Innovative Integration of Engineering and Biological Tools Aids Hydraulic Structure Design for Restoring Threatened and Endangered Fish

John Nestler[1], R. Andrew Goodwin[2], David L. Smith[3], Toni Toney[4]

[1]U.S. Army Engineer Research & Development Center, Vicksburg, MS, USA
john.m.nestler@erdc.usace.army.mil

[2]U.S. Army Engineer Research & Development Center, Vicksburg, MS, USA
andrew.r.goodwin@erdc.usace.army.mil

[3]U.S. Army Engineer Research & Development Center, Vicksburg, MS, USA
david.l.smith@erdc.usace.army.mil

[4]U.S. Army Engineer Research & Development Center, Vicksburg, MS, USA
toni.toney@erdc.usace.army.mil

INTRODUCTION

Linking ecologic response to design elements of hydraulic structures is one of the greatest challenges preventing accurate and complete assessment of water resource systems. A principle reason is the difficulty in linking engineering models used to simulate physicochemical processes (e.g., river and reservoir hydraulics and water quality, nutrient dynamics, coastal circulation, sediment transport, erosion, and deposition) associated with project design or operation with biological models used to forecast biological population processes (e.g., population viability models, growth and recruitment, predator prey dynamics, movement and behavior models). The output of engineering models, typically used to describe detailed physical and chemical processes associated with project design or operation, cannot be directly linked to ecological response models. Similarly, ecological response models typically represent physical and chemical processes using low-resolution methods that cannot accurately describe hydraulic patterns associated with specific design or operational alternatives. A retrospective shows that engineering and ecological modeling traditions can be generally assigned into either an Eulerian or Lagrangian reference framework, respectively. These seemingly disparate methods can be coupled using Eulerian-Lagrangian-Agent Methods (ELAMs) that bridge these different time and space scales. ELAMs allow those processes best simulated by multi-dimensional engineering tools to be linked to processes best simulated by ecological tools. We illustrate application of an ELAM using a fish passage example – the Numerical Fish Surrogate (NFS).

METHODS

The computational backbone of the integrated tool is a modified particle-tracking algorithm that allows interpolation of hydraulic and water quality information integrated within an engineering mesh (Eulerian grid) to interior points located in continuous space (Lagrangian particles) of interest that could represent the location of real or virtual aquatic biota. The integrated tool is used to aggregate, disaggregate, and translate information, as required by each framework, so that processes that differ substantially in scale, such as ecological response and hydrodynamics, can each be accurately simulated. We illustrate the integrated tool with a specialized application in which a fish swim path selection model is coupled to a computational fluid dynamics model (Goodwin et al. 2006).

SITE

Hydropower dams on the Snake and Columbia Rivers in the Pacific Northwest of the USA block the out-migration of juvenile salmon (migrants). Bypass systems are constructed to intercept as many of these fish as possible and thereby prevent them from entering the turbines where they can be potentially injured or killed. To work effectively, migrants must be attracted to the vicinity of the bypasses and the hydrodynamic characteristics of bypass entrances must encourage the entry of migrants. We test the NFS on 23 different project configurations on the Snake and Columbia Rivers.

RESULTS

As described in detail in Goodwin et al. (2006), NFS predictions generally match observed passage proportions with goodness of fit (slope/R-square)

decreasing from spillway (0.95/0.85), bypass (1.07/0.80), to powerhouse (1.15/0.61). The reduced goodness of fit for the powerhouse is likely related to the difficulty of maintaining constant operation of the powerhouse during the collection of fish tracks. Total powerhouse discharge usually remains constant, but the units in operation and the distribution of load across those units typically change during a test. However, the CFD model is run at steady-state and consequently does not capture changes in operation. Spillway operation is held constant during a test and therefore meets the steady-state assumption. Bypass system operation is also held constant, but its location nearer the powerhouse than the spillway for most cases reduces its goodness of fit. Turning the behavioral rules off (passive transport) reduces the goodness of fit (slope/R-square) of the spillway to 0.49/0.50, bypass 0.10/0.10, and powerhouse 0.24/0.08 (Goodwin et al. 2006). Improvement in goodness of fit provided by the rules represents the contribution of the behavioral rules towards the quality of predictions.

The 'traffic rule' used by migrants is derived from the context of fluvial geomorphology of free flowing rivers. We describe total flow field distortion using a metric called 'total hydraulic strain' because it describes the underlying distortion mechanisms of (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.

The behavior of migrants can be related to fluid dynamic patterns in free flowing rivers where flow field pattern results from flow resistance. 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. Flow resistance can be separated into two categories for sub-critical, steady flow: friction resistance and form resistance. Friction resistance in 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 interface. Pattern in the total hydraulic strain field is the inverse of pattern in the velocity field, with lowest total hydraulic strain occurring furthest from sources of friction resistance and highest near the sources. Form friction is created by large woody debris or rock outcrops projecting into the channel. As in the case of friction resistance, total hydraulic strain associated with form resistance increases towards the signal source. In contrast to bed friction (where water velocity decreases towards the friction source), 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. A fish approaching a stump from the upstream direction will sense an increase in total hydraulic strain and an increase in water velocity until solid boundary effects very close to the obstruction are encountered. By integrating information between total hydraulic strain and velocity fields, fish have sufficient information to separate channel structures associated with friction or form resistance, thereby creating a hydrodynamic 'image' of their surroundings.

DISCUSSION

The NFS accurately predicted response of fish to the hydrodynamic fields created by different dam designs and operations allowing water resource managers to optimally design bypass systems and take other steps to minimize the impact of water resource development on emigrants. This tool could not have been developed using concepts restricted to either hydraulic engineering or ecology.

ELAMs allow engineering and ecology based approaches to be integrated to address difficult environmental water-related issues. In addition, ELAMs allow both hydraulic engineers and aquatic ecologists to better communicate. ELAMs offer a number of advantages over single framework modeling approaches because of their ability to realistically simulate ecological processes that occur across a wide range of scales. ELAM models allow the three frameworks to be mathematically coupled and conceptually integrated to accurately simulate processes that occur across a wide range of scales typically encountered in ecosystem analysis and simulation.

REFERENCES

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