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Decision management and the assessment of fishways in the perspective of river ecology

John M. Nestler, R. Andrew Goodwin, and David L. Smith

1 Introduction

1.1 Water Resources Decisions

River ecosystems are broad in spatial scale and complex in their arrangement and connection of subsystems. These ecosystems support and structure biotic communities that are diverse and abundant through climatic and hydrologic rhythms that repeat at different scales and exhibit trends in response to human-induced and natural changes. Often the relationships among the physical, chemical, and climatic variables in these systems and biotic response are unclear or unknown. The inherent complexity of such systems produces suites of uncertainties that defy conventional methods of water resources management that sequentially progress from planning, engineering design, to project construction. Experience has shown that the expected benefits of management actions are typically not completely achieved when water resources management includes ecosystem restoration objectives. The addition of fish passage facilities at dams to address river fragmentation seems particularly prone to post construction performance issues. The problem primarily results from the many unknowns that plague the attraction, entrance, and passage of fish at fishways.

The preferred method for conducting program-scale ecosystem restoration, such as the challenge of reconnecting river reaches by the addition of fish passage at dams, is Adaptive Environmental Assessment and Management (AEAM – WALTERS & HOLLING 1990). AEAM organizes restoration into a recursive, stepwise framework that optimizes informed restoration decision-making over time through the sequential reduction of uncertainties about ecosystem response to management actions. AEAM begins with the conventional water resources management steps of planning, design, and construction, but then adds a monitoring and assessment phase that then informs a new cycle in the water resources development process. The addition of monitoring and assessment to inform future project planning functionally converts the linear planning process associated with conventional planning into a series of loops that progressively reduce project uncertainty (“learning”) as each loop is completed. The individual steps in AEAM are well known (WILLIAMS et al. 2007) and have been applied and refined by many workers.

1.2 Refining Adaptive Environmental Assessment and Management (AEAM)

Conventional methods of water resources management commonly used to address problems that are inherently hydrologic or hydraulic (and subsequently well known) can be used to efficiently estimate project schedules and budgets. Unfortunately, the open-ended nature of AEAM makes the creation of budgets and schedules more difficult and, therefore, makes AEAM execution institutionally challenging for government agencies that manage water resources. The magnitude of these challenges can be reduced by minimizing the number of loops required to execute AEAM because each cycle has a substantial cost and causes a delay in project benefits. Strategic investments made at key points in AEAM cycles can rapidly decrease project threatening uncertainties. An evaluation of AEAM identifies specific steps that can be taken to improve the efficiency of AEAM and increase the ability of water resources agencies to develop realistic project schedules and budgets:

- > developing of a detailed plan that includes all program synergies and feedbacks,
- > creating and regularly updating a detailed conceptual model that embodies understanding of how the ecosystem works and how a management action could alter the functioning of the ecosystem,
- > institutionalizing AEAM by integrating the “learning” phase of adaptive management into project planning, and
- > formulating a strategic monitoring plan that focuses on “learning” at the program level to reduce program threatening uncertainties as efficiently as possible.

While all of the steps identified improve AEAM, the most efficient way to reduce the number of loops required in AEAM is to use a forecasting framework that is as accurate and precise as possible and that can also be easily updated as “learning” about the response of the system to management action progresses.

2 Eulerian-Lagrangian-Agent Methods (ELAMs)

2.1 Description

An emerging technology useful for guiding challenging ecosystem restoration actions such as fish passage design is the Eulerian-Lagrangian-agent Method (ELAM; <http://EL.erd.usace.army.mil/emrrp/nfs/>). ELAMs can reduce the uncertainties inherent in the more traditional statistical approaches. The reduction in uncertainty facilitated by the ELAM is of critical importance because a single bypass system on a major river can cost nearly \$100M USD. Failed systems represent a major financial loss as well as have severe impact on protected fish species.

The ELAM represents a mathematically rigorous framework for fish passage design that accentuates the strengths of:

- > computational fluid dynamics (CFD) modeling to help designers understand and incorporate the complex flow fields associated with river regulation structures into passage structure design and operation;
- > fish behavior studies using advanced tagging technologies to understand the sophisticated movement behaviors exhibited by migrating fish and to use this information in forecast alternatives modeling;

- > agent-based modeling systems to numerically evaluate fish movement hypotheses and ultimately to construct forecast models that can be used to reduce the often considerable uncertainty associated with design and construction of fish passage systems.

The mathematical rigor of the coupling eliminates the uncertainty typical of more conventional approaches in which each discipline contributes its findings according to its own traditions and perspectives. For example, results from tagging studies that are based on statistical analysis must have sufficient replication to separate different bypass designs or fish passage through different outlets (e. g., passage percentage through powerhouse, spillway, and bypass for outmigrating fishes). The need for sufficient replication for statistical hypothesis testing usually requires that changes in river discharge or passage through individual different turbines must be pooled so that these effects are lost from the analysis even though these differences can be very important to bypass design.

We use the ELAM to understand and forecast fish movement in river settings either to understand their movement through a river or to evaluate their behavior in response to the flow field signatures created by different fish ways designs. The following explanation of fish swim path selection is based on the behaviour of juvenile salmon. Swim path selection of juvenile salmon is best understood in the context of the fluvial geomorphology of free flowing rivers (NESTLER et al. 2008). In free flowing rivers, a flow field distorts because of flow resistance (LEOPOLD et al. 1964). Without flow resistance there is no force to distort a unit volume of water once it is set into motion by the force of gravity (OJHA & SINGH 2002). To relate fish swim path selection to flow field distortion, GOODWIN et al. (2006) proposed a flow field distortion metric 'total hydraulic strain' that embodies (1) linear deformation (whose tensor metric components are normal strain rates), (2) rotation (whose tensor metric components are angular velocities), and (3) angular deformation (whose tensor metric components are one-half the true shearing strain rates). Although rotation is not due to normal or shearing strain rates, the same spatial velocity gradients induce both angular deformation (shearing strain) and rotation. In more recent work we refer to 'total hydraulic strain' as the magnitude of the velocity gradient or 'total velocity gradient'.

Two categories of flow resistance, friction resistance and form resistance, occur for sub-critical flows (LEOPOLD et al. 1964). A simple, straight, uniform channel produces a flow pattern in which average velocities are lowest nearest a source of friction (such as the channel bottom and edges) with a zero water velocity occurring at the water-channel boundary. Pattern in the total velocity gradient field is the inverse of pattern in the velocity field, with lowest total velocity gradients occurring farthest from sources of friction resistance and highest near the sources. Form friction, or drag, is created by large woody debris or rock outcrops projecting into the flow. As in the case of friction resistance, total velocity gradients associated with form resistance increase towards the signal source. In contrast to bed friction, water velocity increases towards the signal source for form resistance because of local reduction in conveyance area and increased travel distance of water flowing around an obstruction. For example, a fish approaching a stump from the upstream direction will sense increasing total velocity gradients and an increasing water velocity until boundary effects very close to the obstruction are encountered.

By integrating information between the total velocity gradient and velocity fields, fish have sufficient information to identify specific channel structures and solid boundaries thereby creating a hydrodynamic ‘image’ of their immediate surroundings. That is, they have sufficient information to infer the attributes of the solid boundary from pattern in the flow field. They are thus able to move efficiently through a flow field or select habitats with specific hydraulic and geomorphic attributes. In our explanation, we emphasized downstream migration, but the ability of a fish to respond to hydrodynamic cues that signal channel features also allows it to migrate upstream or to locate and evaluate potential habitat or feeding stations, all in a complex flow field and bed geometry. While we used juvenile salmon as a model system to describe fish movement, it seems plausible that many other species would use a similar movement cue because all fishes share a common mechanosensory system capable of detecting relative velocity magnitude and hydraulic gradients.

2.2 Simulating Fish Movement to Aid Fish Passage Design

Hydrodynamic information generated at discrete points in a hydraulic model (Eulerian) mesh is interpolated to locations anywhere within the physical domain where fish may be. This conversion of information from the Eulerian mesh to a Lagrangian framework allows the generation of directional sensory inputs and movements in a reference framework similar to that perceived by real fish. Movement is treated as a two-step process: first, the fish evaluates agent attributes within the detection range of its sensory system and, second, it executes a response to an agent by moving (BIAN 2003). The volume from which a fish acquires decision-making information is represented as a 3-D sensory ovoid. A virtual fish’s sense of direction at each time increment is based on its orientation at the beginning of the time increment. Directional sensory inputs are tracked relative to the horizontal orientation of the fish because fish response to laterally-located versus frontally-located stimuli can be different (COOMBS et al. 2000). The sensory ovoid has a vertical reference because fish detect accelerations and gravitation through the otolith of its inner ear (PAXTON 2000). It also senses three-dimensional information on motion (BRAUN & COOMBS 2000). In an ELAM we begin with a symmetrical (spherical) sensory ovoid for fish although it can be easily modified.

Behaviour rules (GOODWIN et al. 2006) in the ELAM produce a 3-D swimming vector in which speed and orientation are determined interdependently for each fish at every 2.0-sec increment. The resultant fish swim vector is then decomposed into Cartesian vector components (u_f , v_f , w_f) coinciding with the axes of the Eulerian mesh. These vectors are added to the flow vectors (u , v , w) interpolated to the fish’s centroid location to update the coordinates (x_t , y_t , z_t) at time t from the previous position (x_{t-1} , y_{t-1} , z_{t-1}) after time increment (Δt) as:

$$x_t = x_{t-1} + (u + u_f) \cdot \Delta t$$

$$y_t = y_{t-1} + (v + v_f) \cdot \Delta t$$

$$z_t = z_{t-1} + (w + w_f) \cdot \Delta t$$

Simulating the continuous (Lagrangian) movement of individuals in a (Eulerian) mesh of discrete points is difficult and has limited the use of integrated Eulerian-Lagrangian methods (ELMs) in individual-based modeling (BIAN 2003). The details of the ELAM for simulating fish movement can be found in GOODWIN et al. (2006).

2.3 Performance, Validation, and Sensitivity

Describing trends in movement and passage can be separated into two interrelated tasks: The ability of the CFD model to accurately represent flow field pattern and the ability of the ELAM to correctly capture passage trends. We describe here the methods used to describe passage trends. One method of calibration is to compare ELAM forecasts to field collected calibration data using linear regression (SMITH & ROSE 1995). Forecasts compared to measured passage rates through different dam outlets can be used to produce RSQUARES. Also, the ELAM can be run in a “rules off” configuration so that virtual fish become passive particles for comparison. Accuracy of calibration partially hinges on the constancy of dam operation during data collection. Powerhouse operation is seldom held constant because of changes in hydrology, power demand, and maintenance schedules. In contrast, spillway operation and bypass system operation is usually held constant during the collection of calibration data resulting in improved RSQUARES. Consequently, the calibration is usually best for the spillway and bypass forecasts. During calibration, we try to achieve the best fit of predicted to observed bypass performance at the expense of powerhouse or spillway passage because our studies are typically done to aid bypass design.

3 Discussion

3.1 Fish Movement Categories in Rivers

Once calibrated, ELAMs can be used to systematically explore fish movement either to forecast bypass performance or to better understand how fish make decisions in natural rivers. This second use is possible because fish likely do not exhibit behaviours at dams that are any different than they exhibit in natural rivers. Based on our explorations with virtual fish and evaluations of the behavioural rules, we believe activities of fish in rivers can be broadly separated into two categories from an ecological and life history standpoint: place-specific behaviours or place-searching behaviours. At any one time a fish can be engaged in one of these activities, but not both, although it may switch rapidly between these activities. Moreover, it may be useful to ordinate different life-stages of fish along a gradient that is anchored at one end by life stages that predominantly engage in place-specific activities and anchored at the other end of the gradient by life stages that predominantly engage in searching activities. Other strategies may employ various blends of the two activities depending upon life stage, environmental gradients, and size of the physical domain.

In a place-specific activity, fish maintain their approximate position in an area. For example, a feeding station for a sight-feeding fish such as resident juvenile salmon has the following attributes (FAUSCH 1984; SMITH et al. 2008). The fish body locates itself in relatively slow water to minimize the bioenergetic cost of swimming, but near a shear zone so that it can dart across the shear zone to capture drifting prey carried near its position by the current. The water velocity across the shear zone must be fast enough to transport prey items at a significant rate, but not so fast that the fish must expend substantial energy to return to its original location after feeding. Based on this simple example, two conclusions can be reached about juvenile salmon when they exhibit place-specific activities: Specific hydraulic criteria based on water depth and water velocity and variables associated with water velocity such as shear

or turbulence can be used to describe feeding station locations (SMITH & BRANNON 2007) and these criteria may often be described in terms of absolute values and not relative values. Absolute criteria, keyed to the water velocity on the slow side of the shear zone of the feeding station, are needed because fish must expend energy to maintain position in the face of displacing currents. Therefore, relative difference in velocity across the shear zone does not adequately reflect the bioenergetic realities for a fish trying to maintain position on the slower side of the shear zone.

Fish that engage in place-searching activities must rely on relative values of hydraulic variables because the domain within which they move may experience substantial changes in bedform and discharge over time and space. Therefore, given this “floating baseline condition” associated with dynamic rivers, it is likely impossible for absolute values of hydrodynamic movement cues to exist that can function over the range of encountered hydraulic conditions as fish migrate along the space-time continuum. For example, if the channel cross section area reduces by 50 % and the discharge remains constant, then the average cross section velocity must correspondingly increase by 50 % to maintain mass continuity. Consequently, a fixed velocity criterion that identifies the pathway of a migrating fish is unreasonable unless swimming capabilities are exceeded. However, the overall flow pattern may remain essentially the same with some relatively small movement in space of velocity maxima or minima. Use of relative hydraulic variables allows fish to hydro-navigate as discharge changes or as the coarse shape of the channel changes because the basic flow field pattern described as relative values will be more persistent than absolute values within the field.

3.2 What is a River to a Fish?

From a fish’s perspective, a river is not best represented as a habitat checkerboard or mosaic, but as a waterscape of fluid features that gradually blend into one another in much the same way that a landscape, at large scales, is primarily comprised of elevation gradients and not elevation breaks (i. e. cliffs). These fluid features can be described in gradients (i. e., spatial derivatives) over certain space scales coupled to the solid features of the channel. Understanding the fluid environment from a fish’s perspective is important for river restoration and to manage the impacts of dams and smaller scale structures that alter river flow fields. Importantly, conventional habitat metrics such as average depth and velocity mask gradients and are, therefore, likely insufficient for linking fish movement among habitats to environmental processes related to geomorphology or to biogeochemical processing. By responding to magnitudes of velocity and velocity gradient, fish are able to make directed (nonrandom) movements in flow fields, within geomorphological complexity, and within biogeochemical fields as long as these fields retain their natural interrelationships.

Taken in total, these findings suggest that it is more useful to think of a large river as a machine rather than as an amalgam of habitat patches (NESTLER et al., In press). The physical structure of the machine is a sloping plane that alters the magnitude and direction of an applied force. The kinetic energy that runs the machine ultimately derives from gravity which drives complex hydrologic rhythms that are, in turn, coupled to local to global climate patterns. The force generated by the sloping landform and hydrologic rhythm is hydraulic shear which reconfigures the channel and transports material either through the system or to areas

where it can settle and be transformed, perhaps over multiple cycles. Importantly, we are not de-emphasizing the importance of autochthonous or allochthonous organic matter in structuring river communities, but rather emphasizing the importance of hydrodynamic pattern to the highly advective river ecosystem.

In a large river system, the amount of organic and inorganic material that is transported and transformed is immense. A fish, by evolving complex life histories and sophisticated movement behaviors, can take advantage of the work performed by the river machine as it transports, stores, and transforms materials. This enables fish to limit energy expenditure in foraging for widely distributed food when riverine processes naturally accumulate food and organic matter in parts of the river at certain times. Therefore, the primary challenge for fluvial dependent fishes is not to find specific microhabitats, but to synchronize their life history to cues that describe and predict the rhythms of the system so that they can take advantage of work done by the river. They do this by using basic hydrodynamic cues that allow them to find “hot spots” and “hot moments” of biochemical transformation (*sensu* VIDON et al. 2010) at a system level. For example, the organic matter available to fishes in the lower Mekong River produces a yield of approximately 2.6 million tons per year (HORTLE 2007). Similarly, the Illinois River provided much of the protein needs for the city of Chicago and was considered to be one of the most productive fisheries ever recorded (FREMLING et al. 1989). The Paraná basin contains more than 50 migratory fish species (CAROLSFELD et al. 2003). Fragmentation caused by regulation of many South American large rivers has reduced or even eliminated upstream energy flow transported by migratory fish.

4 Conclusions and Summary

We began with a simple introduction to AEAM to give context and meaning to scientific studies, with a focus on fish passage. We proposed the ELAM as a general investigative and modelling framework to develop tools that are both scientifically robust and provide forecasts of future conditions associated with different fish passage designs. In the course of these studies it became apparent that fish can have no evolutionary experience with dams because dams are a relatively new feature in geologic time. Therefore, the behaviour they exhibit to bypasses is, in reality, the behaviour they use to move through rivers. Consequently, this behaviour is the beginning point to uncover how fish that exhibit pronounced behaviours are interconnected to river processes. Inherently, studies to describe fish movement to aid fish passage design also aid other restoration measures.

Although a robust and useful theoretical benchmark has been developed to explain how large floodplain river systems work, considerably less effort has been devoted to understand how specific biota, particularly fish, respond to the dynamic, multi-scale habitat variables that define large rivers. Unlike low order rivers where relatively simple geomorphologic and hydraulic variables are useful to define habitat requirements, large floodplain river systems pose formidable challenges due to their spatial and temporal complexity. As ARTHINGTON et al. (2006) concluded and as we argue in this paper, place-centered habitat assessment is not appropriate to describe holistic characteristics of large river systems. Fish species have developed strategies (e. g., physiological and morphological adaptations, trophic position, migratory movements, growth, recruitment, and reproductive patterns) to take advantage of the

complexity that is inherent in the river machine concept. We point out how a general hydrogeomorphic guiding principle based on known or plausible effects of the flood pulse was used to propose general seasonal and spatial patterns in the transport, transformation, production, and redistribution of materials within a river corridor. These effects integrate functional and structural linkages among different fluvial components such as floodplains and main and secondary channels.

The natural hydrogeomorphology guiding principle was expanded to mechanistically connect environmental fluid dynamics, fluvial geomorphology, and biogeochemical cycling via velocity magnitude and hydraulic shear and thereby relate more directly to patterns in the abundance and diversity of large river biota. Unlike the general hydro-geomorphology guiding principle, the mechanisms of transport, erosion, and deposition of material that derive from it are sufficiently resolved to be evaluated empirically using status and trends monitoring data or process description data. Ideally, these studies would be supported by the same CFD models used to describe movement of emigrants (GOODWIN et al. 2006). That is, CFD modeling can be used to identify and describe the fine-scale erosion and deposition potential of specific parts of the river and its flood plain. Therefore, mechanisms proposed in this paper can be considered as initial testable hypotheses about how hydrogeomorphology regulates different aspects of biodiversity in large rivers. These hypotheses and others derived in the future can be evaluated and adjusted through the monitoring and assessment phase of adaptive management.

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