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Forecasting 3-D fish movement behavior using a Eulerian–Lagrangian–agent method (ELAM)

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Abstract

We describe a Eulerian–Lagrangian–agent method (ELAM) for mechanistically decoding and forecasting 3-D movement patterns of individual fish responding to abiotic stimuli. A ELAM model is an individual-based model (IBM) coupling a (1) Eulerian framework to govern the physical, hydrodynamic, and water quality domains, (2) Lagrangian framework to govern the sensory perception and movement trajectories of individual fish, and (3) agent framework to govern the behavior decisions of individuals. The resulting ELAM framework is well suited for describing large-scale patterns in hydrodynamics and water quality as well as the much smaller scales at which individual fish make movement decisions. This ability of ELAM models to simultaneously handle dynamics at multiple scales allows them to realistically represent fish movements within aquatic systems. We introduce ELAMs with an application to aid in the design and operation of fish passage systems in the Pacific Northwest, USA.

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Individual virtual fish make behavior decisions about every 2.0 s. These are sub-meter to meter-scale movements based on hydrodynamic stimuli obtained from a hydraulic model. Movement rules and behavior coefficients are systematically adjusted until the virtual fish movements approximate the observed fish.

The ELAM model introduced in this paper is called the Numerical Fish Surrogate. It facilitated the development of a mechanistic biological-based hypothesis describing observed 3-D movement and passage response of downstream migrating juvenile salmon at 3 hydropower dams on 2 rivers with a total of 20 different structural and operational configurations. The Numerical Fish Surrogate is presently used by the U.S. Army Corps of Engineers and public utility districts during project planning and design to forecast juvenile salmon movement and passage response to alternative bypass structures.

Keywords: Fish; Movement rules; Individual-based model; Eulerian; Lagrangian; Agent; Behavior

1. Introduction

Understanding movements of individuals is important for understanding population dynamics (Turchin, 1998). Identifying underlying mechanisms that influence spatial patterns in populations improves forecasts (Harte, 2002) of alternative management strategies on the spatial dynamics of populations critical for assessing and managing fisheries (Schmalz et al., 2002; Pelletier and Parma, 1994) and improving water resource management (Van Winkle et al., 1993). In many systems, the spatial pattern of individuals is driven by environmental factors (Pientka and Parrish, 2002), which can be evaluated separately from biological interactions (Hussko et al., 1996; Pientka and Parrish, 2002).

The need to understand fish movements is particularly acute in the Columbia–Snake River system in the Pacific Northwest of the Unites States where tens of millions of juvenile salmon and steelhead (migrants) migrate downstream through eight dams. This migration consists of dozens of runs, of which 12 are listed under the Endangered Species Act. Since migrants passing through turbines may experience significant mortality (5–15%) research efforts over several decades have been devoted to diverting migrants over spillways and through bypass systems. However, bypass systems have achieved only limited and variable success (Coutant and Whitney, 2000) at considerable cost. Anderson (1988) first proposed using hydrodynamic and behavior information to design bypass systems. Anderson (1991) introduced the first such mathematical model. However, until recently no model has been sufficiently accurate to be of value in engineering design of bypasses.

Tools needed to understand and model fish movements in response to environmental cues are now available. Advances in telemetry (e.g., Steig, 1999; Gerolotto et al., 1999; Johnson et al., 1999; Lucas and Baras, 2000) can provide high-resolution 3-D tracks of individual movements. Computational fluid dynamics (CFD) models can now describe hydrodynamic patterns at scales meaningful to fish, and laboratory studies have defined many sensory abilities of fish to distinguish elements of hydrodynamic fields (e.g., Coombs et al., 2001; Kröther et al., 2002). However, mathematical methods linking fish trajectories to hydrodynamic patterns in terms of fish sensory and behavioral elements remain a challenge (Steel et al., 2001). We describe an integrated mathematical method that couples a (1) Eulerian framework for describing the physical and hydrodynamic domain of a hydropower dam forebay, (2) Lagrangian framework for describing the sensory perception and movement trajectories of individual fish, and (3) agent framework for describing the changes in swimming behavior of individual fish responding to stimuli. Together these coupled elements comprise a Eulerian–Lagrangian–agent method (ELAM) model to mechanistically decode and forecast movement of downstream outmigrating juvenile salmon (migrants) as they approach and pass hydropower dams of the Columbia and Snake Rivers of the Pacific Northwest.

2. Model overview

2.1. *Describing hydrodynamic pattern with the Eulerian framework*

Understanding migrant responses to hydrodynamic patterns close (<10 m) to a bypass entrance is critical