Simulating Fish Movement In Hydropower Reservoirs and Tailwaters

Understanding how fish will move in response to conditions in their environment is critical to predicting how dam operations or reservoir management will affect fish populations. Researchers have combined physical and chemical reservoir modeling with a fish movement simulation model to predict how aquatic species will redistribute themselves in response to changing reservoir conditions.

By John M. Nestler and R. Andrew Goodwin

Many aquatic species show behavioral responses to changes in hydraulic and water quality patterns in their environment, including changes resulting from the operation of dams and water intakes. These species may move to new habitats in the system, change their depth position, or redistribute themselves in more complex ways.

To predict the effects of operational changes, to design fish passage measures, or to assess other aquatic resource management strategies at hydropower projects, it is necessary to predict the relationship between project design or operation and the movement behavior of fish. This can be viewed as a two-step process. First, the effects of the proposed changes on physical factors directly influencing fish movement, such as hydraulic patterns and water quality, must be identified. Modeling tools for accomplishing this step are well established. The second step, however, is more difficult: accurately predicting fish movement behavior in response to predicted physico-chemical changes.

In the absence of simulation tools for predicting fish response, designers and resource managers often must rely on the inefficient "build, operate, and test" paradigm for implementing changes at hydropower projects. Recently, however, we have developed a model that mathematically simulates movements of individual fish or groups of fish as a result of changes to the aquatic environment. The model was developed at the Engineer Research and Development Center of the U.S. Army Corps of Engineers and has been used to simulate blueback herring movement in a stratified southern impoundment.

John Nestler is a research ecologist and the team leader of the Fisheries Engineering Team at the U.S. Army Engineer Research and Development Center. He was responsible for conceptual development of the fish simulation model described in this article. Andy Goodwin, a PhD graduate student at Cornell University working at the center, developed the fish movement model and display system and calibrated the model.

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Principles of the Model

The model, termed the Coupled Eulerian-Lagrangian (CEL) Hybrid Ecological Model, couples together the kinds of models typically used by engineers (the Eulerian module) with the types of models typically used by biologists (the Lagrangian module). The model was originally developed as a building block for predicting and assessing ecosystem-level effects of reservoirs on aquatic species, particularly large, highly mobile aquatic biota such as fish that are difficult to simulate in typical engineering models. The model provides a way of simulating the movement behavior of aquatic biota, but in an engineering framework.

The model represents individual fish and groups of individuals as individual particles in space.[1] The biological component of the model (the Numerical Fish Surrogate module) is based on a particle-tracking algorithm that moves passive, neutrally buoyant "particles" through the system created by a separate hydrodynamic and water quality simulation model. The particle-tracking algorithm follows rules established by the user regarding a fish's movement response to certain stimuli such as water temperature, depth, current velocity, and the presence of predators or prey.[2,3] This algorithm, enhanced by the stimuli-response rules, can create "virtual fish" capable of making individual movement decisions related to spatial information provided by the hydrodynamic/water quality model. Specifically, the response rules determine the speed and direction of virtual fish movement. The rules are adjusted to accommodate different sizes of fish and changes in swimming speed caused by sub-optimum temperature and dissolved oxygen concentrations.

Appropriate environmental variables to use in developing the stimuli-response rules can be obtained from a variety of sources, including published literature, field data, and experience. The behavioral model is stochastic—that is, it includes a random term whose influence is determined by the strength

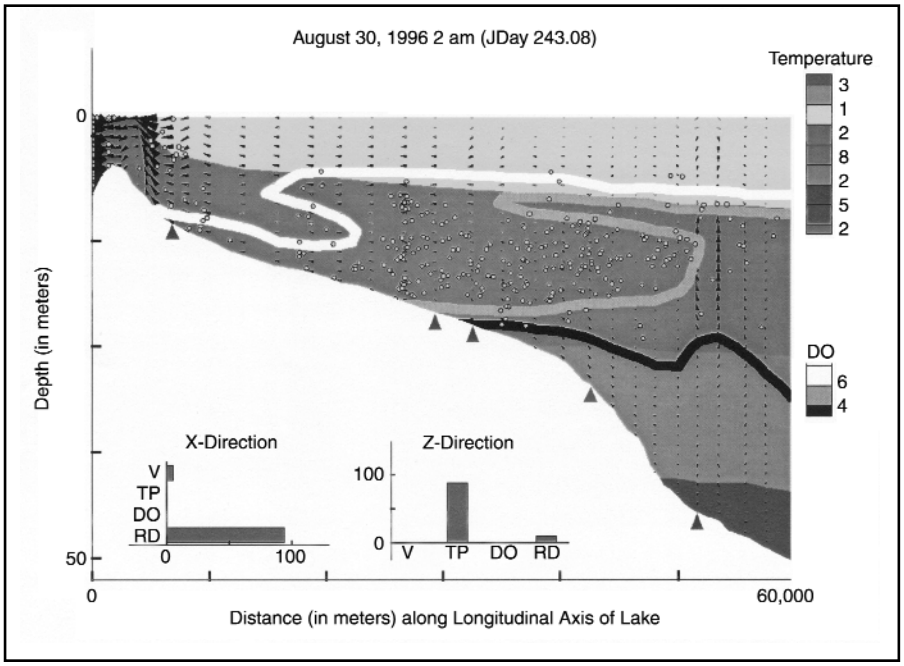

Figure 1: In this image produced by the visualization software developed for the Coupled Eulerian-Lagrangian Hybrid Ecological Model, fish appear as yellow dots, water temperature zones are shown as colored contour fills, and the gray-scaled contour lines represent dissolved oxygen concentrations. The black arrows represent water velocity vectors and the blue and red triangles mark the location of tributaries and cross-sectional area changes, respectively. The charts at the bottom of the figure summarize fish response to environmental factors in each direction.

of the gradient of the selected environmental variables. As the environment becomes more homogeneous, the movement of the virtual fish becomes more random.[4]

Simulating Conditions in J. Strom Thurmond Lake

The initial application of the CEL Hybrid Ecological Model was in a study of the movements of blueback herring in J. Strom Thurmond Lake, a 71,100-acre impoundment on the Savannah River between Georgia and South Carolina. The hydrodynamic and water quality simulation in the study also included an upstream impoundment, the 26,650-acre Richard B. Russell Lake. This portion of the simulation was accomplished by linking an existing model, the CE-QUAL-W2 model developed by the Corps of Engineers, to the biological module.[5] The CE-QUAL-W2 model is a two-dimensional, laterally-averaged, dynamically-linked flow and water quality model. ("Dynamic linking" refers to the updating of water quality as the hydrodynamic computations proceed.)[6]

The upstream boundary of the system simulated with CE-QUAL-W2 is the Corps' Hartwell Dam, a 426-MW hydropower project that discharges into Richard B. Russell Lake. The second dam in the system, Richard B. Russell Dam, was modified to operate as a pumped-storage facility becoming available for operational use in 1996, releasing to and pumping from J. Strom Thurmond Lake. The downstream boundary of the system is Clarks Hill Dam, which impounds J. Strom Thurmond Lake. The model tests used data collected during the full-scale environmental testing of pumped-storage testing that was conducted at Richard B. Russell Dam in 1996.

Water quality and hydrodynamic patterns in J. Strom Thurmond Lake are significantly influenced by operation of Richard B. Russell Dam.[6] In response, blueback herring distribute themselves horizontally and vertically in J. Strom Thurmond Lake. As in many reservoirs, well-oxygenated cool water released from Richard B. Russell Lake, combined with warm stratified conditions in J. Strom Thurmond Lake, may produce seasonal concentrations of blueback herring near the dam.[7] Being able to predict the movement behavior of blueback herring could be a powerful management tool to minimize the effects of operation on this fish species. The methods developed to simulate movement of blueback herring could probably be extended to other species of cool- and cold-water fishes as well.[8]

Testing the Model's Performance

Assessments of the ability of the CEL Hybrid Ecological Model to simulate the movement behavior of blueback herring included the following elements:

— Development of two-dimensional, time-variant sequences of dissolved oxygen, temperature, and water velocity for the CE-QUAL-W2 model domain corresponding to periods in 1996 when hydroacoustic counts of blueback herring in J. Strom Thurmond Lake were made;[6]

— Application of the biological "tracking" model to predict positions of individual virtual fish in J. Strom Thurmond Lake during the same time periods;

— "Virtual hydroacoustic sampling," a computer replication of the actual technique used in the field to determine the numbers and locations of fish in the lake;

— Use of visualization software to display movements of fish along with selected characteristics of the flow and water quality environment (Figure 1), which helped the study team assess whether the virtual fish were responding realistically to changing habitat conditions in the lake; and

— Graphical and statistical analyses of the model's performance relative to field observations.

The behavioral response rules used in the simulation were based on the knowledge of local biologists, qualitative analysis of gillnet samples, and observations about the behavior of the fish made by field crews working at the project.

Distributions of blueback herring, as obtained from the actual and virtual hydroacoustic surveys, were compared in both the longitudinal and vertical directions. The vertical distribution of fish within a managed water body is important to biologists and water resource managers because the operation of dams and reservoirs affects the vertical stratification of lakes. Changes to a lake's stratification may constrain the distribution of fish, affect the overlap in time and space between predators and prey, and possibly reduce the access of planktivorous fish, such as blueback herring, to zooplankton.[9]

The vertical distributions of blueback herring over the length of the lake obtained from virtual sampling of the model results and from field sampling conducted on several days in August 1996 are shown in Figure 2.

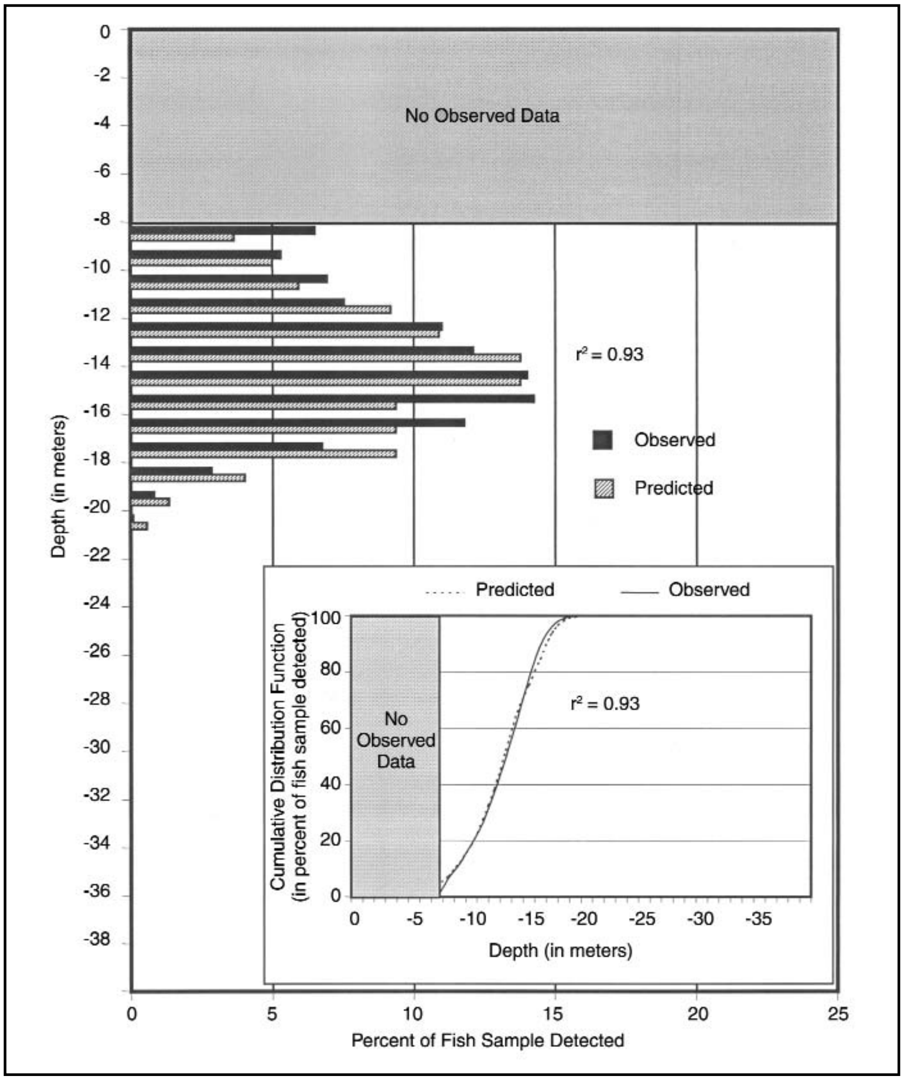

Figure 2: This chart shows the vertical distribution of blueback herring in J. Strom Thurmond Lake as detected by actual hydroacoustic surveys (dark bars) and by the simulated fish movement and hydroacoustic sampling (light bars). No useable data were available for the top 8 meters of the lake. The cumulative curve (inset) shows that the simulation follows the actual observations closely. The departure near the base of the curve is due to the fact that the model included the upper level of the lake and the field sampling did not.

The cumulative distribution plot shows that the actual and simulated distributions are similar, with the main discrepancies occurring near the maximum and minimum depths sampled. The largest discrepancy occurs near the water surface, and is probably attributable to the lack of useable field data near the water surface.

The longitudinal distribution of species within a managed water body is important because the operation of dams and reservoirs affects certain areas more than others. In order to assess whether operational changes will affect the population, fisheries managers need to know the location of fish species in terms of distance from the dam.

Figure 3 shows the longitudinal distribution of simulated and actual blueback herring in 5-kilometer segments of J. Strom Thurmond Lake. No hydroacoustic data are available for the area near Richard B. Russell Dam. The CEL Hybrid Ecological Model reproduced the longitudinal distribution of blueback herring sampled in August 1996 well. However, the simulated distribution departs from the observed one about 15 to 25 kilometers from Richard B. Russell Dam. Zooplankton abundance is often high in this part of the lake, suggesting that a variable not modeled, zooplankton abundance, may be causing the difference between predicted and observed fish distributions 15 to 25 kilometers downstream of the dam.

Implications for Reservoir and Fish Management

The close similarity between the CEL Hybrid Ecological Model's predicted distributions of blueback herring and those observed during actual hydroacoustic sampling are encouraging with respect to the future use of the model in management decisions. The model also can be used to make better use of field data that often include fish distribution data but seldom include detailed, concurrent information on water quality and hydraulic patterns. In the study of J. Strom Thurmond Lake, the model provided detailed patterns of water quality and hydraulics to supplement fish distribution data. The study team was then able to use the model to explore and refine the relationships between reservoir operation and fish distribution by iteratively modifying the behavior rules until the model gave a good fit between predicted and observed data. This approach helps to supplement and verify more traditional statistical methods for relating fish distribution to environmental variables.

In particular, an improved understanding of blueback herring movement behavior at dams would have immediate ecological and economic implications. Herring and similar species, such as alewives, are observed near many dams in great numbers during both pumping and release operations. Being able to understand and predict conditions that attract fish to these areas is critically important in managing the effects of hydropower projects.

Learning from Analytical Simulation of Fish Behavior

The Coupled Eulerian-Lagrangian Hybrid Ecological Model provides a systematic framework for integrating biological knowledge and field experience into physical and water quality models commonly used by engineers. The tests of the model described in this article show that an engineering simulation approach coupled to a biological movement model can successfully reproduce the spatial distribution of fish in a complex and dynamic environment. Future work will add feedbacks between the biological and engineering modules, and also will add population dynamics to the biological module.

Although the initial application focused on one fish species and a limited number of environmental variables (flow, dissolved oxygen, and temperature), a similar approach could be used

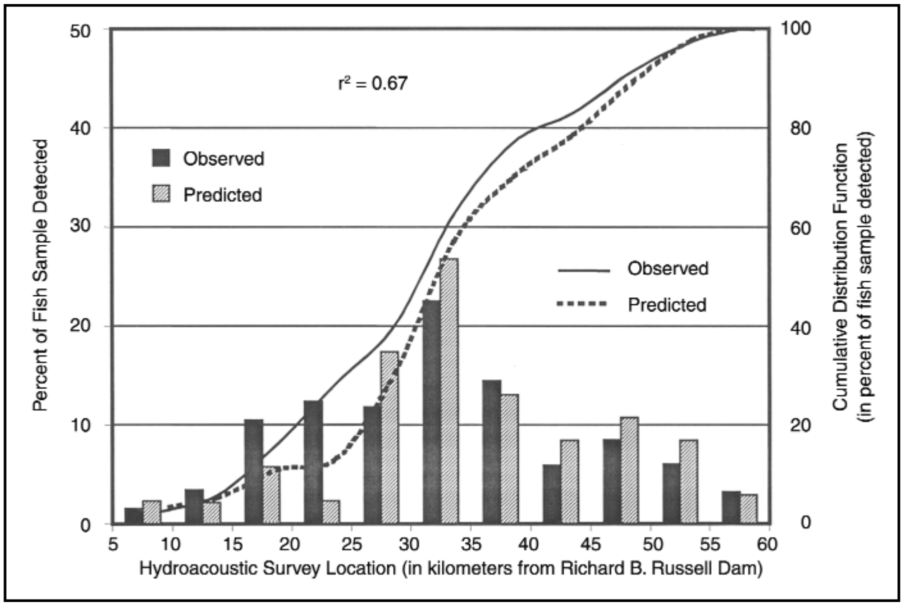

Figure 3: The model reproduced the longitudinal distribution of blueback herring in J. Strom Thurmond Lake well, except in a reach between 15 and 25 kilometers from Richard B. Russell Dam. In this reach, availability of zooplankton, which was not one of the variables considered in the model, may have been the cause of the discrepancy between the simulation and field observations.

to simulate the movement behavior of other species of fish responding to other stimuli in their environment.

There will always be shortcomings and inaccuracies involved in representing an infinitely complex dynamic behavioral system using finite means. However, the model investigations show considerable promise for the systematic and realistic simulation of how large projects can affect the physico-chemical environment and how valuable aquatic species may redistribute in response. ■

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Notes:

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