DEMONSTRATION FLOW ASSESSMENT: PROCEDURES FOR DIRECT OBSERVATION INSTREAM FLOW STUDIES

Short title: DEMONSTRATION FLOW ASSESSMENT PROCEDURES

STEVEN F. RAILSBACK[a*], JOHN KADVANY[b] and WILLIAM J. TRUSH[c]

[a] *Lang Railsback and Associates, Arcata, California 95521, USA*

[b] *Policy and Decision Science, Menlo Park, California 94025, USA*

[c] *McBain and Trush, Inc., Arcata, California 95521, USA*

ABSTRACT

The Demonstration Flow Assessment (DFA) method for instream flow evaluation uses direct observation of river habitat conditions at several flows and expert judgement to rank the alternative flows. The DFA method has the advantage of allowing long river reaches to be assessed at relatively modest cost. However, past applications have often lacked procedures and documentation to assure that results are reproducible and reasonably free of uncertainty and bias. This paper provides procedures to make DFA instream flow studies more credible and defensible while keeping study costs low. The procedures combine established concepts from stream ecology and decision analysis, and are general and adaptable to a variety of sites. Approaches are recommended for studies targeting both a few particular species or the general integrity of the aquatic community, and could be adapted for assessment of flow needs for other resources such as recreation and aesthetics. The procedures use “habitat quantification”: specific types of important habitat are defined and then quantified in the field during demonstration flows. The five major steps are: (1) *Decision framing*, establishing the fundamental assumptions, constraints, and expectations for the instream flow assessment; (2) *Conceptual modeling*, developing high-level mechanistic, empirical, or theoretical/community models for how flow affects fish by affecting food production, feeding, mortality risks, or reproduction; (3) *Metric development*, defining specific, measurable habitat types to be quantified; (4) *Field observations*, quantifying the area of each habitat type at each demonstration flow, using visual estimation aided by detailed maps and other tools; and (5) *Analysis*, calculating the total area of each habitat type for each demonstration flows, then ranking flows according to habitat benefits and resource tradeoffs. A study that used procedures similar to these recommendations to evaluate instream flows for salmon spawning and rearing is presented as an example.

KEY WORDS: demonstration flow assessment; direct observation; expert mapping; habitat; instream flow methods; judgment

*Correspondence to: S. Railsback, Lang Railsback & Assoc., 250 California Avenue, Arcata CA 95521, USA. E-mail: LRA@northcoast.com

flows for salmon—then illustrates many of the issues and procedures we discuss. In our conclusions we briefly compare our DFA procedures to widely used model-based procedures.

DEMONSTRATION FLOW ASSESSMENT PROCEDURES: BASIS AND OVERVIEW

Instream flow assessment can be thought of as a series of decision-making tasks. These tasks can be made with more or less effort, and with goals for greater or less accuracy. Constraints of personnel, time, and other resource require such "effort versus accuracy" tradeoffs (Payne et al. 1993): Do we explicitly assess flow effects on a variety of species or only on a few most important ones? How precisely do we measure habitat variables? The goal is to find a balance between decision-making rigor and scientific validity on one hand, and limited resources for field observations and deliberation on the other hand. Such balancing is sometimes called "prescriptive" (Bell et al. 1988) when formal decision-making approaches are adapted to the limitations of judgment-based choice. Our DFA procedures take this prescriptive approach to habitat assessment tasks.

The DFA procedures are therefore based on two conceptual frameworks. First is a general framework for *judgment-based decision analysis*. Major elements of this framework include (1) Decision framing: clarifying and focusing the assessment by identifying its goals and boundaries, (2) Conceptual modeling: identifying the key processes and mechanisms by which the management variable affects the resources being managed for, (3) Defining metrics—measurable indicators that are based on the conceptual models, (4) Observing how the metrics respond to management variables, and (5) Analyzing results and uncertainties to rank management alternatives.

The second framework is ecological: *habitat quantification* as an approach for assessing effects of management alternatives. This framework includes (1) Identifying specific types of habitat that are desirable for specific reasons, (2) Estimating the amount of these habitat types under each alternative, and (3) Assessing the alternatives by how well they provide the desired amounts of each habitat type. Other instream flow methods, especially PHABSIM (Physical Habitat Simulation System, Bovee et al. 1998), also use habitat quantification. However, the techniques we present differ from PHABSIM in ways other than not using computer modeling. First, we describe and encourage analysis of habitat for resources such as food production and diverse native communities, in addition to individual species. Second, we encourage consideration of biological mechanisms instead depending only on empirical habitat criteria. We also pay attention to issues such as selecting appropriate spatial and biological resolutions that are considered essential in habitat-based analysis (e.g., Manly et al. 2002) yet neglected in many instream flow studies.

The DFA procedures we recommend include defining specific habitat types and why they are important, delineating the area of each habitat type on maps as the demonstration flows are observed, and analyzing how total habitat area varies with flow. The procedures are organized in five steps, summarized in Table 1, and elaborated in the following sections (see also EPRI 2003).

STEP 1: DECISION FRAMING

The objective of Step 1 is to develop the "decision framing" information needed to make subsequent assessment steps credible and efficient. Eight issues should be addressed in Step 1 (and are, in fact, a good starting point for any instream flow assessment).

that may limit the range include: a consensus that flows lower than the baseline flows will not meet instream flow objectives (common if historic flow releases are minimal); other project purposes—there may be no value to considering instream flows that would keep a water project from meeting its fundamental purposes; or limitations on flow imposed by physical facilities, such as the minimum and maximum flows that valves or gates can provide.

STEP 2: DEVELOPING CONCEPTUAL MODELS OF FLOW EFFECTS

Step 2 is to develop conceptual models of how flow affects the target aquatic resources. By "conceptual model" we mean a general, shared understanding of the most important ways that flow affects the resources. Conceptual models can be very specific (e.g., "young-of-the-year trout require foraging habitat that is shallow and has low velocities, until they reach a length of 4-8 cm") or very general (e.g., "the biological integrity of the aquatic community increases with the diversity of habitat types present"). Different conceptual models may be needed for different life stages of a species. We consider three kinds of conceptual models.

Mechanistic conceptual models explicitly consider the ecological mechanisms by which flow affects individual fish, usually direct and indirect ways that flow affects the ability of fish to feed, grow, survive, and reproduce. Modeling these mechanisms allows us to distinguish habitat types that do and do not provide high fitness value to fish. Mechanistic models can be applied to species or guilds of fish for which there is some knowledge of the relevant autecology.

Empirical conceptual models use field experience and data to identify the kinds of habitat that fish often select (or "prefer"), and assume that flows providing more of the highly selected habitat are better. Empirical conceptual models are a subset of ecological techniques known as "resource selection" analysis (Manly et al. 2002). PHABSIM is based on an empirical conceptual model, but empirical conceptual models can be used at a variety of spatial scales, not just at the microhabitat scale used by PHABSIM. Empirical conceptual models may be based on quantitative field data or may simply be the judgment of experienced observers of the target fish. An empirical conceptual model may have a mechanistic basis; these models are more convincing when there is some understanding of *why* fish select the habitat types they use.

Theoretical conceptual models use the fundamental assumption that there are useful, general relations between (1) flow-dependent, large-scale, habitat characteristics and (2) the biological integrity of the aquatic community. We refer to these general relations as "theoretical" even though they tend to be rather speculative hypotheses that are difficult to test. Theoretical conceptual models are most likely to be appropriate in community-oriented assessments; mechanistic and empirical conceptual modeling approaches can be too cumbersome when assessing flow needs for resources as complex as fish communities. For such assessments the theoretical models may be best even when the underlying "theory" is not well tested.

An instream flow study can use a mix of conceptual model types. For example, there may be good empirical information defining feeding habitat for a species, while a mechanistic model is chosen for effects of flow on spawning. Even one conceptual model, e.g., for how flow affects spawning, could combine empirical information defining the depths, velocities, and substrate types best for spawning with a mechanistic understanding of how minimum flow affects where eggs are placed and, therefore, their vulnerability to flood flows.

Developing empirical conceptual models

Empirical conceptual models are based on observed relations between flow-dependent habitat variables and some measure of fish habitat value. Usually, empirical conceptual models are based on the *habitat selection* concept: observing what types of habitat are most commonly selected (or "preferred") by the target fish, and then assuming that flows providing more of the selected habitat have greater benefits for the fish.

The habitat selection concept is widely used in instream flow assessment, being the basis of PHABSIM, but has important limitations. The assumption that populations benefit from providing more selected habitat can be misleading or wrong when resources other than physical habitat (e.g., food) limit fish populations; or when several species or age classes compete for the same habitat (Garshelis 2000). Another concern with the habitat selection concept is that habitat selection varies among sites and over time due to many factors—one species of fish uses different habitat under different conditions. Many field studies (summarized in EPRI 2000) have shown that habitat selection varies with conditions including fish size, season and temperature, turbidity, presence and abundance of competing species or age classes, and habitat availability and structure. The assumption that increasing the amount of selected habitat increases fish populations is very difficult to test; Railsback et al. (2003) tested it in a virtual trout population and concluded that the habitat selection concept could work *if* (a) the target fish are not outcompeted for habitat and (b) the highly selected habitat is identified under very similar conditions to those occurring at the study site and flows. Under other conditions (e.g., juvenile fish, habitat preferences observed at low flows applied to higher flows), Railsback et al. (2003) observed (virtual) population responses to flow opposite those predicted via habitat selection.

The empirical approach should be avoided, or used cautiously, in situations where its fundamental assumption is especially questionable. Empirical relations such as habitat "preference" functions should be used only if based on observations made under conditions similar to those addressed by the instream flow study.

Developing theoretical conceptual models

For situations in which the relation between instream flow and the target resources are complex and uncertain, general "theories" of how aquatic systems depend on flow can be used as conceptual models. Several such "theories" are plausible and useful, though lacking in strong empirical support. Fausch et al. (2002) provide useful background on this general concept. One theoretical approach is the "Riverine Community Habitat Assessment and Restoration Concept" (RCHARC; Nestler et al. 1992), potentially useful when a reference site supporting the desired aquatic community can be identified. This conceptual model can be stated as: The instream flow most likely to support a desired aquatic community is the flow that most closely reproduces the distribution of habitat types (the relative area of each habitat type) at a reference site where the desired community exists.

A similar theoretical approach may be useful when the instream flow objective is simply to support a diverse natural community. Instead of using a reference site, this "maximize habitat diversity" approach simply assumes that greater habitat diversity is better. A few studies (e.g., Schlosser 1982) have concluded that fish species diversity increases with habitat diversity. Studies by Aadland (1993) and Lobb and Orth (1991) showed that a variety of river fish species and life stages use a variety of habitat types. Aadland (1993) also confirmed that habitat diversity

The spatial resolution of a habitat metric is the approximate area over which habitat conditions are aggregated when observing them. For example, good habitat for a pool-dwelling fish could be defined as water with a velocity less than 0.1 m/s using a spatial resolution of 10 m^2, because each fish needs at least about 10 m^2. If we observe an area of "pocket water" having 20% of its area in *small* patches of velocity < 0.1 m/s, we would record the presence of no good habitat because none of the patches of quiet water are big enough to be detected at a resolution of 10 m^2. If instead we defined good habitat to still have velocity less than 0.1 m/s but with a spatial resolution of 1 m^2 (e.g., for juvenile fish feeding over smaller areas), then the pocket water would have up to 20% good habitat because some of the small pockets of low velocity are now counted.

Spatial resolutions are often specified only approximately, and habitat can be quantified over areas greater than (but not less than) the chosen spatial resolution. Table 6 and the example study presented below provide some example spatial resolutions and their basis, for organisms and activities that might be considered in instream flow studies. These examples consider only the biological basis for spatial resolution, ignoring any limitations due to observability.

Selecting spatial resolutions for community-based metrics based on theoretical conceptual models is less clear-cut than for species-specific metrics. The theoretical conceptual models are based on the relative areas of general habitat types, not habitat for a specific species or activity. It is still important to define the resolution to avoid such ambiguities as how small a patch of quiet water should be considered a pool. The choice of resolution is closely linked to the selection of habitat types, as discussed below. Some rare but important habitat types may need special consideration and require observation at a finer resolution.

Biological resolution of habitat metrics

By *biological resolution* we refer to the question of which fish species or life stages are aggregated into the same metrics because they use habitat similarly. An important lesson from several attempts to test PHABSIM (Loar et al. 1985; Studley et al. 1996; Railsback et al. 2003) and behavioral research (Gunckel et al. 2002) is that habitat-based methods cannot predict how separate fish groups respond to flow when those groups use the same habitat. If, for example, adults of two trout species both use the same foraging habitat, a PHABSIM or DFA study will predict that doubling the flow would double the habitat for both species; but in reality an increase in habitat is likely to be occupied only by the species that out-competes the other for it. The inability to resolve between fish groups with similar habitat requirements means that the biological resolution of an instream flow study must be limited: if habitat metrics for two groups of fish cannot be clearly distinguished, then the groups must be combined in the assessment. For example, Studley et al. (1996) assessed rainbow and brown trout, which use habitat very similarly, together as a "total trout" group. Similarly, if yearlings and adults of a species have high overlap in habitat requirements, then the assessment method can only consider the combined group: all age 1 and older fish. (The ability to resolve groups that use similar habitat is not a problem, of course, if the groups are not present at the same time.)

Developing habitat metrics for mechanistic conceptual models

Mechanistic conceptual models can be translated into habitat metrics by using the literature, or judgment based on ecological understanding, to identify the types of habitat

The precision of empirical habitat metrics can be improved by documenting key assumptions, such as: the size of fish being evaluated, the activity the fish use the habitat for (e.g., daytime foraging, nighttime foraging, spawning, winter sheltering), and study site conditions affecting habitat selection (e.g., temperature, turbidity, relative food availability, types and relative magnitude of predation risk).

Developing habitat metrics for theoretical conceptual models

Theoretical conceptual models evaluate instream flows by how well they provide a desirable distribution of several different habitat types, sometimes in comparison to a reference site. Therefore, the primary step in developing metrics is to define these habitat types so that they can be quantified. A second step, in some cases, is to select a reference site.

Defining habitat types. This step requires identifying several specific types that habitat will be classified into during observation of demonstration flows. To be useful, this set of habitat types must be (1) easily distinguishable during observations, (2) ecologically meaningful, and (3) sensitive to flow. Useful example studies of how fish communities vary with habitat types include Lobb and Orth (1991), Aadland (1993), Hawkins et al. (1993), and Inoue and Nunokawa (2002). These studies generally classify habitat using channel units (riffles, pools, runs, etc.) as a basis. No single habitat typing system will work for all DFA studies. Instead, habitat types for community-oriented assessments can be defined by:

- Using the basic channel unit types as the starting basis. These types are standardized and comprehensive: most habitat can be fit into a small number of established channel unit types. Using fewer, more general types (perhaps only pool, riffle, and run) makes them easier to distinguish.
- Identifying habitat types that are important “hot spots” for fish. Examine the study site, a reference site (if one is used), data from similar sites, and literature on the desired stream community to identify biologically important habitat types.
- Breaking the channel unit types into subtypes, if necessary. Characteristics such as depth, substrate type and stability, and cover types can be useful for breaking channel units into more meaningful subtypes. For example, shallow pools generally provide higher production of algae and macrophytes, whereas deep pools provide refuge from predation by birds and mammals; bedrock riffles likely provide lower food production and feeding habitat than cobble or gravel riffles; and pools with trees or undercut banks provide greater protection from predation than do simple pools.

Selecting a reference site and conditions. The primary consideration in selecting a reference site is that it supports the desired aquatic community. There is extensive literature on selecting reference sites, although mostly focused on biomonitoring and water quality; some potentially useful references are: Hughes et al. (1986), White and Walker (1997), and Ehlert et al. (2002). Factors to consider in comparing reference and study sites include longitudinal gradient, geology and geomorphology (channel-forming processes, channel planform, sediment types, etc.), and channel width. Often, and especially for large rivers, suitable reference sites will not be available. Nestler et al. (1992) propose an interesting option in this case: using the instream flow study site itself, in its state before flow regulation, to provide reference habitat conditions. Then the problem becomes how to evaluate the site’s habitat conditions before it was altered.

their lawyer in the instream flow decision process could recruit a qualified consultant to represent them during field observations.

The observation team needs a leader to draw the group's habitat delineation onto the map, mediate disagreements, forge consensus, and keep the team moving. It is likely best to explicitly select a leader that participants are comfortable with instead of leaving this role to be filled by the most forceful personality. Consensus formation will depend both on leadership and a team goal of developing the best possible analysis. Team members also need to keep in mind that they are collecting data at this step, not making choices among flow options.

Selecting demonstration flows

Study design includes determining which instream flows to observe, between the minimum and maximum study flows defined during Step 1. Selecting the number of demonstration flows to observe is one of the most critical precision-cost tradeoffs in a DFA study. Observing more flows can be expensive, due to the costs of both releasing water and making and analyzing observations. But observing few flows reduces the precision with which the relation between habitat and flow is defined. As the example study (below) illustrates, in some streams this relation is complex, so observing only three or four flows would provide only a weak ability to identify good instream flows. It may be efficient to select flows "adaptively", first observing several flows over a wide range, analyzing results, then observing additional flows to provide more resolution in the range that looks most promising.

We strongly recommend including the baseline flow—the flow existing before new flow requirements are instituted—in the observations, even if there is a consensus that the baseline flow is not a viable alternative. Habitat quantity at the baseline flow provides a basis for comparison of habitat quantities at new flows. For example, three alternative flows might be determined by the DFA study to provide 2000, 2200, and 2500 m^2 of habitat. If the baseline flow provided 1800 m^2 of habitat, these numbers would indicate that there is a steady but not spectacular increase in habitat with flow, but if the baseline flow provided 500 m^2 of habitat, the interpretation would be that *any* of the new flows provides a major increase in habitat.

Developing base maps

By "base map", we mean a map or aerial photographs of the study site upon which field observations are drawn. It can be relatively quick and easy to delineate boundaries between habitat types in this way, especially when the river and map have ample landmarks (rocks, trees, etc.) as reference points. With accurate base maps and the analysis techniques recommended for Step 5, observation uncertainty in habitat quantification is unlikely to be high compared to the other uncertainties.

To make field observations quicker and more accurate, the maps need to show many easily recognized points of reference and to depict the site accurately. Base maps need to be recent and have low distortion. The size of the river and the spatial resolution of the habitat metrics determine what map scales and resolution are best. Another factor affecting the usefulness of a base map is the flow occurring when the map was made: photographs taken during high flow may not reveal landmarks needed for delineating habitat at lower flows.

Especially for big rivers, existing air photographs or topographical maps may suffice as base maps. However, it will often be worthwhile to develop new maps. Alternative methods include commercial aerial photography and the hand-operated balloon technique used in the feel expected to provide definitive answers. Even the best study will produce uncertainties which should be recognized by the assessment team, decision-makers, and stakeholders.

Providing observation aids

Inexpensive aids can improve the observers' ability to quantify habitat during demonstration flows. Boats and hydraulic lifts might help observers see the site as well as possible; staff and equipment to take spot measurements of depths and velocities, locations, or distances are essential for "calibrating" and supplementing visual estimation. Participants should have summaries of the habitat metrics for reference during observations. Field data sheets can provide a brief description (perhaps graphical) of the habitat types to be observed, along with places to record relevant information. Identifying such aids is yet another reason to practice the observations before the real assessment.

Quantifying habitat types in the field

Normally the field study is conducted by releasing a demonstration flow long enough for river stage to stabilize, then taking observations to estimate areas of each habitat type. Flows can be observed from lowest to highest, or in random order, which might help prevent bias from observers' unconscious expectations of how habitat should change with flow.

We recommend that habitat be quantified by having the observers, acting together, draw the boundaries among habitat types on a base map. During observations, it is desirable to encourage all members of the team to express their judgment instead of letting a single person or perspective dominate; a continual dialog among participants can provide checks and balances. One way to encourage all participants to think independently is for each person to delineate an area's habitat on their own map, then develop a consensus delineation, all before moving on to the next area.

When the group cannot arrive at a consensus in delineating a patch of habitat, separate delineations can be made for each opinion. If such disagreements are few, then it may be clear that they have no significant effect on results. If disagreements are many and consistent, then it may be necessary to analyze separate delineations produced by different participants. In this case, the group leader (or the participants who disagree with each other) can document causes of disagreement so they can be considered by decision-makers.

Uncertainties in field observations

Concern about uncertainty in DFA studies has historically focused on the field observation step, because this step is the key difference between the DFA method and other habitat-based approaches such as PHABSIM. The following sources of uncertainty could affect Step 4, although it is not clear that they are the most important overall uncertainties in habitat-based assessment methods: (1) Observer biases based on preconceived notions or desired outcomes; (2) Inconsistency in habitat metrics, e.g. habitat metrics that change over time or vary among observers; (3) Distortion or low resolution of base maps; (4) Error and variability in habitat quantification, e.g., uncertain visual observation due to habitat varying too gradually to delineate habitat types sharply; and (5) error in measuring and controlling the flow rates during observations.

ability to resolve how fish benefits vary with flow. As the following example study shows, the relation between habitat area and flow can be quite complex; a study that examines only 3 or 4 flows could do a poor job of defining the relation. Second, judgment and models used to link changes in habitat area to changes in the status of fish populations or communities will inevitably be simplified and uncertain.

EXAMPLE: A SALMON SPAWNING AND REARING STREAM

Many of the procedures we recommend are illustrated by a DFA study that was conducted below a small hydroelectric diversion on Oak Grove Fork of the Clackamas River, Oregon (CIFGS 2003). (The study preceded and partially motivated methods described in this article.) The DFA study was conducted after previous studies using other methods (including PHABSIM) had produced controversial results. In particular, the one- and two-dimensional hydraulic models used in PHABSIM-like studies were considered incapable of adequately representing the site's complex and steep hydraulic conditions.

Step 1: Decision Framing

Stakeholders making up the assessment team included the company operating the diversion, state and federal fisheries management agencies, and several non-governmental conservation organizations. McBain and Trush, Inc., was chosen by the assessment team to facilitate the DFA study.

The study site has a moderate gradient and contains many large boulders, small pools and runs, and steep riffles. The river is roughly 15 m across and most of the site can be waded easily. The flow often exceeds the diversion capacity in winter and spring, so uncontrolled high flows are not unusual during the spring spawning and egg incubation period. During summer and fall, instream flows are usually equal to the minimum flow release from the diversion plus tributary inflows.

The stream reach affected by the diversion is approximately 7,300 m long, and decreases in gradient as it approaches its confluence with the mainstem. The assessment team selected two study sites to represent the lower and higher gradient parts of the reach. The upper and lower sites are 340 and 500 ft long, respectively, together making up 11% of the total affected reach.

The site supports spawning and juvenile rearing of coho salmon (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*). The fisheries agencies had clear objectives for the instream flows: enhancing the production of these anadromous species.

The range of feasible instream flow releases was established as zero to 9.2 m^3/s. At the baseline flow release of zero, inflows from tributaries and groundwater result in flows of 0.3-0.6 m^3/s at the study sites. The upper limit of 9.2 m^3/s was chosen because it approaches the range of natural (undiverted) flows and because much of the stream could not be waded (making habitat quantification difficult and more uncertain) at higher flows.

Step 2: Developing Conceptual Models of Flow Effects

With the general goal established as enhancing production of anadromous salmonids, the assessment team used the following reasoning to establish two conceptual models of how the minimum flow affects the management goal. Both empirical and mechanistic conceptual models were used.

there is some overlap, coho generally use distinctly lower velocities than steelhead. One-year-old steelhead were determined not to be of sufficient importance to represent in the habitat metrics, in part to keep the habitat delineation from getting too complex.

Observer judgment was selected as the primary basis for the habitat metrics. The team decided to quantify habitat that, on the basis of their experience and judgment, appeared to be high quality for foraging or spawning. Judgment of spawning habitat was based mainly on availability of appropriate depths, velocities, and gravel sizes. Judgment of foraging habitat considered proximity to adequate velocities to provide drift food, availability of velocity shelters to reduce swimming speeds, and proximity to hiding cover for escape from predators.

Some team members preferred to use published PHABSIM habitat criteria as a "quantitative" guide to their habitat delineations. The team decided that members could use PHABSIM habitat criteria as an aid in delineating habitat but that their judgment could overrule the PHABSIM criteria in case of disagreement.

One issue discussed extensively in developing the habitat metrics was whether to evaluate habitat quality as well as quantity. Should the observers delineate "good" from "marginal" habitat? The team explicitly decided not to include marginal habitat but instead to simply delineate "good" habitat. This decision was made to keep field observations from being overly complex and to avoid having to deal, in the analysis step, with comparing marginal habitat areas to areas of good habitat.

Combining these considerations, three specific habitat metrics were identified for delineation during the demonstration flows:

- *Coho and steelhead spawning habitat*. The area of habitat judged to provide high quality spawning and egg incubation.
- *Coho foraging habitat*. The area judged to be highly selected foraging habitat for age one and older coho.
- *Steelhead foraging habitat*. The area judged to provide highly selected foraging habitat for age two and older steelhead.

Example Step 4: Designing and Conducting Field Observations

Much of the study's effort and cost was in preparing for the field observations. The primary issue was developing detailed and accurate maps of the site to facilitate habitat delineation—maps needed an abundance of clear landmarks (down to individual boulders and trees) to help the assessment team draw boundaries of habitat patches rapidly and accurately. The maps needed to lack distortion that could bias results. A set of recent aerial photographs was unusable because overhanging trees obscured much of the channel.

McBain and Trush, Inc. solved this problem by using a commercial balloon-mounted digital photography system (Floatograph Technologies, Napa, California). Three technicians could rapidly photograph the entire study reach from an elevation of about 15 m. Highly visible targets were placed in each photo to aid in rectification. The overhead photographs were rectified and assembled to produce a small number of composite photos that each show a long reach of stream at a consistent scale and without distortion (Figure 2). The photos were produced at a single, relatively low, flow.

The assessment team considered which among its members had sufficient expertise to participate in the habitat delineation. Experience observing the target fish was especially

- The DFA method was not limited by complex hydraulics and habitat. Experienced observers have mental models of habitat that can be more useful than the hydraulic simulation and habitat criteria used by PHABSIM, especially in complex habitat.
- Far more habitat could be evaluated, and rapidly, with the DFA approach, whereas modeling only a very small subset of a site's habitat is a major source of uncertainty in many PHABSIM applications. On the other hand, the DFA study quantified habitat at only seven flows.
- The DFA approach facilitated the use of mechanistic, not just empirical, conceptual models of how flow affects the target fish.
- The DFA method encouraged open consideration of the many assumptions and judgments that are involved in any instream flow study; more rigid approaches such as PHABSIM can hide assumptions and discourage their reconsideration.

However, the DFA method and PHABSIM are fundamentally similar, both based on the assumption that habitat area is a reliable indicator of how flow affects aquatic resources. Both are therefore subject to the inherent limitations of habitat-based approaches, including: (1) producing estimates of habitat change, not testable predictions of how flow affects fish populations or communities; (2) not considering the effects of variation in flow and other conditions over time; (3) being especially unreliable for groups likely to be out-competed for habitat; and (4) producing separate results for each life stage and species, which cannot be reliably integrated into a measure of overall population or community status (EPRI 2000; Railsback et al. 2003).

ACKNOWLEDGEMENTS

This work was sponsored by EPRI, the Electric Power Research Institute, under agreement EP-P1149/C433 with Lang, Railsback & Assoc. Doug Dixon was the EPRI project manager. The authors thank Ken Cummins (Institute for River Ecosystems, Humboldt State University) and Bret Harvey (U.S. Forest Service, Pacific Southwest Research Station) for input on river ecology; and Bill Trush, Geoff Hales, and Scott McBain (McBain and Trush, Inc.) for making the Oak Grove Fork study available. The DFA procedures were discussed at a Bay-Delta Modeling Forum workshop on instream flow assessment, December 9-11, 2002 in Davis, California; we thank workshop organizer John Williams and other participants for their feedback.

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Table 1. Summary of the recommended DFA procedures.

Assessment step and objective	**Typical products**
Step 1: Decision framing. Identify assumptions, constraints, and expectations for the instream flow assessment.	Identification of: assessment participants, target aquatic resources and management objectives, study site bounds, seasonality of flow requirements, range of flows to assess, and how minimum flows fit into an overall flow regime that may also consider other flow needs.
Step 2: Conceptual modeling. Identify important and observable ways that flow affects habitat and, therefore, the target resources.	Conceptual models, documented as simple statements of how flow affects habitat and aquatic resources. Models may be (1) mechanistic, based on a specific process such as providing adequate food production or feeding habitat; (2) empirical, with flow affecting the availability of "preferred" habitat types; or (3) theoretical, with flow affecting the relative amounts of habitat types considered necessary to support a desired community.
Step 3: Metric selection. Define observable measures of flow effects on target resources. These measures are usually the area of specific types of desirable habitat.	A description of the types of habitat to be quantified during demonstration flows, and the spatial and biological resolution of the observations. Habitat types must be described precisely enough to make observations reproducible. A practice assessment to refine the metrics is highly recommended.
Step 4: Field observations. Design the methods used to evaluate the metrics during demonstration flow releases. Conduct the field observations.	A field observation plan describing what measurements are to be taken, how, by whom, and where; and field data for each demonstration flow. Field data typically are maps showing where each type of habitat was observed, at each flow.
Step 5: Analysis. Calculate the area of each habitat type at each flow. Rank the alternative flows and summarize uncertainties.	A ranking of the alternative flows, based on the observed habitat quantities and conceptual models.

	velocities are moderate and substrates are stable.		
Larger rivers	Energy input[†] may be dominated by algae production, which may be limited by depth and turbidity. In turbid systems, energy input may be dominated by matter transported from upstream. Zooplankton and macroinvertebrate production: same as for small streams with little vegetation.	Same as above, except: pools are less important where turbidity is high, and if energy input from a reservoir is high, then pool habitat is likely not as important.	For less-turbid rivers, same as for small streams with little vegetation. If energy input is dominated by transport from upstream, then flow to transport material from upstream may be more important than habitat types.
Mid- to large rivers that support (or could support) rooted aquatic plant beds	Rooted plants are promoted by stable flows. Stems typically support algae, and grazing invertebrates that some fish eat. Rooted plants do not contribute directly to the food base until they die (which can be promoted by flow fluctuation) and may consume nutrients that otherwise would support algae and riffle insects.	Stable flows that produce suitable depths and velocities may promote aquatic plant beds, which provide hiding cover and food for some (but not all) fish species. Flow variation that discourages rooted aquatic plants may increase food for fish that do not use plant beds.	The area with velocity, depth, and substrate type suitable for rooted aquatic plant beds. (For many rivers these conditions are low velocities, intermediate depths, and fine substrates.)

[*]Except where other citations are provided, these concepts are from the River Continuum Concept (Vannote et al. 1980; Minshall et al. 1983; Minshall et al. 1992) and K. Cummins (personal communication).
[†]At some sites, especially downstream of reservoirs, energy input may be dominated by dissolved and particulate organic matter from upstream. At such fertile sites, flow and habitat effects on energy input may be unimportant; however, habitat for production of zooplankton and invertebrates may still be important.

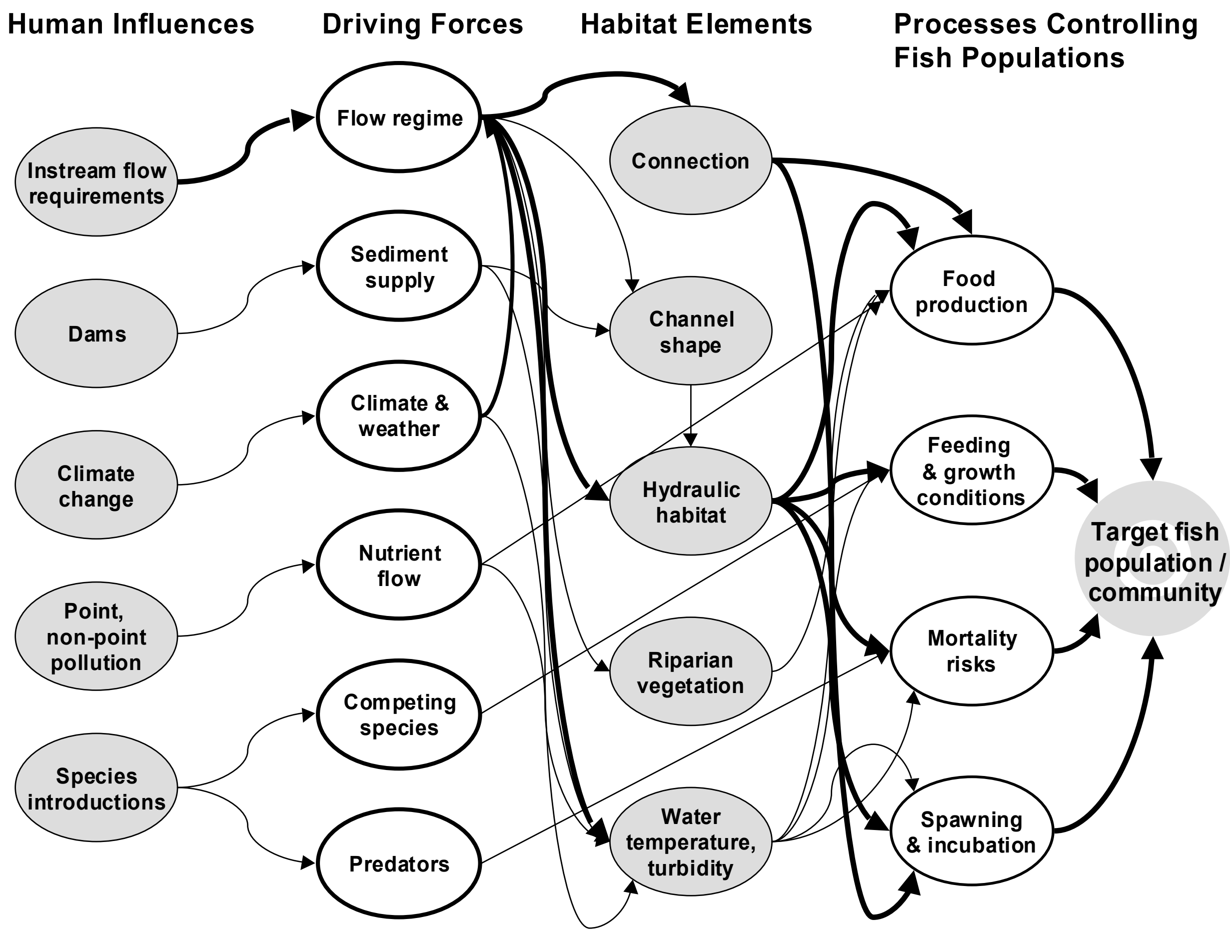
Table 4. Ecological mechanisms and conceptual models for how flow affects **mortality risk**.

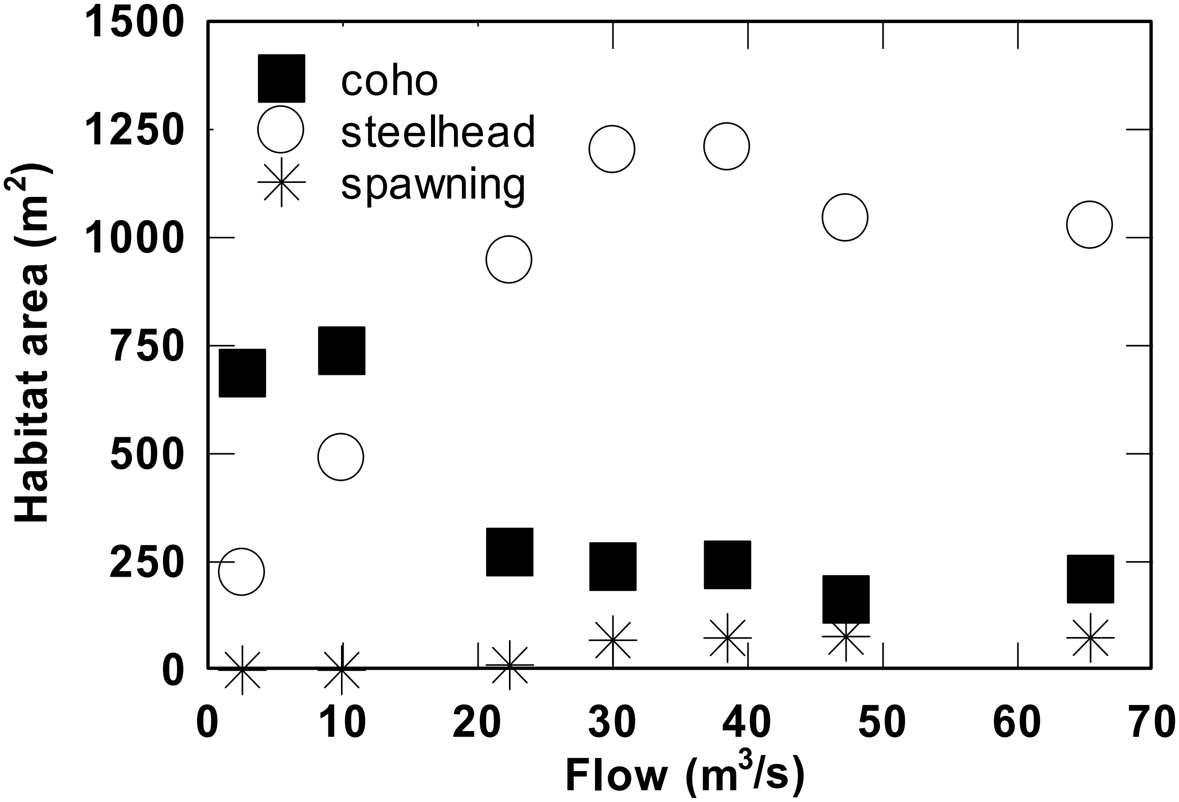
Situation	Ecological mechanisms	Potential conceptual models*
Small fish (juvenile game fish; small species)	The greatest risk is likely due to piscivorous fish, potentially avoided by using shallow water, aquatic vegetation, or crevices as cover. As fish grow, they become less vulnerable to other fish and more vulnerable to terrestrial predators. The size at which vulnerability to predator fish ceases depends on the size and species of predator fish.	For fish vulnerable to predation by other fish, survival is higher at flows that provides both cover (shallows, vegetation, etc.) and suitable feeding conditions.
Intermediate and large fish	Once more than a few cm in length, fish are vulnerable to terrestrial predators that depend at least partly on vision from the surface (Alexander 1979; Metcalfe et al. 1999). This risk increases as fish grow. In clear water, hiding cover (rock crevices; vegetation) in proximity to feeding habitat reduces risk. Deep and fast water also offers cover. In turbid water, predation risk is generally lower and cover has less value.	In clear water, survival is highest when feeding habitat is close to cover provided by depth, velocity, or hiding places. In turbid water, flow may have little effect on survival.

*Conceptual models of predation risk should not be used by themselves because predation typically happens while fish are foraging. See the text of this section concerning foraging.

Table 6. Example **spatial resolutions** for habitat metrics.

Organism and activity	Basis for resolution	Spatial resolution
Zooplankton growth and reproduction	Zooplankton move with the current so habitat for them can only be evaluated over large areas.	Channel units or subunits (e.g., the area of shallow habitat within pools).
Benthic insect growth and reproduction	Insects each use only small areas, and their mobility allows them to find and use small patches of suitable habitat.	Less than 1 m^2.
Foraging by trout and other fish that use sit-and-wait feeding	Trout can capture food over distances up to several body lengths in either direction, with this distance decreasing as velocity increases (Hill and Grossman 1993; Hughes and Dill 1990). Observed territory sizes are 1-5 m^2 for trout 10-20 cm in length (Grant and Kramer 1990).	1-5 m^2; lower values for smaller fish or fast water.
Smallmouth bass foraging (an example warmwater piscivore)	Bass forage over entire pools and into adjacent riffles.	Entire pools plus adjacent habitat units.
Spawning by nest-building fish	Spawning nests are immobile, so resolution need not be larger than the nest (and possibly the area used by spawners to build and defend the nest).	An area slightly larger than the size of a nest.


Human Influences
Driving Forces
Habitat Elements
Processes Controlling Fish Populations
Instream flow requirements
Dams
Climate change
Point, non-point pollution
Species introductions
Flow regime
Sediment supply
Climate & weather
Nutrient flow
Competing species
Predators
Connection
Channel shape
Hydraulic habitat
Riparian vegetation
Water temperature, turbidity
Food production
Feeding & growth conditions
Mortality risks
Spawning & incubation
Target fish population / community



1500
1250
1000
750
500
250
0
0
10
20
30
40
50
60
70
Habitat area (m2)
Flow (m3/s)
coho
steelhead
spawning