned about periodic dewatering of natural streams during the spring runoff and the low flow season while water was stored in these large reservoirs. In addition, throughout most of the West, the irrigation season coincides with a period of low stream flow. Consequently, the diversion of streamflow into irrigation canals and fields can completely dry up sections of natural streams during late summer and fall. The occurrence of these two types of pertubations caused fisheries biologists to seek identification of a base streamflow that would ensure fish survival through periods of low flow and the phrase "minimum flow" was coined (Orsborn and Allman 1976). The minimum flow was a streamflow "standard" which was meant to constrain either project storage or irrigation diversion during the low flow season. Throughout the remainder of the year, projects did not affect flows, streamflows were usually greater than the "minimum flow", and fish populations were assumed to be out of danger. Thus, a standard-setting methodology evolved that is defined as any set of methods (techniques) designed to generate flow recommendations to maintain the fishery or recreational activity at some acceptable level (see table 1 for definitions).

A second major stimulus for identifying instream flow "needs" was the water allocation procedures of the western States. The States' water planning policies were meant to assist the state engineer, state water administration office, or the State legislature in establishing some end point or limit on water use permits for out-of-stream consumptive uses. Within the institutional framework and philosophy of water administrators, minimum flows were "reserved" by the State to maintain instream fishery resources.

In practice, the degree of protection afforded the fishery varies considerably both within and among the States (Lamb and Meshorer 1983). In the relatively "water rich" Pacific Northwest, minimum flow standards were meant to protect a viable and diverse fishery, often existing prior to the proposed development and the term "resource maintenance flows" came into vogue.

In other western States where streamflow was scarce and economic incentives associated with out-of-stream uses were readily apparent, minimum flow standards were adopted to provide the minimum amount of water necessary to keep the stream channel wet. Minimum flows of this type could maintain a fishery of some sort but were not intended to maintain fish populations at predevelopment levels.

Because of the diversity in "minimum flow" objectives, many different methodologies were developed by State fishery agencies to quantify the "minimum flow", each narrowly focused on a particular definition of minimum flow. Many of

Table 1. Definitions of methods as used in this paper.

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| Instream Flow Methods | techniques to measure, describe, or predict the value of some variable assumed to be important to the general well being of some instream use or user. |
| Instream Flow Methodology | a collection and integration of several instream flow methods (techniques) arranged in an organized process for the purpose of: (1) developing flow recommendations for stated management objectives; (2) quantifying the impacts of potential water management alternatives on instream resources; (3) developing mitigation plans for specific water management schemes; or (4) negotiating project operating rules and flow releases. |
| Standard-Setting Methodologies | measurement and interpretive techniques designed to generate a flow value(s) which is intended to maintain the fishery at some acceptable level. |
| Incremental Methods | techniques designed to generate a relationship between the quality of an instream resource, such as the fishery habitat, and streamflow. |
| Incremental Methodology | an organized and repeatable process by which: (1) a fishery habitat/streamflow relationship and the hydrology of the stream are transformed into a baseline habitat time series; (2) proposed water management alternatives are quantified and compared with the baseline; and (3) project operating rules are negotiated. Items 2 and 3 are often iterative processes involving trade offs among instream and out-of-stream uses. |

these methodologies and their associated criteria are described by Stalnaker and Arnette (1976) and Wesche and Rechard (1980).

A third stimulus for the quantification of a "minimum flow" was the Clean Water Act of 1972 and its subsequent amendments. In order to design sewage treatment plants so that effluent would not degrade water quality in receiving streams during low flow periods, engineers at the Environmental Protection Agency (and the former Public Health Administration) chose the 7 day $Q_{10}$ low flow statistic as the low flow quantity (standard) of the receiving water in which the effluent must be diluted. This flow is the lowest which occurs for 7 consecutive days in a 10-year period, thus waste treatment plants designed to meet water quality standards at this level were assumed to be adequate.

Most standard-setting methodologies can generally be categorized as either hydrologic,

which lead to minimum flow recommendations based on streamflow statistics (e.g., 40% of mean annual flow), or hydraulic, which lead to recommendations based on some streamflow-dependent habitat index (e.g., the break in the wetted perimeter vs. flow relationship). Methodologies developed to set minimum flow standards on streams for the purpose of State water allocation or to protect water quality in receiving streams were nearly always based on analyses of the historic streamflow record. Minimum standards were often indexed to flow amounts equalled or exceeded 90% of the time; 10% of the mean annual flow; 7 day $Q_{10}$, or even the lowest daily flow on record. An excellent discussion of these different standard-setting methods are found in Wesche and Rechard (1980) and Loar and Sale (1981).

The problem with basing the well-being of fish populations on low-flow statistics is that the long term effects of artificially maintaining these minimum flows is seldom the same as infrequent, naturally occurring, short term effects that may appear in the historic record (e.g., three drought years in a row is uncommon). The ability of fish populations to compensate for a one-in-ten-year low flow event may give the false impression that the fish population will remain healthy and viable if this minimum flow (drought) condition were imposed year after year. As water projects were built and operated, it became apparent that in many cases the fishery resources were decimated as a result of the planners' and hydrologists' illogically assigned low-flow statistics.

Streamflow releases immediately downstream from the large federal water impoundments built during the 1950's and 60's were not as constrained by the low-flow statistics of the particular stream because upstream storage was very large, and water could be stored and carried over from one season to another and, in many cases, from one year to another. Therefore, instream flow methodologies developed to determine minimum flow recommendations below large reservoirs tend to focus upon stabilizing or even enhancing the downstream fishery. This came about because the normal project operation tended to provide fairly cold water releases in amounts often in excess of natural, mid-summer, preproject streamflows. In addition, many of the large storage reservoirs were built on streams in arid environments and as a result of the cool water release the downstream fishery was often converted from warm water species to trout. Hence, maintenance of the predevelopment fish population was not always the motivating factor when quantifying the minimum flow. In several instances intentionally replacing the predevelopment fishery with a viable trout fishery was the objective of the "minimum flow."

Definition of acceptable levels of the post-development fishery is quite variable and ranges from the minimum flow needed for the maintenance of the existing fishery to enhancement or even changing or maximizing of fish populations. In the past thirty years, several of the resource agencies have conducted biological studies on unregulated streams for the purpose of examining correlations between fish standing crop and the instream flow as determined from one of the standard setting methods. Trout populations in the intermountain west have been shown to remain healthy and viable when minimum flows during the summer low flow months are in the range of 30 to 60% of the mean annual flow (Elser 1972; Wesche and Rechard 1973; Stalnaker and Arnette 1976), keeping in mind that flows are well above these minimums during most of the remainder of the year. In trout streams possessing a relatively rectangular cross-sectional shape, it has also been found that a "minimum flow" at or above the inflection point of a wetted perimeter versus discharge plot generally maintains the fishery in a healthy status (Nelson 1980), but again, streamflows associated with these studies were well above the "minimum" value during most of the year.

Post audit studies conducted for the Fish and Wildlife Service by Hazel (1976) and Nelson et al. (1976) found that for 90% of the western Federal water projects evaluated, the minimum flow agreed upon was frequently violated during drought cycles. Inasmuch as the identification of minimum streamflows had evolved with the understanding that they would protect the fishery during the low-flow season and droughts, the wide-scale violation of these standards prompted notable concern on the part of the general public, fisheries managers, and the water planning community.

The Water Resources Council and the numerous River Basin Commissions provided an impetus throughout the 1960's for planning the multiole use of water. This impetus on multiple use planning and the poor track record of protecting instream values using standard-setting methodologies led to the request by many resource agencies for stricter permitting requirements, including monitoring and enforcement clauses. Enforcement is likely only when the trade-offs between offstream uses and instream uses are clear. Hence, more sophisticated methodologies were needed to address the "what if" questions and in particular, "What happens to the fishery resource when the streamflow (standard) identified for maintaining the fishery is not delivered?" (Orsborn and Allman 1976).

This state of affairs in the late 1960's and early 70's led to many symposia and meetings where a need was expressed for methodologies which would answer the "what if" questions proposed by the water development and planning community. Allred (1976) presented the perspective of the water administrator when he said "if instream flow interests expect to compete with other uses for limited water supplies, they must be able to demonstrate with the same type of

analyses and approach as other uses the need for instream flows and the affect of not obtaining those flows".

Consequently, during the last decade we have seen the develoomen of instream flow assessment methods which attempt to evaluate fish habitat on the basis of the hydraulic, structural, and water quality aspects of the stream environment. These methods are generally referred to as "incremental" in nature because of the need to examine different increments of streamflow (table 1). The common product of incremental methods is a relationship between fish habitat and stream flow. Important pioneers of this approach were Collings et al. (1972), who used binary depth, velocity, and substrate criteria to evaluate the influence of incremental changes in streamflow on the quality of spawning habitat for salmon in Washington streams. Also Waters (1976) applied weighted criteria for depth, velocity and substrate/cover and introduced computer simulation to evaluate the response of rainbow trout habitat to streamflow variations in California. The application of hydraulic modeling methods in conjunction with streamflow dependent criteria for fish habitat began with single transect methods such as the R2 CROSS procedure introduced by the Forest Service (Issacson 1976; Weatherred et al. 1981). Single transect methods were followed by more sophisticated multiple transect, hydraulic modeling methods adapted from Water Surface Profile simulation models commonly used by the Corps of Engineers, the Bureau of Reclamation, and the Soil Conservation Service.

The Bureau of Reclamation assisted the Montana Department of Fish and Game by modifying their water surface profile program to provide greater resolution of hydraulic conditions in stream channels. Single values for mean reach velocity and depth were replaced with depth and velocity predictions in a number of cells across transects within the study site, and the wetted perimeter at each transect was calculated as a function of streamflow (Dooley 1976). The development and refinement of hydraulic simulation methods to facilitate evaluation of habitat conditions under broader ranges of instream hydraulic conditions has continued to the present (Milhous 1984). A well known example is the physical habitat simulation model-PHABSIM (Milhous et al. 1981) which is an important component method within the Instream Flow Incremental Methodology (IFIM) as described by Bovee (1982).

In this overview of instream flow methods and methodologies, it is important to consider the fact that all techniques have evolved from experience gained through empirical studies. The predictive techniques and computer simulation models which can be used today with limited field measurements are based upon the experience and knowledge gained from previous field studies. For most cases more can be learned about the dynamics of the stream system today with fewer field measurements than were necessary 20 years ago. However, there are still many situations in which an extensive number of repetitive field measurements are necessary. As more elaborate simulation models become available for use in the determination of instream flow requirements, a greater need exists to critically evaluate and fully document the underpinning assumptions of the simulation models chosen for each instream flow study. Whenever natural conditions cannot readily be described by existing formulae or theory, empirical data is always as good as, and in most cases better than, simulated data. For example, in those situations where instream hydraulic conditions are not compatible with standard application of existing hydraulic simulation models, additional time and resources will be required to conduct the necessary empirical studies before reliable incremental solutions can be provided.

It should also be recognized that simplified "rule-of-thumb" methods and methodologies are generally derived from large data bases. Once these empirical data bases have been obtained and sufficient knowledge of the interactions between physical processes and biologic responses is gained simplifying assumptions can be made without jeopardizing the reliability of forecasts. A good, simplified, rule-of-thumb methodology cannot be developed prior to acquiring broad experience with the situation.

We now have two basic types of instream flow methodologies for fisheries: (1) those for protecting existing resources by setting instream flow standards for streams, which can then serve as constraints on development; and (2) those for quantifying trade-offs by describing the response of fish habitat to streamflow alterations.

All instream flow investigations should be viewed as part of a phased process in which standard setting can be a precursor to incremental analyses and each have an important role. Whenever a specific project: (1) has relatively benign impacts; (2) is proposed where limited fisheries or recreational values exist; or (3) is not anticipated for development for several years in the future, standard setting as the first phase is most appropriate. In such cases the specific methods chosen depend on the resource agencies' management policy, the region of the county, and the aquatic organisms of concern.

The second phase commences when alteration of the streamflow, stream temperature, channel structure or water chemistry is proposed and has prompted questions concerning the effects of these alterations on the fisheries and recreation interests. In other words, phase two commences when the water development interests begin asking what will happen if the minimum flow standards are violated. This could also be initiated by the resource agencies seeking opportunities to improve the existing fish populations or to alter the species composition.

This phase is site-specific and data intensive. Streamflow time series, project operating rules, and species habitat response curves are necessary intermediate products of this phase.

Despite the successes, fisheries biologists have not yet achieved the capability of forecasting the number of fishes produced in response to any particular water management scheme. This question is being brought up more and more in present-day water development and constitutes a third phase. Within the next decade or so a scramble is expected for research and method development aimed at predicting changes in numbers of fish resulting from flow and channel alterations. This will be similar to the 1970's when methods to quantify the response of fish habitat to streamflow were developed. Only after reaching this third phase can we begin to quantify the economic value of altering the instream resource. This will provide an equivalent basis for comparison of fishery resources with other instream/out-of-stream values.

The numerous instream flow methods and methodologies that now exist provide sufficient analytical tools to evaluate hydropower development on small streams. Perhaps the most difficult aspect of evaluating the instream flow concerns associated with a small hydropower development is in the selection of appropriate cost-effective study methods and agreeing on a methodological process. In brief:

Standard Setting is most appropriate for:

- Protecting the existing instream resource;
- State Water Plans;
- State Water Allocation permits or reservations; and
- Identifying target flow for use during project feasibility studies.

Incremental Methods are most appropriate for:

- Time series analysis to identify limiting flow conditions;
- Fine tuning a resource maintenance objective (maximum utilization of available water);
- Avoiding or minimizing flow-related impacts; and
- Comparing mitigation alternatives.

When undertaking instream flow studies to support the licensing or relicensing of a small hydro project it is wise to divide the process into three distinct levels of analysis. Depending on the nature of the development and the instream flow related issues, a license application could be successfully supported at any one of these levels. Each level of analysis: reconnaissance; feasibility; and operational design; is intended to provide relevant answers to technical questions of increasing complexity. These analysis levels are summarized in table 2.

It is important to avoid the pitfall of implementing a complex design level field study (e.g., IFIM modeling study) without first completing a feasibility level analysis. Based on experiences of the authors, the most common mistake being made when initiating instream flow studies at small hydro sites has been that of partially completing a reconnaissance level study and immediately undertaking an operation level IFIM modeling study. Too often this is done without first implementing the hydrologic and biologic elements of the feasibility level analysis to determine: (1) if the project has the potential for being compatible with agency policy; and (2) if it is necessary to initiate a complex operational modeling study to design conditions assuring that compatibility.

All participants should recognize that licensing hydro projects is generally a multi-year iterative process and therefore adopting the suggested hierarchical approach outlined in table 2 for the instream flow studies as is common in traditional engineering studies, will, in the long-run, be most cost effective.

Once outside the realm of reconnaissance and feasibility level studies and the application of standard-setting methodologies, the instream flow analyst can no longer ignore the influence of channel structure, channel dynamics, water quality, temperature, and food production on the instream uses. Unfortunately, much of the ability to forecast changes in these habitat components is still predominantly based on empiricism necessitating more time and financial resources. However, these habitat components can be evaluated and integrated into an instream flow assessment. The hydro developer and the fishery manager must therefore assess the decision-making arena in which they are being asked to participate and tailor the methodology accordingly. If identification of a resource maintenance flow is adequate to protect the predevelopment resource for several years in the future, then application of a standard-setting methodology is all that is warranted. If, however, the proposed development will obviously change the predevelopment fishery or recreational value of a stream system, then application of a methodology incorporating the hydrologic, thermal, morphologic, chemical, and biologic aspects of the stream becomes essential to the long range management of the stream system for multiple uses. In order to be useful for decision making, results from incremental methods should be presented in some form of a time series comparison between existing (pre) and post project habitat conditions with the limiting habitat conditions clearly identified. Alternative management scenarios can be evaluated by quantifying the frequency, magnitude and duration

Table 2. Three levels of instream flow analyses for supporting the licensing or relicensing of hydropower projects.

Reconnaissance Level: Goal is to identify questions and concerns.

- Identify project location, configuration and generation.
- Identify fish or recreational interest that may be affected.
- Identify stream segments of primary and secondary concern.
- Identify applicable agency policies, guidelines, and fish management goals.
- Determine whether major issues are likely to arise from project incompatibility with resource requirements or with agency policy.
- If project appears benign and compatible with agency policies proceed to Exemption Process.
- If project compatibility with fish management goals cannot be adequately defined then proceed to feasibility study.

Feasibility Level: Goal is to establish the compatibility of the proposed development and existing instream uses.

- Quantify streamflow regime
  1) annual hydrograph
  2) monthly duration curves
  3) baseline time series analysis
- Identify seasonal species distribution and relative abundance.
- Discuss influence of streamflow on distribution and abundance.
- Determine maintenance streamflow "standards" for stream.
- Forecast with-project streamflow regime.
- Compare with-project streamflows to maintenance standards and identify major issues.
- If the proposed project or proposed project and accompanying mitigation is compatible with agency policy, prepare an Exhibit E using the maintenance standards as conditions for licensing.

Table 2. (concluded)

- If the proposed project appears c[illegible]ible with agency policy, but impacts need to be quantified or mitigation measures agreed upon, proceed to design and operation level studies.

Operation Level: Goal is to quantify impacts, develop mitigation measures, establish project operating rules and conditions.

- Convene scoping meeting to:
  1) Determine major issues and establish format of the analytic comparison needed for decision-making.
  2) Design project-specific methodology.

     (Assemble appropriate methods and criteria to evaluate the physical, chemical, and biological issues identified during the feasibility study and scoping process).
- Conduct necessary field investigations and analyses.
- Quantify impacts.
- Determine mitigation opportunities.
- Negotiate settlement and conditions.
- Proceed with licensing.

of the limiting habitat conditions associated with each alternative.

All in all, the state-of-the-art has greatly advanced from the early 1950's when instream flow concerns first arose. When water is available and legal and institutional recognition exists for protecting and managing an existing fishery resource technology is available for maintaining existing habitat conditions. This can be done quite well for salmonid fishes in cold water stream environments, and fairly well for cool water species because of the numerous studies made of these species. Given sufficient time and resources for studying and developing appropriate habitat criteria for warm water species, management for protection of these stream environments is also quite feasible. However, when physical and chemical changes are imposed upon a stream system, producing a very different mix of these conditions, and the flow regime is radically changed, the ability to predict the response of the physical habit[illegible] the bentnic organisms, and consequently the [illegible]

population is rather poor and represents an area for needed physical and biological research.

The current (third) phase of methods development focuses on stream channel dynamics, sediment transport, temperature, water quality, and species interactions. Only when changes in the physical/chemical components of the environment can be integrated with aquatic species response models will the desired predictive third phase of water management become operational.

## ISSUES RELATED TO THE SMALL HYDRO/FISHERIES ARENA

- Agency promulgated instream flow methodologies must include well documented criteria for interpretation, stated management goals, and policy relevant to the type of development proposed.
- Standard-setting of protection or maintenance flows should be a part of every water planning process and incorporated into the feasibility phase of hydro-project developments.
- Channel form and substrate transport conditions are too often overlooked and can be critical in alluvial streams and gravel limited streams.
- Hydraulic simulation and hydrograph synthesis techniques are only building blocks in some overall process and should not be referred to as instream flow methodologies.
- Basic research is needed on aquatic organisms and community response to stream environment changes before the state-of-the-art can move from the present single species habitat protection or enhancement approach to water development forecasting and economic comparisons among instream and out-of-stream uses.

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