Simulating Movement of Highly Mobile Aquatic Biota: Foundation for Population Modeling in an Ecosystem Context

by John M. Nestler, R. Andrew Goodwin, and Lillian Toney

PURPOSE: This technical note describes an approach for incorporating population dynamics into ecosystem-level assessments. The tool described herein is termed the Coupled Eulerian-Lagrangian (CEL) Hybrid Ecological Model. The CEL Hybrid Ecological Model couples the kinds of models typically used by engineers (the Eulerian module) with the types of models typically used by biologists (the Lagrangian module). The CEL Hybrid Ecological Model can be applied singly or in concert with other tools and methods that describe the physical environment and hydro-biogeochemical processes having ecosystem significance.

INTRODUCTION: The Corps of Engineers is required to address ecosystem-level impacts and to develop plans that guarantee sustainable development. Many important 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 in more complex ways.

To predict the effects of operational changes, to design fish passage measures, or to assess aquatic resource management strategies at Corps projects, it is necessary to predict the relationship between project design or operation and the movement behavior of highly mobile aquatic biota, such as fish. Most critically, simulating the movement behavior of aquatic biota is necessary to link population biology to ecosystem processes. This linkage can be used to integrate population models and engineering models so that population level dynamics can be viewed in an ecosystem context. The linkage 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. Second, however, is a more difficult step: 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 have to rely on the inefficient "build, operate, and test" paradigm for implementing changes at projects.

PRINCIPLES OF THE MODEL: The CEL Hybrid Ecological Model was originally developed as a building block for predicting and assessing ecosystem level impacts 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 (Matuda, Liang, and Sannomiya 1993). 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 (Okubo 1980, Parrish and Turchin 1997).

The particle-tracking 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 rules were initially based on the knowledge of local biologists, qualitative analysis of gillnet samples, and observations about the behavior of the fish observed by field crews working at the project. The behavioral model is stochastic; that is, it includes a random term whose influence is determined by the inverse of the strength of the gradient of the selected environmental variables. As the environment becomes more homogeneous, the movement of the virtual fish becomes more random. Details of the model can be found in Goodwin, Nestler, Loucks, and Chapman (2001), and Nestler et al. (2002).

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 (Figure 1). 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 developed by the Corps, CE-QUAL-W2, to the biological module. The CE-QUAL-W2 model is a two-dimensional, laterally averaged, dynamically linked (meaning that water quality is updated as the hydrodynamics are updated) flow and water quality model (Cole and Buchak 1995).

The upstream boundary of the system simulated with CE-QUAL-W2 is Hartwell Dam, another Corps hydropower project having a capacity of 426 megawatts, which 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. This study uses data collected during the full-scale environmental testing of pump-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 (Cole and Tillman 1996). 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 (Isely 1996). Being able to predict the movement of blueback herring could be a powerful management tool to minimize the effects of operation on this fish

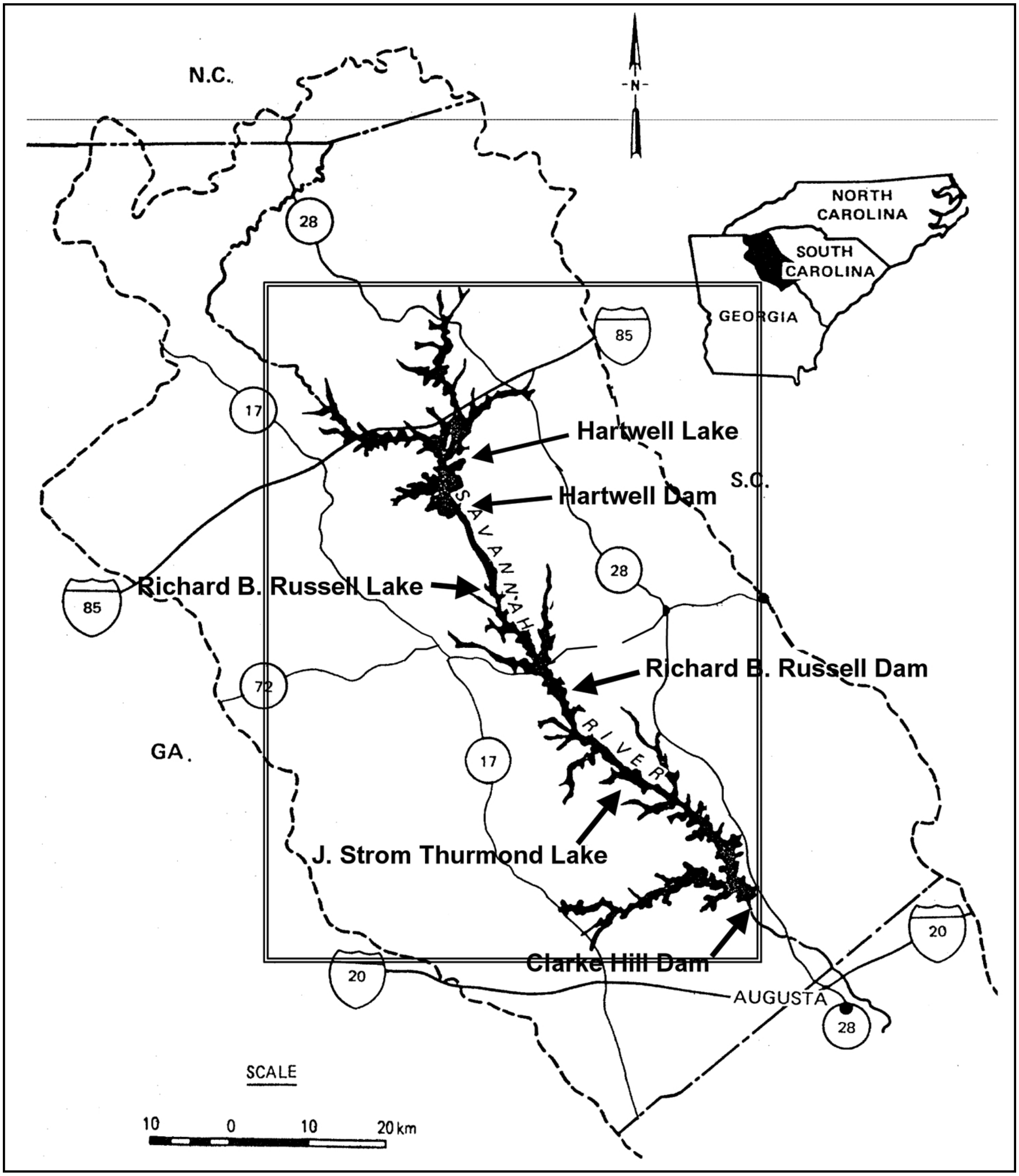

Figure 1. Area modeled by CE-QUAL-W2 in J. Strom Thurmond and Richard B. Russell Lakes

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.

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:

- Developing 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 (Cole and Tillman 1996).
- 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 2), which helped the study team assess whether the virtual fish were responding realistically to changing habitat conditions in the lake.
- Graphical and statistical analyses of the model's performance relative to field observations.

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 (Stockwell and Johnson 1997).

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 3. The cumulative distribution in Figure 3 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 4 shows the longitudinal distribution of simulated and actual blueback herring in 5-km segments of J. Strom Thurmond Lake. No hydroacoustic data are available for the area near

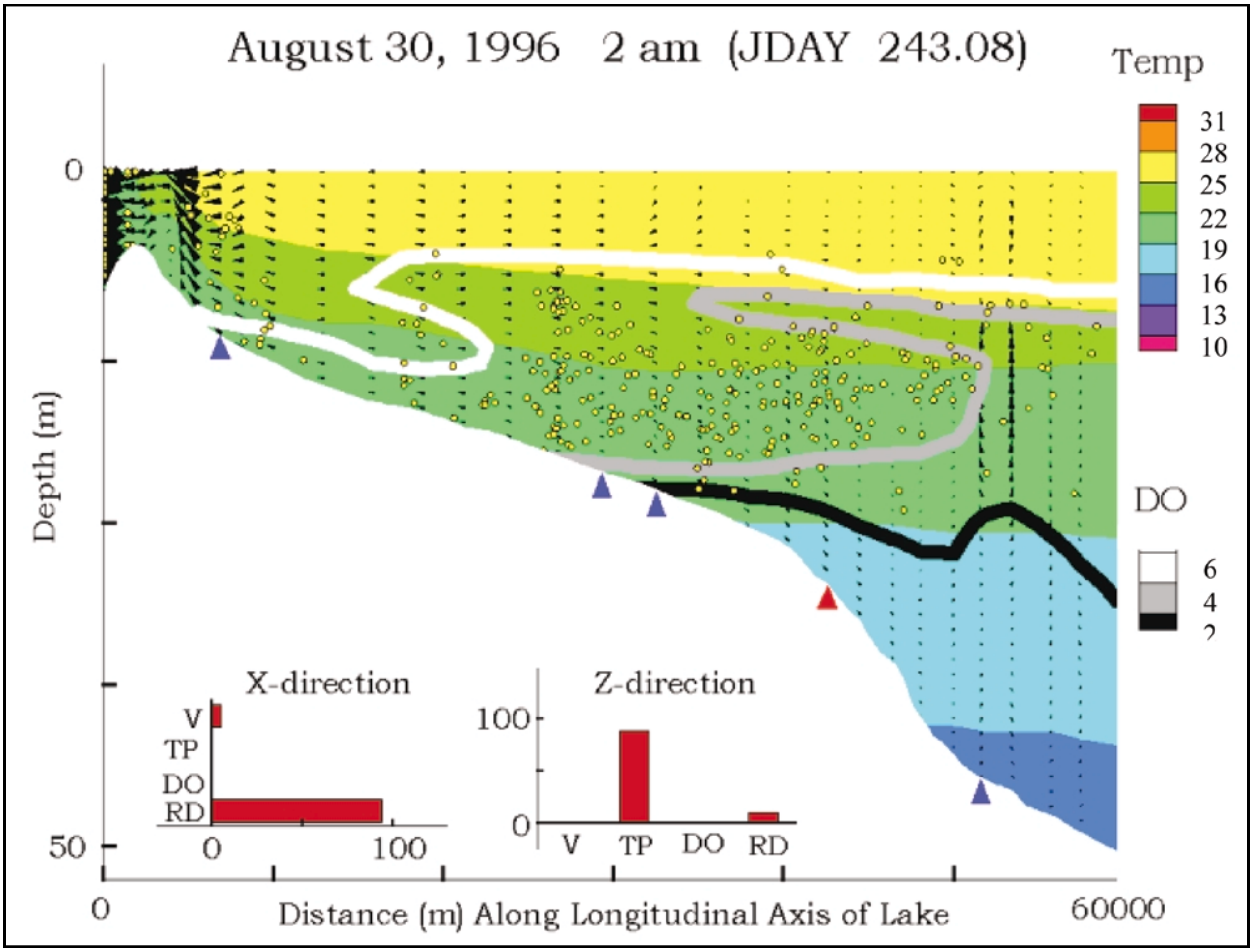

Figure 2. In this image, produced by the visualization software developed for the CEL Hybrid Ecological Model, fish appear as yellow dots, water temperature zones are shown as colored contour fills, and the gray-scaled contour lines represent dissolved oxygen concentrations. The black arrows represent 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, where V = velocity, TP = temperature (centigrade), DO = dissolved oxygen (mg/l), and RD = random

Richard B. Russell Dam. The CEL Hybrid Ecological Model accurately reproduced the longitudinal distribution of blueback herring sampled in August 1996. However, the simulated distribution departs from the observed one about 15 to 25 km 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 15-25 km downstream of the dam. The model placed virtual blueback herring in the appropriate proportions in two-dimensional space, with the exception of the reaches between 15 and 25 km downstream of Richard B. Russell 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 is encouraging with respect to future use of the model in management decisions. The model also makes better use of field data that often include fish distribution data but seldom include detailed, concurrent information on water

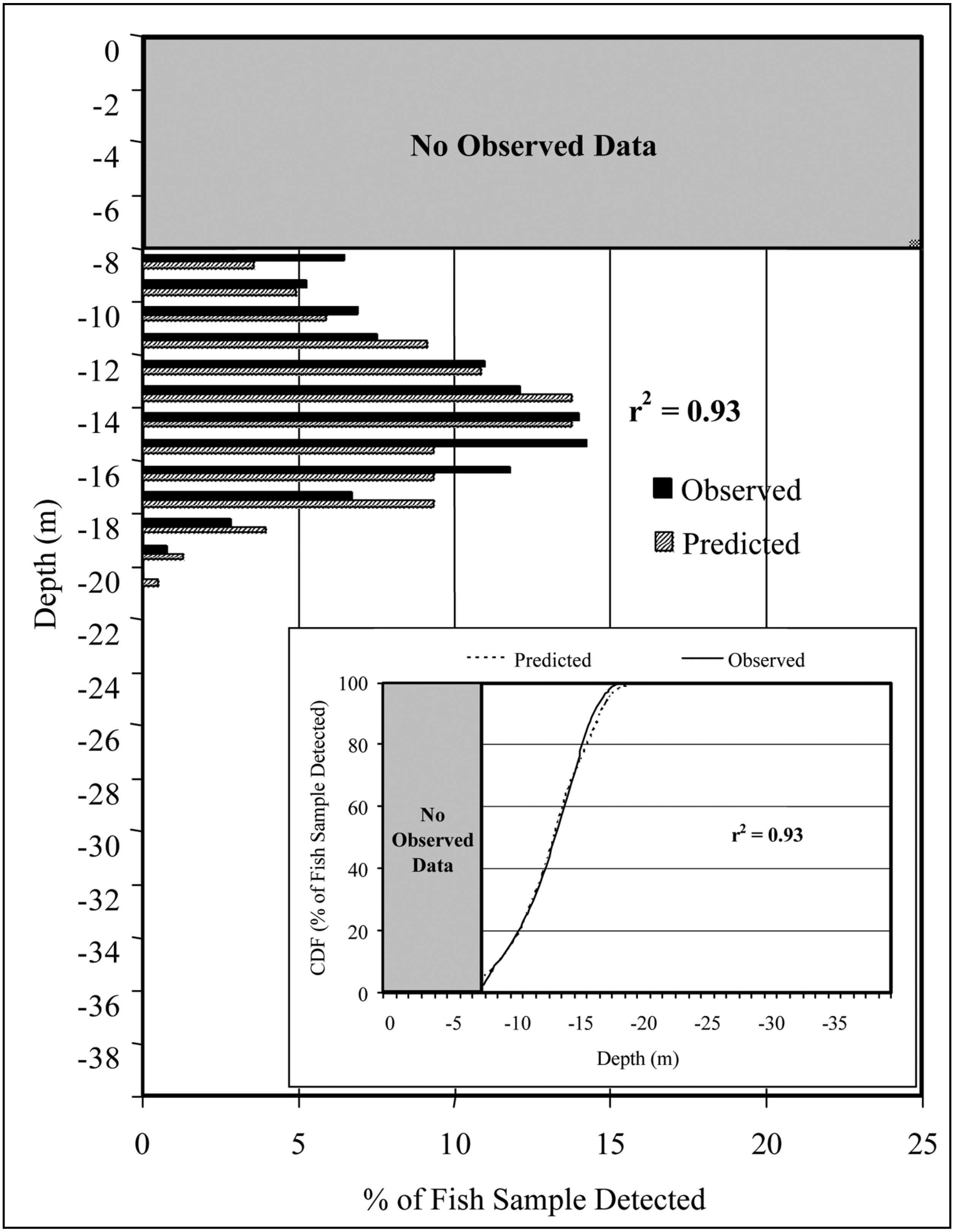

Figure 3. Vertical distribution of blueback herring in J. Strom Thurmond Lake as detected by actual hydroacoustic surveys (dark bars) and by simulated fish movement and hydroacoustic sampling (light bars). No useable data were available for the top 8 m of the lake

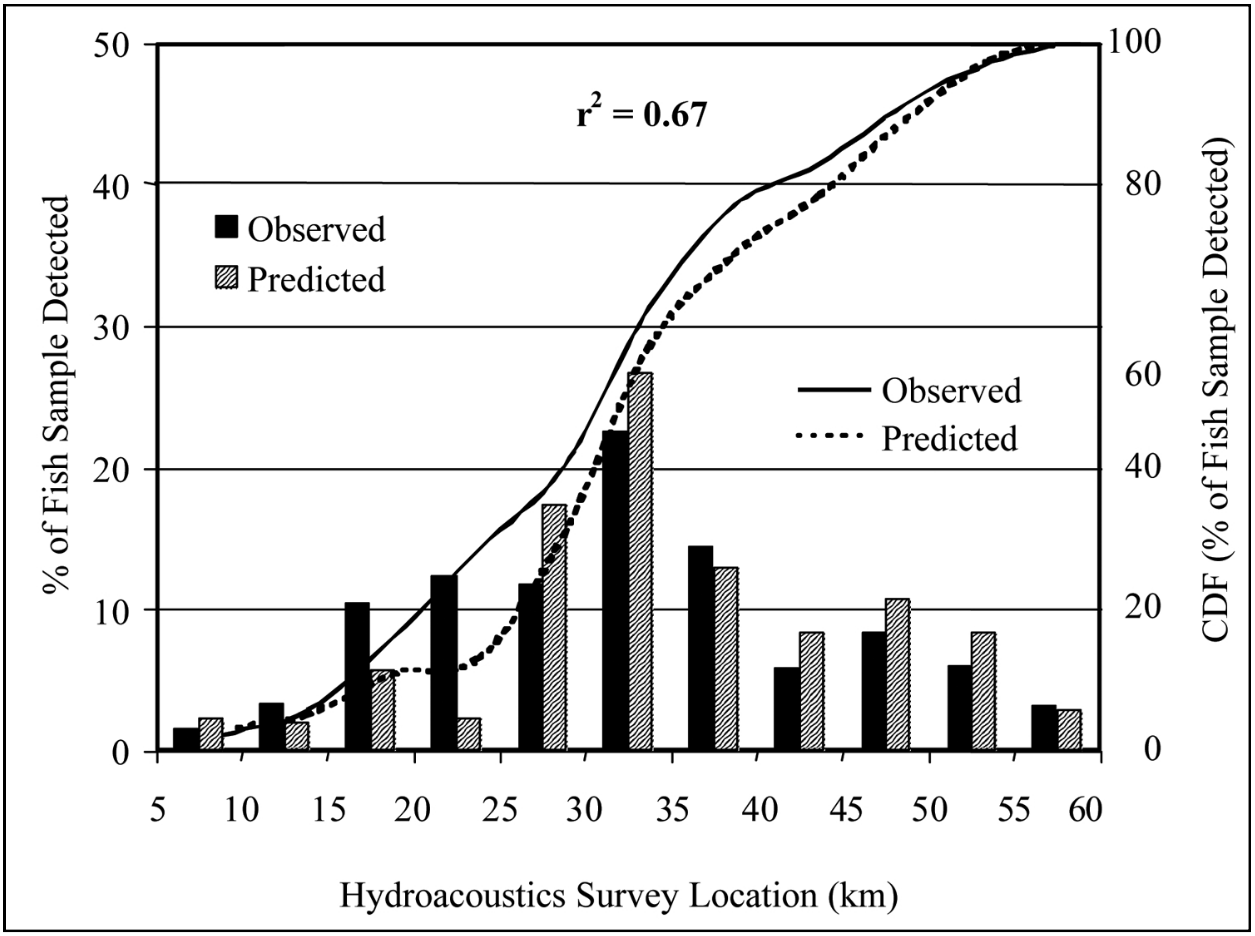

Figure 4. The model reproduced the longitudinal distribution of blueback herring in J. Strom Thurmond Lake well, except in a reach between 15 and 25 km from Richard B. Russell Dam

quality and hydraulic patterns. In the case described here, the model provided the detailed patterns in water quality and hydraulics to supplement fish distribution data. The model was used to explore and refine the relationships between reservoir operation and fish distribution by iteratively modifying the behavior rules until a good fit was obtained between predicted and observed data. Such an approach is also a good supplement to and test of 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 impacts of hydropower projects. However, of greatest significance, CEL Hybrid Ecological models offer a means to link the physico-chemical environment to population dynamics of highly mobile aquatic biota such as fishes, large macroinvertebrates (shrimp and crabs), and other species that require access to and move between spatially distributed habitats. These highly mobile species are often of commercial or sport fishing importance or are keystone species whose activities affect the rest of the aquatic ecosystem. This linkage can, in turn, be the foundation for integrating the physico-chemical changes in the environment typically caused by Corps activities into impact predictions based on population modeling. That is, the linkage can serve as a means of describing and predicting population impacts at an ecosystem level.

LEARNING FROM SIMULATION OF FISH BEHAVIOR: The CEL 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 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 to simulate the movement behavior of other species of fish responding to other stimuli in their environment. There will always be shortcomings and inaccuracies in representing a 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.

SUMMARY: To predict the effects of operational changes, to design fish passage measures, or to assess aquatic resource management strategies at Corps projects, it is necessary to predict the relationship between project design or operation and the movement behavior of highly mobile aquatic biota, such as fish. One approach for incorporating population dynamics into ecosystem-level assessments is the Coupled Eulerian-Lagrangian (CEL) Hybrid Ecological Model. This model couples the kinds of models typically used by engineers with the types of models typically used by biologists. The CEL Hybrid Ecological Model was applied 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. There was close similarity between the CEL Hybrid Ecological Model's predicted distributions of blueback herring and those observed during actual hydroacoustic sampling. The model provided detailed patterns in water quality and hydraulics to supplement fish distribution data. The model was also used to explore and refine the relationships between reservoir operation and fish distribution by iteratively modifying the behavior rules until a good fit between predicted and observed data was obtained. 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 as well as add population dynamics to the biological module.

ACKNOWLEDGEMENTS: The work was performed under the Corps of Engineers Ecosystem Management and Restoration Research Program and the Richard B. Russell Dam Fish Entrainment Study by the U.S. Army Engineer Research and Development Center, Waterways Experiment Station, in Vicksburg, Mississippi. Permission was granted by the Chief of Engineers to publish this information.

POINTS OF CONTACT: This technical note was prepared by the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Waterways Experiment Station (WES), Vicksburg, MS. This study forms part of the Ecosystem Management and Restoration Research Program (EMRRP) Work Unit 33067 and the Richard B. Russell Dam Fish Entrainment Study(RBRFES). The EMRRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Dr. Russell F. Theriot, EL, is the Program Manager for the EMRRP. The RBRFES is sponsored by Savannah District, U.S. Army Corps of Engineers.

This report was written by Dr. John M. Nestler, Water Quality and Contaminant Modeling Branch (WQCMB), Mr. R. Andrew Goodwin, Graduate Student at Cornell University, and Ms. Lillian Toney, also of the WQCMB, under the general supervision of Dr. Mark S. Dortch, Chief, WQCMB; Dr. Richard E. Price, Chief, Ecosystems Processes and Effects Division (EPED), EL; and Dr. Edwin Theriot, Acting Director, EL. At the time of publication of this report, Dr. Jim Houston was the Director of ERDC, and COL John Morris was Commander.

This technical note should be cited as follows:

> Nestler, J. M., Goodwin, R. A., and Toney, L. (2002). "Simulating movement of highly mobile aquatic biota: Foundation for population modeling in an ecosystem context," *EMRRP Technical Notes Collection* (ERDC TN-EMRRP-EM-02), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/emrrp*

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