A Roadmap for PIER Research on Instream Flow Determinations for Hydropower Applications in California

PIER FINAL PROJECT REPORT

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Executive Summary

This *Roadmap for PIER Research on Instream Flow Determinations for Hydropower Applications in California* addresses the research needed to identify and reduce adverse impacts on aquatic species and habitats from instream flow variations caused by the operation of California hydropower facilities. The term *instream flow, as used in this roadmap, refers* to the amount of water flowing in a natural stream or river that is needed to sustain aquatic species and habitats. Hydropower operation affects instream flows mainly through the retention of water behind dams and/or the diversion of water from the stream or river. In general, increases in instream flows downstream of a hydropower facility means reduced generation from that facility.

Hydropower represents an important, low-cost renewable energy resource for California, representing approximately 27% of the state's installed generating capacity. Between 1983 and 2001, hydropower has on average accounted for 15% of all the electricity used within the state. Perhaps even more important than its contribution to overall capacity is hydropower's ability to meet peak electrical demand quickly—a very important factor for meeting California's electricity needs. Yet, even though hydropower generation does not contribute to the air and greenhouse gas emissions associated with fossil-fuel generation, it does contribute to the degradation of California's freshwater ecosystems.

These ecosystems have suffered massive alteration, with many fish populations in precipitous decline. It is estimated that 58% of California's freshwater species are extinct or are in serious decline (Moyle 2002). Although many factors have contributed to this continuing decline, California's hydroelectric power plants and associated dams have been identified as a contributing factor and a key effect caused by dams and water diversions on aquatic species and habitats is the reduction of instream flows.

Hydropower impacts on aquatic ecosystems are receiving increased scrutiny because of the large number of hydropower plants that will be undergoing the Federal Energy Regulatory Commission's hydropower relicensing process in the near future. Approximately 5,000 megawatts of hydropower in California will undergo relicensing by 2015, approximately one-third of the state's installed hydropower capacity. It is likely that the most contentious topic for most projects during the relicensing process will be the determination of the appropriate instream flows.

This roadmap recommends research that would improve laboratory and field analyses and modeling for aquatic habitats and species, as well as California-focused efforts that would improve the use of bioassessment and indices of biological indexes in the state. The research would determine the extent of hydropower generation on instream flows and the state's freshwater ecosystems and develop cost-effective methods and technologies for reducing and resolving the adverse effects on those ecosystems.

In the short-term (1–3 years) this roadmap recommends that the following objectives be addressed:

Roadmap Organization

Objective	Projected Cost ($000)
Document the Ecological Effects of Existing Flow Alterations	25
Standardize the Application of PHABSIM under the IFIM	
• Establish Quality Control Standards for PHABSIM	10
• Establish Standards for Use of 1-D and 2-D models	10
Refine and Standardize Alternative Instream Flow Methods	
• Establish California Tennant Method	10
• Establish IHA Parameters and Thresholds	10
• Techniques for Expert Panel Assessment Method	5
Total	**70**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure.

This roadmap also identifies mid-term (3–10 year) and long-term (10–20 year) goals, some of which build on the short-term work listed above.

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

Section 1: Issue Statement states the issue being addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how the PIER program plans to address those needs. *Section 3: Background* establishes the context of PIER's work addressing instream flow determination methodologies. *Section 4: Research Needs*: surveys different approaches to instream flow determination and identifies those that are most appropriate for California applications. Section 5: Research needs identifies research gaps regarding instream flow determination methodologies and then identifies proposed PIER Environmental Area (PIER-EA) to address these needs. Section 6: Leveraging R&D Investments identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. Section 7: Areas Not Addressed by this Roadmap identifies areas related to instream flow research that the proposed activities do not address.

1. Issue Statement

There is a need to improve our ability to allocate water among competing demands, including hydroelectric generation, while ensuring protection of the aquatic species and habitats of the state's streams, rivers, and reservoirs.

2. Public Interest Vision

The primary mission of the California Energy Commission's Public Interest Energy Research (PIER) program is to conduct research that helps deliver "…environmentally sound, safe, reliable, and affordable electricity…" to the citizens of California. The mission of PIER's Environmental Area (PIER-EA) is "…to develop cost-effective approaches to evaluating and resolving environmental effects of energy production, delivery, and use in California, and explore how new electricity applications and products can solve environmental problems."

The *PIER Environmental Area Research Plan: Environmental Context and Key Environmental Issues* (California Energy Commission 2001) identified hydropower generation's impacts on the natural ecological and hydrological functions of California's aquatic systems as a high priority for research. That effort separated the effects of hydropower generation on California's freshwater ecosystems into three issues: water quality, fish passage, and instream flows. This roadmap focuses on the research needs to improve instream flow determination methodologies.

Hydropower is an important component of California's electricity system, representing about 27% of the state's total installed generation capacity. It is a low-cost renewable energy resource with many environmental benefits, including the absence of greenhouse gas and other air emissions that are inherent in fossil-fueled generation. It also provides recreational opportunities, such as boating, whitewater rafting, and fishing—as well as the resulting economic benefits of those activities to local communities and the state. In addition, hydropower generation can be brought online quickly when California's electricity needs demand it. Yet, the role of hydropower in California's electricity system is being reduced as a result of hydropower's effect on aquatic species and habitat. Minimal capacity increases have occurred in the hydropower generation sector within the last generation, and what growth has occurred is the result of the expansion of existing facilities or new offstream generation, usually associated with water delivery facilities such as canals and pipelines.

The reasons for these significant concerns regarding hydropower as an energy source in California are tied to the drastic alteration of the state's freshwater ecosystems. This alteration is reflected in the precipitous decline in many of the state's freshwater fisheries. Peter Moyle (2002) estimated that approximately 58% of all inland native fish species in California are already extinct or in serious decline. Although many factors have contributed to this continuing decline, California's hydroelectric power plants and associated dams have been identified as a significant contributing factor.

Virtually every hydropower plant located on a stream or river in California has been the center of controversy. Of 14 California hydropower projects recently relicensed by the Federal Energy Regulatory Commission (FERC), 11 were required to modify the volume and timing of their discharges to increase instream flows, with a resulting decrease in generation (California Energy Commission 2003). Given that approximately 5,000 megawatts (MW) of hydropower generation will be subject to FERC relicensing between now and 2015, improvement in our ability to accurately determine the flows necessary to sustain healthy freshwater ecosystems is important to ensure environmental protection while minimizing unnecessary curtailment of hydropower generation.

To ensure that California is able to utilize the full capacity of its hydropower resources while maintaining adequate flows to adequately sustain freshwater ecosystems, research and development is needed in a number of areas. The components of needed research that are listed in Section 2 all map to the actual projects suggested in Section 5. The research described in this roadmap will aid in improving instream flow determinations that are environmentally protective while avoiding unnecessary curtailment of hydropower production

Californians will benefit from this work in a variety of ways—chief among them being a better balance of resource protection and electricity generation, which is a key goal of this research. In particular, this program offers an opportunity to protect aquatic habitat by improving the science that enables researchers to determine the necessary instream flows to sustain aquatic species and habitats. California's rich freshwater fishery is a public resource used and enjoyed by millions of residents and visitors, and a vital component in some rural California economies. A healthier freshwater aquatic habitat would help ensure the stability of that resource. Results from this effort could also reduce cost and permitting efforts for operators, agency staff, and other stakeholders. Industry and stakeholder participation in the research identified herein would also promote partnerships and cooperation towards solving water quality issues associated with hydropower generation.

3. Background

The term *instream flow,* as used in this roadmap refers to the amount of water flowing in a natural stream or river that is needed to sustain aquatic species and habitats. Historically, the approach to instream flow determinations in California have focused on determining the minimum flow levels to sustain aquatic ecosystems. In recent years, the importance of mimicking natural flow variation has been recognized (Richter et al. 1996, Richter et al. 1997).

While there are many factors affecting the health of freshwater ecosystems, instream flow determinations focus solely on the availability of physical habitat. Determination of instream flow levels requires integrating biotic and abiotic factors over a variety of spatial and temporal scales (Instream Flow Council 2002). There are a vast number of ways to quantify instream flow needs and while there is no one right way, common practice

Hydropower operation affects instream flows mainly through the retention of water behind dams and/or the diversion of water from the stream or river. Determining Instream flows is invariably the most contentious issue for hydropower relicensing projects within California. This is true because instream flows levels are viewed as the most limiting factor for healthy aquatic ecosystems. In addition, these flow levels are (mostly) controlled by the hydropower operator under levels set by the FERC permit conditions. Finally, instream flow downstream increases generally mean reduced electricity generation from the project.

The following sections describes California's hydropower generation sector, discusses why instream flow is a significant concern, and outlines the different approaches to instream flow determination.

3.1 The Role of Hydropower in California's Electricity System

Hydropower is an important component of California's electricity system, representing about 27% of the state's total installed generation capacity. Actual hydropower generation, however, varies greatly in response to hydrologic factors. Between 1990 and 2000, hydropower actually contributed from 9% to 25% of the in-state supply, as a result of annual variations in runoff (California Energy Commission 2002). In 2001, a drought year, hydropower represented only 10% of the total in-state generation. Over an 18-year period between 1983 and 2001, hydropower represented just over 15% of electricity used within the state, including imports (California Energy Commission 2002). The ability to dispatch hydropower on short notice is perhaps an even greater benefit to the state's electrical system than its contribution to the state's overall installed capacity. Unlike many other generation sectors, hydropower units can start up and meet capacity load in a matter of minutes, as well as provide spinning reserve[4] to meet transmission line voltage requirements. Although drought years will reduce overall hydropower production, hydropower generation has been able to meet peak demand, even during the driest years. In addition, hydropower plants are highly reliable, with generally achieving availabilities in excess of 90% (EPRI 2001). Although only limited information was available, EPRI (2001) found that the average capacity factor for California facilities was 52%, reflecting both equipment (e.g., outages) and flow limitations. Hydropower also contributes to the state's electricity system by providing low-cost energy. Many hydropower facilities in the state produce electricity at less than 1 cent per kilowatt-hour (kWh), significantly less than the cost of electricity from most fossil or renewable energy sources.

[4] *Spinning reserve* refers to unused capacity that is available to provide power to the grid at a moment's notice.

3.2 Environmental and Social Benefits of Hydropower

Besides being an inexpensive, renewable energy resource, hydropower generation does not contribute the greenhouse gas and other air emissions associated with fossil fuel and even some other renewable energy sources. Furthermore, hydropower provides significant recreation opportunities, such as recreational boating and fishing that are a significant source of income in many rural portions of the state.

3.3 Research Methodology

The research efforts identified in this roadmap are a result of an extensive literature review, professional experience and consultation with experts in the field.

3.4 Historical Review of Instream Flow Assessment Methodologies

Many different approaches for determining instream flow needs have been developed and applied since the early 1970s. Some of these have persisted and become incorporated into what might be considered standard methods, some remained regional without broad dissemination or acceptance, some were improved and updated, and some quickly faded. Since the objectives of instream flow recommendations vary, particular methods may be targeted at certain life stages or biological activities, such as spawning or migration, so not all single methods can be broadly applicable, and some may be used in combination.

Several research summaries capture the evolution of methods development. The first, “Methodologies for the Determination of Stream Resource Flow Requirements: An Assessment” (Stalnaker and Arnette 1976), identified 20 methods and methodologies that assess fishery and stream habitat flow requirements, then listed 10 topics for future research needs. (Note: *Methods* are nominally those approaches defined by rules which allow no user flexibility or choices; whereas, *methodologies* provide optional pathways to be selected at user discretion.) In 1980, Wesche and Rechard (1980) wrote “A Summary of Instream Flow Methods for Fisheries and Related Research Needs” that listed 16 instream flow methods and included five topic areas for additional research.

These reports were followed by “Instream Flow Methodologies” (Morhardt 1986), a comprehensive document that summarized and reviewed 70 instream flow and habitat quality methods (although several were applications of similar methods to different species). Morhardt (1986) listed five areas and 20 specific topics as recommendations for future research. At about this time, two other reviews were prepared covering roughly the same scope; “Analysis of Environmental Issues Related to Small-Scale Hydroelectric Development. V: Instream Flow Needs for Fishery Resources” (Loar and Sale 1981), and “Models that Predict Standing Crop of Stream Fish from Habitat Variables: 1950-1985” (Fausch, Hawkes, and Parsons 1988).

Several reviews of the latest methods have been made within the last decade. The most extensive of these were conducted overseas, where researchers have been attempting to implement recent changes in environmental law, and started with assessments of well-established methods. In some instances, new approaches were initiated for application to unusual hydrologic patterns or species assemblages, where more traditional methods have been judged inadequate. Tharme (1996), in South Africa, wrote a "Review of International Methodologies for the Quantification of the Instream Flow Requirements of Rivers" that identified and critiqued many of the earlier methods but added descriptions of methods for flushing flows, riparian vegetation, and water quality, plus holistic and alternative approaches.

In the United Kingdom, "Overseas Approaches to Setting River Flow Objectives" (Dunbar et al. 1998) started with a review of techniques used in 20 countries and focused on nine key methods for applicability to rivers and streams in England and Wales. These methods are ranked according to whether they are *standard setting* (i.e., set fixed flows for specific times of the year) or *incremental* (i.e., allow alternative flows, depending on variables), and whether they are species-based or ecosystem-based. A report by Railsback (2000), "Instream Flow Assessment Methods: Guidance for Evaluating Instream Flow Needs in Hydropower Licensing," focuses on a review of methods used recently for hydropower licensing in the United States. Finally, the Tharme review was updated to "A Global Perspective on Environmental Flow Assessment: Emerging Trends in the Development and Application of Environmental Flow Methodologies for Rivers" (Tharme 2002). This last paper covers virtually all of the most recently developed instream flow approaches and provides additional critique of many other early methods, enumerating over 200 individual techniques from 50 countries.

3.4.1 Categories of Instream Flow Assessment Methodologies

Most instream flow methodology reviews categorize each approach into types by technical basis or primary function. A recent publication by the Instream Flow Council (IFC 2002) puts all methods into three groups: *standard setting, incremental,* and *monitoring/diagnostic.* The IFC (2002, p. 175) defines *standard setting* as a "…a predetermined set of formulas or numeric rules that is used to define a flow regime." *Incremental* is defined by the IFC as analyzing "…single or multiple variables to enable assessment of different flow management alternatives," while *monitoring/diagnostic* to the assessment of conditions and how they change over time. Tharme (2002) classifies flow determination techniques as hydrological, hydraulic rating, habitat simulation, holistic, combination, and "other" types; these definitions are used here to allocate the methods into more specific and descriptive categories.

Hydrological. Hydrological methods are those using percentages of annual, monthly, or other interval flow statistics, either as set percentages of flow or as exceedance thresholds applied to flow duration data. These percentages or thresholds may be modified by consideration of hydraulic, biologic, or geomorphologic criteria. The primary example of a hydrological method is the Tennant (Montana) Method (Tennant 1975), created by Don Tennant of the U.S. Fish and Wildlife Service in the mid-1970s and still in widespread use. Others include the 7Q10, Q90, Q364, "modified" Tennant, Texas Method, Basic Flow Method, Range of Variability Approach, and Flow Translucency Approach. Most of these methods are referred to as *standard- setting methods,* because they derive fixed flow recommendations with no deviation, modification, or negotiation once the flow percentages or minimum thresholds are chosen.

Hydraulic Rating. Hydraulic rating (or habitat retention) methods use measurements of stream channel variables (typically along cross-sections), such as wetted width or maximum depth, as a surrogate for some biological function (like food production from riffles) that is known or suspected to be limiting to aquatic populations. When the variable is plotted against discharge, inflections or break points in the plot are assumed to represent the threshold below which the biological function will degrade. The oldest examples of hydraulic rating methods are Wetted Perimeter and R-2 Cross, although Tharme (2002) found 23 methods altogether. Hydraulic rating methods have been infrequently used in recent years, and also fall into the standard-setting category.

Habitat Simulation. The habitat simulation category of instream flow methods are those linking computer models of stream channel hydraulics with biological response data to create quasi-numeric relationships between flow and indices to physical habitat. The indices of habitat are treated as surrogates for actual populations (which have often been found to correlate with factors related to flow) to either derive flow recommendations or serve as a basis for project alternatives analysis and negotiation. The 58 habitat simulation methods worldwide (Tharme 2002) include Physical Habitat Simulation (PHABSIM), Norwegian River System Simulator (RSS), French Evaluation of Habitat Method (EVHA), Computer Aided Simulation Model (CASIMIR), and Riverine Community Habitat Assessment and Restoration Concept (RCHARC). Many of these methods can be used both for standard setting and for more advanced incremental alternatives analysis.

Holistic. This relatively new instream flow method category evolved for application to river systems subject to wide flow variability on an annual basis (typically between dry and complete floodplain inundation) in South Africa and Australia. Holistic methods are scenario-based, where multidisciplinary teams of experts identify the consequences of instream flow alteration within social, ecological, geomorphological, and economic modules. The Building Block Methodology (BBM) and the Australian Holistic Approach are the forerunners of 16 holistic methods found worldwide (Tharme 2002), including Downstream Response to Imposed Flow Transformations (DRIFT) and the Flow Restoration Methodology (FLOWRESM). Holistic methods can be considered either standard setting or incremental, depending on the level of stakeholder participation, the scope of alternatives, and the legal or regulatory environment.

Combined. Numerous (35) combinations of these first four categories were found by Tharme (2002) and classified as “combined,” although some were judged difficult to document or describe accurately. The most well-known of the combined methods is the Habitat Evaluation Procedure (HEP), developed by the U.S. Fish and Wildlife Service in 1976. The HEP has been applied primarily to terrestrial impact mitigation but also has lacustrine (lake) or riverine (river) components. Other combined methods include the Basque Method, Managed Flood Release Approach, the Hill, Platts and Beschta Method, and a Collaborative Settlement Approach recently applied to the Mokelumne River in California. As in the case of holistic methods, combined methods can be standard setting if imposed by regulatory agencies or incremental if applied collaboratively.

Other. A few of the instream flow methods developed around the world fall into the "other" category. The Professional Judgment method is the principal representative of other methods, which also include various regression models of fish population data and physical parameters. Except for Professional Judgment, the other methods are infrequently used to recommend flow regimes, but do have potential for future extension.

3.4.2 Research Needs

Over the years there have been a variety of research needs identified for instream flow methodologies. Some of these needs have seen progress or resolution and some have remained unstudied and unaddressed. In general, these research needs are aimed at improving our understanding of the underlying relationships between aquatic ecosystems and other physical factors. Other research needs specifically address improving our understanding between flow and habitat quality.

3.4.3 Principal Instream Flow Assessment Methodologies for California

The diversity of instream flow approaches developed over the years across many countries derives from a mixture of varied combinations of environmental attitudes, laws, and regulations, priorities in management styles, hydrologic patterns, species life histories and needs, river channel morphology, and water quality effects, among many factors. Additional variables include the availability of time and money, knowledge of site-specific conditions and organisms, and the experience and perspective of researchers, mixed with a little regionalism or preference for locally derived methods. The following methods are either known to have been utilized in California or believed to have potential applicability to California circumstances, at least with additional testing and research. References for each method are provided to minimize the length of this document, and they are presented in no particular order. Research opportunities for each of these flow determination techniques are discussed in Section 4.

Tennant Method. The Tennant Method was developed by Don Tennant, a biologist with the U.S. Fish and Wildlife Service in Billings, Montana. He conducted relatively detailed studies of 196 river miles on 11 streams and rivers in three states at 58 stations and 38 flow levels over ten years. His study parameters included: width, depth, velocity, substrate, side channels, bars and islands, cover, fish migration, temperature, invertebrates, fishing and floating, and esthetics and natural beauty for coldwater and warmwater fishery conditions. From this database, he concluded that 10% of the annual average flow would sustain short-term survival habitat, with numerous negative consequences. Thirty percent of the average flow would sustain good survival habitat as reflected in his parameters, and 60% average annual flow is described as providing excellent to outstanding habitat for most aquatic life forms (Tennant 1975; 1976).

The three original levels of aquatic condition (10%, 30%, and 60% of mean annual flow, or MAF) were subsequently amended by Tennant (1978) to add seasonal variability (30% MAF became 20% October through March and 40% April through September) and channel condition flows (200% MAF). Tennant applied his method in 11 states with the assistance of district fishery biologists to produce over 100 streamflow recommendations (Tennant 1978) and “substantiated” the correlations on a wide variety of streams (Bayha 1978). Tennant believed his method to be valid and useful in his experience; however, he cautioned others to be sure to calibrate it to different hydrologic, geomorphic, and biotic conditions prior to using his parameters.

Contrary to his explicit caution, the Tennant Method has been utilized in many areas of the world (Tharme 2002) either directly as described, or “modified” according to the judgment of others, with no documented attempts at local calibration. In California, the Tennant Method has been informally applied to hydropower licensing by the Department of Fish and Game as a means of evaluating flow recommendations derived by other methods (Schuler, pers. comm.). One of these applications (60% MAF for summer and 30% MAF for winter) resulted in a legal challenge to a hydroelectric project that went to the U.S. Supreme Court (*California v. FERC*)[5]. In another case, the method was “modified” to take a percent of the annual volume of streamflow to shape a monthly hydrograph as a flow recommendation (Trihey 1996).

At heart, the Tennant Method is subjective (e.g., referred to as “good,” “excellent,” “outstanding”), based on poorly quantifiable criteria (e.g., cover, side channels, aesthetics), and arbitrary in defining flow levels (e.g., 30%, 40%, 60%). Despite these quantitative limitations, however, the method undoubtedly does correlate to observable levels of stream protection or degradation in the subjective judgment of fishery biologists. Most likely because of this intuitive correlation, the Tennant Method has persisted in use and has been legally accepted in several states for instream flow reservations (Robertson, pers. comm.). The method may be useful for certain categories of instream flow recommendations in California, but it absolutely must first be calibrated to local circumstances, as Tennant advised. Any attempted modifications of the method are not the Tennant Method any longer and should be renamed to avoid the appearance of endorsement.

Range of Variability Approach. The Range of Variability Approach (RVA) is a hydrological method conceived under the premise that natural ranges of flow variation are integral to the sustainability of aquatic ecosystems (Richter et al. 1996; 1997), or in short—natural is better. It was developed in response to the increasing sophistication of habitat-based instream flow methods in the belief that it is unrealistic to expect each evaluation to acquire the comprehensive level of ecological information required for such methods. The use of natural flow patterns is therefore postulated as a surrogate for the potentially unattainable information.

The RVA evaluates 32 hydrologic parameters (Indicators of Hydrologic Alteration, or IHA) having five fundamental characteristics—magnitude, timing, frequency, duration, and rate of change—that are derived with a custom computer program from long-term (20-year) records of average daily discharge. The range and standard deviation of each parameter from pre-project and post-project records are compared to quantify the extent of alteration.

[5] 495 U.S. 490 (1990). Also known as the Rock Creek case.

Differences on the order of one or two standard deviations between the periods point to a probable ecological response.

As a practical matter, the RVA is useful for evaluating past changes in flow regime (where data are available) to identify more subtle impacts (large impacts should already be apparent) and to tailor hydrographs for restoration purposes. The RVA is less useful for anticipating or predicting impacts because it must use existing data; future daily hydrographs by nature must be synthetic and speculative. It also has no specific quantitative thresholds to establish flow objectives (e.g., is 1 standard deviation all right and 2 too many?) and does not discriminate among the relative importance of parameters (e.g., are some critical and others not?). The primary utility of the RVA, therefore, is as a diagnostic or monitoring tool (IFC 2000). Only a couple of California rivers have been evaluated with the RVA, with inconclusive results (Railsback 2000; Preszler 2002). Additional case studies using California hydrology are likely to shed light on the applicability of the RVA as a tool for hydroelectric licensing.

Expert Panel Assessment Method (EPAM). Instream flow recommendations based on the opinions of experts have been used informally for quite some time. Prior to the creation of more quantitative methods, water development project proponents may have asked fisheries biologists what a protective flow might be (and the answer was then either used or not). As an alternative where other methods have been found inappropriate for various reasons, expert opinion in a more structured context has been sought. In Australia, the Expert Panel Assessment Method has been documented twice (Swales and Harris 1995, Thoms et al. 1996) and identified for potential application to England and Wales (Dunbar et al. 1998). Qualitative Observation has been used in the United States for a number of hydroelectric relicensing cases (Railsback 2000, 2004), and the Incremental Flow Index has been applied once in Maine (Acres 1989) and once in California (Thomas R. Payne and Associates 2001). The IFC (2002) describes the method as Demonstration Flow Assessment and primarily useful for assessing recreation flow needs.

The EPAM uses a team of experts to observe physical conditions provided by target flow releases and these experts rank or rate the conditions by any number of subjective criteria. These criteria can include the estimated suitability of depth and velocity patterns for various fish species and life stages, association of flow with cover elements, visual esthetics, fishability, recreation, or any number of other factors that are determined prior to the site visit. (Interestingly, the criteria largely correspond to those used by Tennant.) Scales between 0 and 3 may be used for each factor, for example, to provide a measure of quantification, and these numbers can be combined or averaged for a composite ranking.

The EPAM has not been used frequently enough to establish a track record of typical criteria, scaling standards, or composite scoring to really qualify as a method, so it should more properly be termed an approach. As Railsback (2000, 2004) has pointed out, EPAM has several distinct advantages, chief of which is its open discussion of professional judgment in place of obfuscation behind elaborate but poorly validated ecological models. With some effort applied to improvement in discrimination of criteria, minimum qualifications for participants, and standardization of decision making processes, EPAM could prove quite useful under the right conditions, possibly in combination with more quantitative measures of habitat. Disadvantages include its limitation to existing channel conditions, the need for flow control at the time of site visits, and a spirit of cooperation among participants, among others.

Instream Flow Incremental Methodology (IFIM). Enough has been written about the Instream Flow Incremental Methodology over the last 25 years to fill a library (and in fact has). The IFIM was developed in the late 1970s as a way of approaching decision-making and project alternatives analysis under the National Environmental Policy Act (Stalnaker 1994, Trihey and Stalnaker 1985). When properly implemented, the IFIM involves several steps or phases, starting with problem identification and diagnosis, legal and institutional analysis, and study planning, followed by study implementation, alternatives analysis, and problem resolution through negotiation (Bovee et al. 1998). The developers of IFIM considered it to be primarily a process for solving water resource allocation problems that include concern for riverine habitat resources. Since the IFIM is a process, it cannot be easily categorized as a type of instream flow method.

Unfortunately, because the IFIM contains many computer models to help quantify the effects of flow alteration on aquatic habitat, the IFIM is often not distinguished from some of its components. Even though the IFIM contains a model for legal and institutional analysis (LIAM), a model for water temperature analysis (SNTEMP), and a model for network habitat analysis (Time Series), it also contains a series of models for hydraulic and habitat simulation that are collectively called PHABSIM. PHABSIM has proven to be immensely popular, mostly because it creates plots of relationships between streamflow and an abstract index to habitat suitability which is often mistakenly thought of as habitat area (Payne 2003). This index typically has a peak at relatively high flows, drops to a low value at high and low flows, and provides an impression of quantifying habitat that meets the requirements of regulatory processes.

The popularity of PHABSIM has subsumed the full IFIM to the point where most other aspects of IFIM are routinely bypassed—especially LIAM, alternatives formulation, times series analysis, and flow-index correlation with aquatic populations or biomass. When PHABSIM is applied out of the context of IFIM, it becomes a standard-setting method instead of an incremental method, loses much of its ecological credibility, and is susceptible to intense (and often accurate) criticism (Williams 1996; Kondolf et al. 2000; Railsback 2000). For most of the 1980s and early 1990s, the California Department of Fish and Game had an unwritten policy to make flow requirements on the basis of the highest point of the highest flow-index curve. The Federal Energy Regulatory Commission has modified this approach somewhat by often applying an 80%-of-peak rule. The National Marine Fisheries Service is even now considering the use of a varying percentage of the peak of the flow-index curve to define “take” under the Endangered Species Act (NMFS 2001). None of these approaches to flow recommendations have been validated by controlled studies, and none are described as acceptable procedures under of the IFIM.

Use of full IFIM is actually quite rare in commercial application, and the terms *PHABSIM* and *IFIM* are often used interchangeably. Surveys of IFIM usage do not discriminate between the two and report PHABSIM studies as if they were IFIM (Reiser et al. 1989; Tharme 2002). Sometimes this confusion is a matter of carelessness and sometimes it is deliberate; the instream flow study guidelines for the State of Washington, for example, promote the use of

“IFIM” yet actively discourage time series analysis, a principal component of IFIM (Beecher et al. 1996). For there to be significant progress in the validity of habitat simulation methods, either PHABSIM should be modified to stand alone as an ecological model (Railsback 2000) or the IFIM should be applied as it was intended by its originators (Bovee et al. 1998).

Individual Based Models (IBMs). Ecological models based on the predicted behavior of an organism in response to its environment, or Individual Based Models, have been under research and development for a number of years. To date, there has been only one documented commercial application, on the lower Tuolumne River in California (Jager et al. 1997; Railsback 2000) and a few research applications (Jager et al. 1993; Railsback and Harvey 2001). Individual Based Models incorporate computer simulation of an individual animal (bass or trout), computer simulation of physical habitat, computer replication of individuals, and simulation of interactions among animals and between the animals and their physical habitat. The goal of simulation is to mechanistically replicate the population-level response of animals to changes in their environment, and thereby predict the consequences of altered habitat or flow regimes.

Of necessity, IBMs are highly complex, because they attempt to incorporate as many ecological variables as possible which are believed to affect fish populations and not just the principal ones of depth, velocity, and substrate or cover. Current versions include habitat cells with these elements but also include: food availability (drifting and stationary), velocity shelters, hiding cover, and spawning gravel; fish behavior for spawning, movement, feeding, growth, and survival; and spawning nest characteristics of substrate type, overall size, and hydraulics (Railsback 2000). Individual Based Models represent the pinnacle of habitat simulation methods and are at the opposite end of the spectrum from such methods as the RVA. The philosophy behind IBMs is that adequate knowledge of ecological processes is attainable, while the philosophy behind the RVA is that it is not attainable.

Individual Based Models are viewed as difficult to understand and calibrate, experimental and therefore risky for applied situations, susceptible to misuse by non-experts, having potentially very high costs for data collection and model development, and lacking a track record of successful validation and use (Railsback 2000) However, given sufficient progress in addressing these deficiencies, IBMs are likely to find their place in the instream flow methods toolbox. Their broad foundation in accepted ecological theory may ultimately result in commercial applications that survive legal challenge.

Bioenergetics. Instream flow methods that incorporate bioenergetics are similar to IBMs, in that they attempt to mechanistically link physical conditions to the ability of fish to acquire food at the least energy cost (Addley 1993; Hughes and Dill 1990; Alfredsen 1999; Flore et al. 2001). Bioenergetic models are described as, by their very nature, requiring a considerable knowledge of bioenergetics and the behavior of target species/life stages (Parasiewicz and Dunbar 2001). Existing models, however, have been found to be sensitive to only a few parameters, which has apparently simplified the modeling procedure (Addley 1993).

Bioenergetics models for use in decision support systems are still in the prototype stage, but may lead to a better understanding of habitat requirements and overall life history strategies of fish (Parasiewicz and Dunbar 2001), and thereby improve related habitat methods and models. As with the IBMs, bioenergetics models also require intense and detailed information on competition, predation, and fish behavior aside from feeding and resting. Bioenergetics models are suggested as worth investigating in the search for tools to study flow alteration affects fish and fish habitat (Alfredsen 1999).

Polygon Habitat Mapping Method. Polygon Habitat Mapping is a habitat simulation method that merges habitat suitability criteria with detailed aerial photographs of selected stream reaches. Originally developed in Oregon, there are as yet no published descriptions of the approach. The Klamath Hydroelectric Project Study Plan for the Copco No. 2 bypass reach (PacifiCorp 2003) relates that the photographed surface area of a stream is visually divided into predominantly uniform habitat patches (polygons) that are rated with binary criteria for their physical suitability as fish habitat at different flows. The visual maps are calibrated as needed with observations or measurements of depth, velocity, substrate, cover elements, and fish density obtained through electrofishing. Once the maps are completed, the polygons are digitized and the total suitable area for each target species and life stage is tabulated and graphed, and the graph of all mapped flows illustrates the relationship between habitat area and discharge.

The method is closely related to one of the early variants of PHABSIM, which was applied to high-gradient, large-bed element streams believed unsuitable for hydraulic modeling. The Empirical Approach (Trihey and Baldrige 1985), also known as Direct Entry IFG4, used one-dimensional cells along cross sections (instead of two-dimensional polygons) to quantify habitat area in relation to discharge without the use of simulation models. Polygon Habitat Mapping has the advantage of visual confirmation of "suitable" habitat, but polygon data is less precise than cell-vertical data, and the method must use binary (suitable/unsuitable) criteria instead of sliding (suitable to unsuitable) criteria. Both variants produce point estimates of habitat versus discharge and cannot be either extrapolated or accurately interpolated between data points. Polygon Habitat Mapping has been applied to the Pit River and is proposed for use on the Klamath River in California.

MesoHABSIM. A recently published method, mesoHABSIM, is a larger-scale approach to defining stream fish-habitat relationships (Parasiewicz 2001). Instead of using microhabitat suitability, as do several other methods (e.g. PHABSIM, IBM, Bioenergetics), mesoHABSIM assigns suitability to whole mesohabitat units, calibrated with fish abundance data obtained by electrofishing. The approach is applied over entire stream segments instead of to the sub-samples required for microhabitat analysis (results of which must be extrapolated to the segment level). Thus, small-scale habitat use resolution is lost. This approach is comparable to that of Hankin and Reeves (1988) for fish population sampling, where it was concluded that better estimates of total population could be obtained through lower resolution (snorkel) sampling over a wider area than through higher resolution (electrofishing) sampling in a restricted area.

MesoHABSIM is being developed by the Department of Natural Resources at Cornell University, has been applied at least once (to the Quinebaug River in Massachusetts and Connecticut), and is proposed for a project on the Santee River in South Carolina.

These rivers are either large with warmwater fish assemblages or smaller with poor water visibility, either of which condition makes it difficult to collect microhabitat suitability data and confidently apply microhabitat models. Additional applications and experience with mesoHABSIM will ultimately determine its broader utility and acceptability.

Aquatic Habitat Evaluation Procedures. Habitat Evaluation Procedure (HEP) models were developed by the U.S. Fish and Wildlife Service in the late 1970s as a way of documenting the quality and quantity of available habitat for selected fish and wildlife species (USFWS 1980). The models consist of Habitat Suitability Indices (HSI) for any number of habitat variables believed to be significant determinants of habitat, all of which are combined and multiplied by the total available habitat area. Resulting weighted habitat areas are used to evaluate the relative value of different areas at the same time or the relative value of the same area at some future point in time. Mostly designed for federal environmental evaluation of federal projects, there have been at least 60 HSI models developed and published for various terrestrial and aquatic species.

Specific riverine and lacustrine (non-terrestrial) HSI application guidelines were described in 1982 (Terrell et al. 1982), and many examples of aquatic HEP can be found in the literature (Layher and Maughan 1985; Layher et al. 1987; Ross et al. 1993; Schmitt et al. 1993). Even though aquatic HEP is a very different approach to habitat evaluation from PHABSIM and contains many of the habitat variables identified as deficient in PHABSIM (Railsback 2000), it is only noted in passing in many of the instream flow method reviews. Use of aquatic HEP has tended to be dismissed fairly readily (Morhardt 1986), mostly because early models had a low correlation with biomass or fish population data and because a high degree of biological information is typically required. Nevertheless, one of the most recent uses of HEP in the Netherlands (Duel et al. 1996) concluded that further development of habitat evaluation methods is an urgent need in water management policy.

Adaptive Management. The concept of Adaptive Management (Holling 1978) is included in this review because it is often promoted in place of reliance on predictive habitat models, which have not yet been proven to be completely accurate or reliable. There are two views of Adaptive Management, one of which could be described as "do something and see what happens." The other view, more true to the concept, is to make very specific predictions of habitat or population change (usually based on modeling), implement a management scenario, carefully test and monitor results, revise and improve predictions, and continue to test and monitor results. The former viewpoint is more common than the latter, because the latter requires more thought, resources, and the courage of one's convictions.

There are at least two ongoing Adaptive Management programs that follow the Holling (1978) model—one on the Colorado River for Glen Canyon Dam (Glen Canyon Adaptive Management Program, USBR 1997) and in California, one on the Trinity River for Trinity and Lewiston dams (Trinity River Adaptive Environmental Assessment and Management Program, USFWS 1999). Adaptive Management programs often last for many years without conclusive results, due to the lag time in definitive biological or habitat responses and because large changes in existing operations are very difficult to implement. After considerable preparation, high flows were released from Glen Canyon Dam into the Grand Canyon segment of the Colorado River and the effect of the water on sediment transport, sand bar formation, backwater creation, fish reproduction, and other functions were directly evaluated. Implementation of recommendations for riparian vegetation and channel maintenance through flow releases in the Trinity River has been delayed by litigation.

Collaborative Approach. The Collaborative Approach is a term applied recently in California (PG&E 2000) to describe the process of defining a hydrograph for a hydroelectric project relicense through negotiations among stakeholders. Many different scientific disciplines and studies are considered in defining the hydrograph to address as many significant ecological or sociological aspects of a project as are known. During some periods, flows can be recommended on the basis of microhabitat or sediment transport studies, and during others by consideration of historic hydrologic patterns, expert opinion, or by balancing varied objectives. For example, the IHA was applied in a collaborative approach to relicensing for the Mokelumne River Hydroelectric Project to develop desired flows from impaired and regulated stream flow data (PG&E 2000). International equivalents of the Collaborative Approach are categorized as *combined* or *holistic* methods, including BBM, DRIFT, FLOWRESM, and IFIM (as it was designed, not as it is used as standard setting).

Methods such as the Collaborative Approach are likely to become more common. This is partially due to the promotion by the Federal Energy Regulatory Commission (FERC) of alternative licensing procedures that emphasize the early and frequent participation of stakeholders, instead of traditional licensing that typically limits participation to principal agency representatives of stakeholders only. This alternative licensing seeks to minimize conflict at the end of the licensing project, avoid the need for FERC to impose resolutions on the parties, and address the increasing awareness of (and consideration for) a broader range of resource issues. Instead of just looking at trout fisheries and boating recreation, there are now stakeholders for riparian vegetation, channel maintenance, whitewater rafting, amphibians, “ecosystem integrity,” and “properly functioning condition” at the table, some of which have been highlighted by the Endangered Species Act.

Integrated Fish Population Models. Weaknesses in all of the preceding approaches are widely acknowledged, because they typically fail to explicitly address many of the more subtle factors that can govern the response of fish populations to habitat or biotic variables. Several research efforts have been implemented with increasing levels of sophistication in attempts to more precisely model and predict observed or expected responses. Individual Based Models such as those discussed by Jager et al. (1993) and Railsback and Harvey (2001) are examples, as are the more elaborate models of the Fort Collins Instream Flow Group (Stream Network Analysis - Bartholow and Waddle 1986; SALMOD - Williamson et al. 1993, Bartholow et al. 1993, and Bartholow et al. 2001; and SIAM - Bartholow et al. 2002), a model created by EA Engineering, Science, and Technology (Cheslak and Jacobsen 1990), and the Oak Ridge Chinook Model (Jager et al. 1997; Jager and Rose 2003).

Data requirements for these models are extremely high, and assumptions must be made for factors thought to be important for which little or no data is available. Examples (taken from Jager et al. 1997) include: the movement rate at zero flow for fry, coefficients and exponents in territory size versus fish length relationships, minimum flow needed to upmigrate and spawn, average size of predators in river, baseline daily mortality risk in the redd, fraction of maximum food intake obtained by smolts, and lower flow threshold for behavioral predator avoidance. Each of these parameters (and at least 50 more) is estimated and revised through "calibration" to reproduce observed fish population data, and conclusions are made concerning the most important variables. The intensity of data input requirements, the variability of parameters between rivers, population structures and flow regimes, and the likelihood of multiple solutions from the same data combine to produce a broad skepticism and lack of acceptability in the regulatory arena, and consequently, very limited application.

3.5 The PIER Focus

Existing approaches to determining flow and habitat needs for aquatic resources affected by hydropower operation need to be improved to minimize adverse effects on California's aquatic resources while minimizing the unnecessary curtailment of hydropower generation.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. The issue of hydropower's impact on instream flows and aquatic biota and habitats is one such issue. PIER-EA intends to address this topic through its own targeted research and to attract collaborators that will share data and work with PIER-EA to develop improved instream flow assessment methodologies. PIER-EA is also developing roadmaps to address fish passage and water quality effects on aquatic species research needs. Whenever possible, PIER-EA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Research Needs

4.1 Historical Research Needs

Each of the methods described in Section 3 has its respective strengths and weaknesses; requires more or less technical training and detailed biological, hydrological, or geomorphologic knowledge for appropriate application; and has varying levels of acceptability or "buy-in" from project proponents, resource agencies, and other stakeholders. The wide variety of legal requirements, participants, and projects that utilize stream flow virtually guarantees that no one single method will be best for all situations.

The most likely future scenario is that some methods will be used for planning or initial project evaluation (Tennant, RVA), some will offer study structure and assessment guidance (IFIM, Collaborative Approach, Adaptive Management), some will function as useful tools

(Aquatic HEP, PHABSIM, MesoHABSIM, EPAM, Polygon Mapping), some will continue to expand scientific knowledge (Individual Based Models, Bioenergetics, Integrated Fish Population Models), and some will be used in combination.

To help ensure that these tools and methods meet the ecological, operational, and regulatory needs, additional research is necessary. This section identifies historical research needs and recommends current research needs. A large number ofHistorical research needs are grouped following Morhardt (1986).

4.1.1 Identification and characterization of affected species

- A list of important fish species as target organisms by U.S. drainage area and by geohydrologic zone. (Stalnaker and Arnette 1976)
- A list of important aquatic invertebrate species as target organisms, as above. (Stalnaker and Arnette 1976)

4.1.2 Characterization of affected species

- Develop more fish life history information. (Reiser et al. 1989)

4.1.3 Characterization of the optimal habitat for affected species

- Depth, velocity, substrate, cover, and migration needs of trout in winter. (Wesche and Rechard 1980)
- Flow needs for egg incubation including intragravel flow rates, water exchange rates, temperatures, and dissolved oxygen. (Wesche and Rechard 1980)
- Habitat criteria for depth, velocity, substrate, and cover for non-salmonid species. (Wesche and Rechard 1980)
- Develop species habitat information and preference curves threatened and endangered, warmwater, and regional fish species. (Reiser et al. 1989)
- Assess the adequacy of existing flows for the maintenance of fishery resources. (Reiser et al. 1989)
- Improve understanding of the primary factors that determine the biological, physical, and chemical characteristics of riverine ecosystems (Instream Flow Council 2002)
- Address the interrelation of geomorphology, water quality, connectivity, and streamflow level on individual (fish or insect population) ecosystem components (Instream Flow Council 2002)
- Determine flow/habitat needs of unionid mussels (including host fishes) (Payne questionnaire)
- Research the interactions between flow regime and other factors affecting stream systems (e.g., watershed change) (Payne questionnaire)

4.1.4 Characterization of rivers, streams, and other water bodies

- Refinement of large river channel mapping and velocity measurement techniques. (Stalnaker and Arnette 1976)

- Hydraulic aspects of overwinter conditions in extreme climatic conditions. (Stalnaker and Arnette 1976)
- Understanding the subtle and cumulative changes in sediment and organic particulate movement in rivers. (Stalnaker and Arnette 1976)
- Understanding nutrient cycling and transport in rivers in relation to flow changes. (Stalnaker and Arnette 1976)
- Quantitative data on removal of fines and stream channel maintenance for flushing flows. (Wesche and Rechard 1980)
- Develop more hydrologic and water resource data. (Reiser et al. 1989)
- Determine flushing flow requirements for streams. (Reiser et al. 1989)
- Better understand the relation between streamflow and ice forming processes (Instream Flow Council 2002)

4.1.5 Better understanding the relationship between in-stream flows and habitat and species health

- Effects of extreme fluctuations and short-term fluctuations in stream flow on fish. (Stalnaker and Arnette 1976)
- Spatial dependencies of target fish species in relation to velocity preferences. (Stalnaker and Arnette 1976)
- Studies of insect and fish production in relation to flow to quantify the incremental effects of flow on carrying capacity. (Stalnaker and Arnette 1976)
- Stream carrying capacity or the relationship between habitat variables and fish populations. (Wesche and Rechard 1980)
- Determine if a relationship exists between flow, habitat, and fish production. (Reiser et al. 1989)
- Study what aspects of flow regime are most strongly related to mechanistic processes that affect species, populations, and assemblages (Payne questionnaire)
- Link processes across ecological space and time scales to better understand structure and function of system components (Payne questionnaire)
- Find better, more reliable linkages between flow, habitat, and species, populations, and assemblages (i.e., improved metrics that have reasonable predictive power as to biological response to altered flow) (Payne questionnaire)
- Provide insight into underlying mechanisms and important temporal and spatial scales and processes within and among hydrology, biology, geomorphology, water quality, and connectivity (Instream Flow Council 2002)
- Document the ecological effects of existing flow alterations (Morhardt 1986)
- Experimentally manipulate and monitor existing flow alterations. (Morhardt 1986)
- Evaluate the effects of physical habitat alteration on fish populations and food production. (Morhardt 1986)
- Improve understanding of the primary factors that determine the biological, physical, and chemical characteristics of riverine ecosystems (Instream Flow Council 2002)

4.1.6 Improve, refine, and evaluate existing methods

- Research and incorporate the effect of amount and timing of habitat availability into flow recommendations [i.e. time series, not peak-of-curve]. (Morhardt 1986)
- Examine the amount and causes of site-specific variability in habitat suitability indices. (Morhardt 1986)
- Research methods for incorporating habitat availability into habitat suitability indices. (Morhardt 1986)
- Research bivariate and multivariate habitat suitability indices.
- Examine site-specific variation between PHABSIM weighted usable area and fish populations. (Morhardt 1986)
- Improve techniques for habitat modeling in habitat types with complex hydraulics. (Morhardt 1986)
- Characterize the geographic variability of flow recommendations using standard hydrologic methods [e.g. Tennant 1976] (Morhardt 1986)
- Modify and adapt [PHABSIM] to high gradient streams or large, deep rivers. (Reiser et al. 1989)
- Improve components of the IFIM to provide a smoothly working set of analytical tools for fish population analysis. (Stalnaker 1994)
- Leclerc et al. (1995) suggested improving the accuracy and resolution in predicting the effects of altering physical habitat variables through the use of two-dimensional hydraulic models. (Leclerc et al. 1995)
- (Bird 1996) described several “problems” with PHABSIM and recommended that Combine field-based habitat selection studies should be confined to critical periods and sensitive life stages under specific guidelines:
  - A diverse sample of pristine sites at approximate carrying capacity should be selected by expert judgment and habitat evaluation methods such as HABSCORE. (Bird 1996)
  - Microhabitat criteria should be stratified into mesohabitats (e.g. riffles, pools, glides) to account for scale effects in habitat selection. (Bird 1996)
  - The full range of flow conditions within critical periods should be sampled to account for behavioral switches. (Bird 1996)
  - Microhabitat gradients at fish locations should be quantified, particularly water velocity shear zones. (Bird 1996)
  - Improving the use of cover as a habitat variable is a challenging objective that should be considered in separate R&D investigations. (Bird 1996)
  - The relative importance and interaction of habitat variables should be assessed by multivariate statistical analysis. (Bird 1996)
  - Statistically pure sampling designs should be used with sample sizes large enough for criteria to meet precision requirements. (Bird 1996)
  - Literature based habitat selection criteria will be adequate for non-critical periods and less sensitive life stages provided they are carefully screened for transferability. (Bird 1996)
  - The selection of reaches for PHABSIM should involve habitat mapping and be appropriate to the investigation. (Bird 1996)

    - Temporal habitat variation should be analyzed to identify habitat bottlenecks and these should be validated by fish abundance data if possible. (Bird 1996)
    - Sensitivity analysis should be used to compare the different types of habitat criteria and the effects of various flow setting scenarios. (Bird 1996)
- Williams (1996) suggested that PHABSIM results would be improved if confidence intervals around weighted usable area vs. flow relationships are developed by bootstrap analysis.
- Robert Milhous, one of the developers of PHABSIM, has conducted research on habitat modeling methods since 1978. In a recent paper, Milhous (1999) made three specific recommendations for improvement of PHABSIM:
    - Consider time series analysis of habitats that may limit the populations of aquatic animals, such as high winter flows or drought survival flows (Milhous 1999)
    - Improve the use of substrate information in the simulation of physical habitat, such as including substrate porosity as velocity shelter (Milhous 1999)
    - Develop habitat suitability criteria for metal or other stream contaminants (Milhous 1999)
- Railsback (1999) made four recommendations to reduce uncertainty in PHABSIM studies and suggested two research objectives as PHABSIM improvements:
    - Make accurate representation of habitat the highest priority in hydraulic data collection and modeling (Railsback 1999)
    - Model enough habitat to represent the study reach. (Railsback 1999)
    - Use appropriate precision in measurements and analysis. (Railsback 1999)
    - Use the same spatial resolution for hydraulic simulation, habitat criteria development, and habitat criteria testing. (Railsback 1999)
    - Research the most appropriate spatial scale for PHABSIM analyses to minimize the errors from mismatched scales. (Railsback 1999)
    - Research methods for determining the number of transects needed and the ways they should be placed to represent a stream reach with adequate accuracy and minimum cost. (Railsback 1999)
- Estimate the best spatial resolution for modeling habitat use by a variety of fish (Railsback 2000)
- Improve habitat representation sampling methods for completeness and accuracy, possibly with multiple phase sampling. (Railsback 2000)
- Improve methods and tools for input data collection, model building and calibration, and output analysis for finite element hydraulic models and habitat scaling. (Railsback 2000)
- Research individual-based models for mechanistic effects of food availability, feeding rate, energetic costs and growth, mortality risks, and spawning success and egg incubation for a wide range of important fish species or guilds (Railsback 2000)
- Design, test, and evaluate a credible, useful instream flow method for assessing the instream flow needs of diverse aquatic communities (Railsback 2000)
- Rebuild the approach to PHABSIM, issue a set of standard practices, and implement a validation program (Railsback 2000)

- Develop a protocol for Expert Panel Assessment methods to produce results with adequate reliability and credibility (Railsback 2000)
- Test, improve, and validate the ability of existing trout individual-based models to predict population level responses to changes in flow (Railsback 2000)
- Apply the modeling concepts developed for trout to other groups of fish and establish a toolbox of approaches and software (Railsback 2000)
- Develop additional user tools to facilitate the use of individual-based models. (Railsback 2000)
- Evaluate the efficacy of management strategies (i.e., more pre- and post-change monitoring w/ enough spatial and temporal extent to get an idea of what's going on at the system level) (Payne questionnaire)
- Determine success and limitations of adaptive management practices (Payne questionnaire)

4.1.7 Test the validity of existing models

- Establish criteria for regional testing and validation of instream flow models. (Morhardt 1986)
- Test the assumption in PHABSIM that large amounts of low-suitability habitat area are equivalent to small amounts of high-suitability habitat area. (Morhardt 1986)
- Test the assumption in PHABSIM that equivalent weighted usable area values occurring at two different flow levels are biologically equivalent. (Morhardt 1986)
- Validate the predictions by instream flow models for biological response in regulated streams using experimental control protocols. (Morhardt 1986)
- Validate the predictions by instream flow models for biological response in regulated streams using habitat variability over time. (Morhardt 1986)
- Devise and evaluate techniques for integrating limiting factors into instream flow methods. (Morhardt 1986)
- Validate if PHABSIM weighted usable area relates to fish production. (Reiser et al. 1989)
- Validate and test existing Habitat Suitability Index HEP models on local conditions. (Reiser et al. 1989)
- Validate existing water quality models. (Reiser et al. 1989)
- Validate existing hydraulic models. (Reiser et al. 1989)
- Test habitat bottleneck [population limiting factor] hypotheses. (Stalnaker 1994)
- Test strategies for long-term fish population support. (Stalnaker 1994)
- Evaluate the effects of physical habitat alteration on instream flow models. (Morhardt 1986)

4.1.8 Develop new instream flow methodologies

- Make maximum use of modeling techniques used in other branches of ecology. (Morhardt 1986)
- Develop new regional regression models between flow and habitat response variables. (Morhardt 1986)
- Research non-flow related fish population limiting factors and use in mechanistic models. (Morhardt 1986)

- Develop new instream flow methods for assessing high gradient streams, peaking impacts, channel maintenance, short-term flow fluctuations, sport fishing and recreation, egg incubation, overwintering, and planning purposes. (Reiser et al. 1989)
- Develop new water quality models. (Reiser et al. 1989)
- Develop new hydraulic models. (Reiser et al. 1989)
- Develop and validate a dynamic fishery population model that includes flow-related limiting events such as physical habitat and water temperature. (Stalnaker 1994)
- Develop processes for evaluating water management strategies to achieve fish population objectives. (Stalnaker 1994)
- Determine the limits of predictability for various methods (Payne questionnaire)

5. Goals

The goal of the *PIER Research on Instream Flow Determinations for Hydropower Applications* roadmap is to improve our ability to assess appropriate instream flows to sustain healthy freshwater ecosystems while minimizing the unnecessary curtailment of hydropower generation. The achievement of that goal will depend on the improvement of methods, tools, and data that California can use to make informed decisions about the environmentally responsible use of its hydropower facilities.

Implementation of this research program will benefit California through healthier aquatic ecosystems and more robust fishing and tourism industries, and will reduce unnecessary curtailment of hydropower production.

The goals and objectives identified herein are based on the information summary and synthesis developed in previous sections, from discussions with agency and utility staff, and questionnaire responses.

The PIER-EA program recognizes that some work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIER-EA will identify existing efforts and form partnerships to leverage resources.

As discussed in Section 4, future research should be designed to promote the better understanding and improvement of existing tools, since, according to Railsback (2000), Williams (1997), and others, there is pressing need. Totally new tools are not on the horizon, but even if developed, would take many years of case studies and training to become useful in common practice. Merging past research ideas and the current reality of instream flow methods with the intention of improving existing tools results in the following recommendations.

5.1 Short-term Objectives[6]

5.1.1 Document the Ecological Effects of Existing Flow Alterations

A. *Design a protocol to study the effects of existing flow alteration.* The first priority of future research should be to design a protocol for a broadly based study of the effects of existing flow alterations that will specifically address resource protection objectives, while remaining cost-effective and useful for improving understanding of ecological processes. Once the protocol is designed, it should be implemented as soon as possible to increase understanding of ecological responses to existing flow alterations and contribute to improved instream flow assessments and recommendations. ($25,000)

Activities needed: (1) Design a protocol for a broadly based study of the effects of existing flow alterations that will specifically address resource protection objectives, while remaining cost-effective and useful for improving understanding of ecological processes. (2) Implement the protocol.

5.1.2 Standardize the Application of PHABSIM under the IFIM

Even though PHABSIM and the IFIM have been in use for nearly twenty-five years, there are no published standards for what constitutes a high-quality application. Development of a protocol should address the following:

A. *Establish Quality Control Standards for PHABSIM.* One reason that PHABSIM should always be used in the context of IFIM is that there are numerous pathways to achieve results and group consensus should always be sought to minimize conflict. Some of these pathways can be shortened if reasonable and appropriate quality control standards for PHABSIM are established. Standards are needed for sampling strategies, such as reach stratification, study site selection, transect number and placement, and amount and type of hydraulic calibration data. These standards can be derived through meta-analysis of existing data. Habitat suitability criteria are universally recognized as more important to results than hydraulic accuracy, and standard methods for the creation, selection, and testing of criteria for many species and life stages should be developed. More standard methods for results interpretation, such as time series analysis, should be explored, refined, and required as part of the IFIM. ($10,000)

Activities needed: (1) Through a meta-analysis of existing data, develop and establish quality control standards for PHABSIM, focusing on reach stratification, study site selection, transect number and placement, and amount and type of hydraulic calibration data. (2) Develop standard methods for the creation, selection, and testing of habitat suitability criteria for many species and life stages.

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[6] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

(3) Evaluate and refine standard methods for results interpretation, such as time series analysis, and incorporate them as part of the IFIM.

B. *Establish Standards for Use of 1-D and 2-D models.* The use of two-dimensional modeling has recently been advanced as preferable to standard one-dimensional modeling on the assumption that more accurate cell velocity data and analysis of more highly complex habitat types will improve results. This assumption should be tested through comparison of 2-D habitat index results with both 1-D habitat index results and fish population metrics such as biomass. The known correlation between 1-D habitat indices and biomass that forms the basis of PHABSIM in the first place should be replicated with 2-D indices before the additional expense required for 2-D modeling can be justified. Guidelines for use of the two approaches should also be developed, including gradient limits, influence of degree of habitat complexity, field data collection constraints, and differences in sampling strategies. The guidelines should incorporate examples where the methods may be combined within the same study. Hybrid methods should also be investigated based on respective strengths and weaknesses; for example, 2-D could be used to model flow splits on islands or side channels and 1-D used to represent resulting physical conditions below the split. ($10,000)

Activities needed: (1) Compare 2-D habitat index results with both 1-D habitat index results and fish population metrics. (2) Replicate the known correlation between 1-D habitat indices and biomass that forms the basis of PHABSIM with 2-D indices, to ensure the need for 2-D modeling. (3) Develop guidelines for use of the two approaches, including gradient limits, influence of degree of habitat complexity, field data collection constraints, and differences in sampling strategies. Incorporate examples where the methods may be combined within the same study. (4) Determine the strengths and weaknesses of hybrid methods, to identify their optimal applications.

5.1.3 Refine and Standardize Alternative Instream Flow Methods

There are many circumstances where PHABSIM or even the broader IFIM process may not be the best approach to determining instream flow needs. For such cases, several other existing methods should be refined and standardized, and the conditions for their appropriate application specified.

A. *Establish a California Tennant* Method. For cases where simple threshold flow recommendations or general planning targets are the objective of a flow prescription, the Tennant Method should be customized to California hydrology and species mixes. As Don Tennant has recommended for years, the steps he took to arrive at his method should be replicated at many sites, and customized, region-specific, seasonal percentages of mean annual flow recommendations developed

Activities needed: (1) Customize the Tennant Method to California's hydrology and species mixes.

B. *Establish IHA Parameters and Thresholds.* The Range of Variability Approach using Indicators of Hydrologic Alteration is a potentially valuable tool for identifying potentially subtle hydrologic effects on aquatic habitat, for tailoring controlled annual hydrographs, and, in some cases, for making specific flow recommendations. There are two elements of the method lacking specificity which should be addressed prior to broad application in California. First, the physical, chemical, and biological importance of each of the 32 current IHA parameters should be described for local conditions so that less important parameters may be given reduced emphasis and critically important ones retained. For example, one of the parameters is the 1-day maximum flow, which can be very important to a stream, yet not be fully provided for reasons of flood-control. Second, the acceptable degree of alteration should be established to provide some limit on the extent of hydrologic change. In the IHA literature, ± 1 Standard Deviation about the mean is suggested as a default RVA target. The focus of the concept is natural variability, however, not a simple inflexible statistic, and the actual target for particular situations and parameters is left to "flexible application". ($10,000)

Activities needed: (1) Describe the physical, chemical, and biological importance of each of the 32 current IHA parameters for local conditions. (2) Establish the acceptable degree of alteration, to provide a limit on the extent of hydrologic change.

C. *Techniques for Expert Panel Assessment Method.* There are times when there is no substitute for having a group of expert aquatic habitat specialists actually observing and ranking various levels of streamflow to accomplish certain objectives. Often the judgment of experts is more reliable than the most sophisticated model. The protocol for EPAM should be more extensively researched and techniques and standards should be established, including which disciplines should participate, what the minimum expert qualifications should be, how expert bias can be minimized, how many flows over what range should be evaluated, what factors or criteria should be considered, how a ranking system should be devised, how consensus, resolution, or recommendations should be concluded, and how results can be documented, defended, and validated. The paper recently written by Railsback (2003) has substantially implemented this recommendation. ($5,000)

Activities needed: (1) More extensively research the protocol for EPAM, and establish techniques and standards for it. Research should focus on which disciplines should participate, what the minimum expert qualifications should be, how expert bias can be minimized, how many flows over what range should be evaluated, what factors or criteria should be considered, how a ranking system should be devised, how consensus, resolution, or recommendations should be concluded, and how results can be documented, defended, and validated.

Table 2. Short-term Budget

Objective	**Projected Cost ($000)**
5.1.1.A Document the Ecological Effects of Existing Flow Alterations	25
5.1.2. Standardize the Application of PHABSIM under the IFIM	
5.1.2.A Establish Quality Control Standards for PHABSIM	10
5.1.2.B Establish Standards for Use of 1-D and 2-D models	10
5.1.3. Refine and Standardize Alternative Instream Flow Methods	
5.1.3.A Establish California Tennant Method	10
5.1.3.B Establish IHA Parameters and Thresholds	10
5.1.3.C Techniques for Expert Panel Assessment Method	5
Total	**70**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure.

5.2 Mid-term Objectives

5.2.1 Research and Standardize Alternative Instream Flow Methods

A. *Detailed Population Modeling.* While they may never evolve into practical tools that are widely acceptable and useful for commercial application, highly sophisticated ecological models such as individual-based and smolt outmigration models may be able to focus management interest on significant (and poorly understood) aspects of population regulation. This focus in turn could have ripple effects on simpler models by making their design and interpretation more ecologically meaningful. Research into detailed population models should continue in an effort to more completely understand biological processes in relation to hydrology and physical habitat. ($100,000)

Activities needed: (1) Continue research into detailed population models, to more completely understand biological processes' relation to hydrology and physical habitat.

B. *Habitat Index Rulemaking.* A common practice in flow recommendation using PHABSIM (out of IFIM context) has been to select either the peak of the habitat index curve for the species or life stage able to utilize the highest depths and velocities, to select a percentage of this peak (typically 80%), or to average or otherwise "optimize" multiple curves and apply similar rules. Due to the many ways habitat indices may be generated (with varying results), PHABSIM habitat indices only have internal comparative value and are unlikely to possess intrinsic "truth" suitable for such treatment. In some cases, however, especially for threshold setting required under water rights legislation, habitat index rulemaking may have value. Research into habitat index rulemaking should include steps for standardization of methods (e.g. study design, species selection, habitat suitability criteria, stream-type stratification), biologically defensible justification of proposed rules (including methods for reconciling or combining conflicting results from different species and life stages), and a public process to establish legitimacy. ($50,000)

Activities needed: (1) Research habitat index rulemaking, with a focus on steps for standardization of methods (e.g. study design, species selection, habitat suitability criteria, stream-type stratification), biologically defensible justification of proposed rules (including methods for reconciling or combining conflicting results from different species and life stages), and a public process to establish legitimacy.

C. *Flow Frequency Rulemaking.* There have been several attempts to use hydrologic data for flow recommendation rulemaking, some using percentages of mean annual flow or mean monthly flow, some using typical summer low flows, and some using percentages of monthly or daily flow exceedance probabilities. Few of these methods have been explicitly used in California, but a similar approach customized to California species and hydrology may be useful for preliminary instream flow needs assessments or as a screening tool. A method for flow frequency rulemaking should be developed, including types of data required (species life history information, flow records), method of data compilation (monthly averages, monthly flow exceedance, seasonal flow exceedance), and levels of threshold setting, possibly varying by water year classification. ($50,000)

Activities needed: (1) Develop a method for flow frequency rulemaking that includes types of data required (e.g., species life history information, flow records), method of data compilation (e.g., monthly averages, monthly flow exceedance, seasonal flow exceedance), and levels of threshold setting—possibly varying by water year classification.

D. *Habitat Evaluation Procedures.* The Habitat Evaluation Procedures in an aquatic setting can be valuable for identifying habitat limiting factors (such as pool/riffle ratios, summer water quality, instream cover, or turbidity), for assigning benefits to migration barrier removal, for designing habitat restoration projects, and for quantifying mitigation. Existing HEP models should be adapted to California aquatic species and stream types by reviewing model parameters and consolidation formulas, adapting and improving them where necessary, and validating model results. ($100,000)

Activities needed: (1) Adapt existing HEP models to California aquatic species and stream types by reviewing model parameters and consolidation formulas, adapting and improving them where necessary, and validating model results.

5.2.2 Promote Methods Training and Information Exchange

A. *Information Dissemination.* In addition to the creation of new methods or refinements of existing methods resulting from the proposed research, there should be an effort to disseminate the knowledge and experience gained from this work. The following actions would expand the information exchange:

- Develop guidelines to promote consistency in study design, implementation, and proper use of models and approaches
- Sponsor workshops and publish research results to facilitate the exchange of ideas and the rapid assimilation of improvements

($50,000)

Activities needed: (1) Develop guidelines to promote consistency in study design, implementation, and proper use of models and approaches. (2) Sponsor workshops and publish research results to facilitate the exchange of ideas and the rapid assimilation of improvements.

5.2.3 Research Non-Fishery Ecological Effects of Flow Alterations

A. *Field Studies.* Much of the existing research on ecological effects of flow alterations incorporated into instream flow methods has focused on fish. Less is known about other resources of concern to regulatory agencies and stakeholders, particularly riparian vegetation (mountain streams), amphibians (threatened species), and macroinvertebrates (food source/aquatic health indicators). More knowledge about these resource areas would allow tools to be developed and standardized and contribute to improved flow recommendations. Research could be conducted either in association with evaluation and monitoring of existing projects or on experimental streams or laboratories such as the University of California Sagehen Creek and SNARL programs. ($100,000+ per topic)

Activities needed: (1) Conduct research on the ecological effects of flow alterations on non-fish resources of concern to regulatory agencies and stakeholders; particularly riparian vegetation (mountain streams), amphibians (threatened species), and macroinvertebrates (food source/aquatic health indicators).

5.3 Long-term Objectives

5.3.1 Standardize the Application of PHABSIM under the IFIM

A. *Validate Resulting Flow Recommendations.* Whenever flow recommendations are made and implemented based on PHABSIM and IFIM, they should be monitored and results added to the ecological effects database recommended above. Retrospective evaluations of past instream flow determinations are needed to gauge the accuracy of methods, specifically identify shortcomings, and develop ways to improve assessments and recommendations. (Cost would vary by project and objective)

Activities needed: (1) Whenever flow recommendations are made and implemented based on PHABSIM and IFIM, monitor the results and add them to the ecological effects database developed in the short-term work. (Cost would vary by project and objective.)

6. Barriers to Research

Although many of these recommendations are likely to be supported by developers, regulators, and stakeholders, some are likely to encounter obstacles. Evaluating the impact of existing projects or monitoring new flow recommendations may be subject to barriers such as:

- *Lack of Funding.* Depending on the level of data resolution, the costs of case studies can be quite high. The amount of information required to understand broader trends, however, will be less if more effort is directed at a larger number of case studies, rather than at a few highly detailed studies.
- *Lack of Incentive.* There have been few studies of existing flow alterations, because neither the resource interest groups nor the project owners have been interested in knowing actual impacts. The main expressed reason for lack of interest by the resource groups is overwork (too many time demands), and the unexpressed reason is fear of having approved negative consequences. Project owners, after struggling through the permitting process, are not interested in spending any more money and are also fearful of data on negative consequences.
- *Lack of Comparative Controls.* Water development projects are often located in relatively unique areas that do not lend themselves to comparison with unaltered control sites. There are also few areas in California which can be considered even relatively unaltered. This objection should also be able to be addressed through a larger number of case studies.
- *Lack of Impact Resolution.* Natural variation in aquatic populations is typically quite high, so impact studies often must either run for many years, have a large number of study sites, or have rigorous control sites in order to define population levels with a higher degree of confidence. Again, a large amount of data for the determination of broader trends can often substitute for a need for high resolution.
- *Habitat is Already Degraded.* Resource interest groups often express a lack of interest in directing study effort towards “degraded” habitat, instead preferring to focus on “natural” or “pristine” habitat. This distinction raises the question of the difference between what might be considered either degraded or pristine, and what mechanisms might create the difference.

Many of these research recommendations can be implemented with less difficulty; however, results may not be widely accepted unless care is exercised to minimize potential sources of bias (that might tend to favor some interests over others), and to encourage peer review and participation in all phases of the work. Acceptability of this research will be greatly enhanced with broader buy-in, and greater progress toward developing and implementing instream flow recommendations can be achieved.

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