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Development of a Fluvial Egg Drift Simulator to evaluate the transport and dispersion of Asian carp eggs in rivers

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ABSTRACT

Asian carp are migrating towards the Great Lakes and are threatening to invade this ecosystem, hence there is an immediate need to control their population. The transport of Asian carp eggs in potential spawning rivers is an important factor in its life history and recruitment success. An understanding of the transport, development, and fate of Asian carp eggs has the potential to create prevention, management, and control strategies before the eggs hatch and develop the ability to swim. However, there is not a clear understanding of the hydrodynamic conditions at which the eggs are transported and kept in suspension. This knowledge is imperative because of the current assumption that suspension is required for the eggs to survive. Herein, FluEgg (Fluvial Egg Drift Simulator), a three-dimensional Lagrangian model capable of evaluating the influence of flow velocity, shear dispersion and turbulent diffusion on the transport and dispersal patterns of Asian carp eggs is presented. The model's variables include not only biological behavior (growth rate, density changes) but also the physical characteristics of the flow field, such as mean velocities and eddy diffusivities. The performance of the FluEgg model was evaluated using observed data from published flume experiments conducted in China with water-hardened Asian carp eggs as subjects. FluEgg simulations show a good agreement with the experimental data. The model was also run with observed data from the Sandusky River in Ohio to provide a real-world demonstration case. This research will support the identification of critical hydrodynamic conditions (e.g., flow velocity, depth, and shear velocity) to maintain eggs in suspension, assist in the evaluation of suitable spawning rivers for Asian carp populations and facilitate the development of prevention, control and management strategies for Asian carp species in rivers and water bodies.

1. Introduction

Asian carp are invasive species whose populations have surged exponentially in the Mississippi River Basin (Kolar et al., 2007; Chick and Pegg, 2001; Sampson et al., 2009; DeGrandchamp, 2006; Chapman and George, 2011a). Efforts are being made to keep Asian carp from migrating into and establishing a successful recruiting population in the Great Lakes Basin where they may cause ecological and economic damage. These efforts to control Asian carp populations include, but are not limited to: poisoning, commercialization and exportation of Asian carp for food, electrofishing, and netting. An important factor in controlling Asian carp is understanding its spawning processes and early life stages behavior. To assess the risk of spawning and successful recruitment, the required hydraulic and water-quality conditions must be understood.

In Asia, Asian carp commonly spawn in the spring and early summer (Kolar et al., 2007; Peh-Lu and Liang, 1964; Jennings, 1988). Spawning initiates when water levels rise (which reflects an increase in flow velocity) during rainy seasons (Peh-Lu and Liang, 1964). One of the most important factors affecting spawning of Asian carp is water level fluctuation (Stainbrook et al., 2007; Jennings, 1988; Duan et al., 2009; Schrank et al., 2011; Yih and Liang, 1964). Other important factors are turbulence (presence of eddies and bubbles), flow velocity, temperature, and turbidity (Yih and Liang, 1964; Yi et al., 2010; Peh-Lu and Liang, 1964). The spawning grounds are normally located in mixing waters such as river confluences, rock rapids, behind sandbars, and stonebeds or islands, where bubbles and eddies are present (Jennings, 1988; Kolar et al., 2007; Yih and Liang, 1964; Peh-Lu and Liang, 1964).

Asian carp eggs are semibuoyant drifting eggs and are thought to have to be in suspension in order to hatch (Chapman, 2006; Jennings, 1988; Kolar et al., 2007; Yi et al., 2010). The near-neutral

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buoyancy of each egg is due to the increase in volume and decrease in both density and fall velocity caused by the large amount of water absorbed by the egg after deposition (Jennings, 1988; Chapman and George, 2011a). After this process the eggs are referred to "water hardened". It is thought that Asian carp eggs may die when they sink to the bottom of a river (Aitkin et al., 2008; Lohmeyer, 2008; Yi et al., 2010; Kolar et al., 2007; Rach et al., 2010; Chapman and Deters, 2009; Jennings, 1988; Whittier and Aitkin, 2008; Peh-Lu and Liang, 1964; Chapman and George, 2011a). However, there is no clear understanding of what ultimately causes the death of carp eggs when they sink to the riverbed; possible reasons include: lack of oxygen when buried by sediments, damage incurred by hitting the bottom, or predation by organisms that live on or near the bottom (Kolar et al., 2007; Rach et al., 2010; Garvey, 2007).

Current assessments of potential recruitment success are made based mainly on river temperature, velocity, and undammed river length (Kocovsky et al., 2012; Kolar et al., 2007). However, conclusions regarding potential recruitment success require a more critical assessment based on predictions made from a reasonable amount of data characterizing the river and its variability in flow and depth over the study reach. In addition, the estimation of spawning times and location has been limited to an assessment based solely on developmental stage of field-sampled eggs, temperature and mean water velocity (Deters et al., 2013). Managers and stakeholders need to employ the best methods available to make informed decisions for controlling undesirable aquatic invasive species in rivers and other bodies of water in North America. Assessing potential spawning in Great Lake tributaries requires a thorough understanding of the transport and dispersal patterns of Asian carp eggs.

The understanding of spawning behavior and transport and dispersion of Asian carp eggs has the potential to create prevention, management, and control strategies before the eggs hatch and develop into larvae. This is imperative due to the exponential reproduction rates (Kolar et al., 2005; Chick and Pegg, 2001; DeGrandchamp, 2006; Chapman and George, 2011a) and the fact that Asian carp can spawn up to three times a year (Ruebush, 2011). Transport of eggs and fish in the early stages of development is considered an important factor in life history and recruitment success of many species (Hinckley et al., 1996; Parada et al., 2003). The study of the transport and dispersion of eggs would enable the estimation of minimum river lengths for recruitment, give information regarding the trajectories of single carp individuals and mass of eggs transported from spawning areas to nursery areas and identify the effects of physical and biological factors on the dynamics of Asian carp populations.

The main objective of this study was to develop a tool capable of evaluating the influence of flow velocity, shear velocity and turbulent diffusion on the transport and dispersal patterns of Asian carps eggs. The key goal was to understand how Asian carp drifting eggs are kept in suspension and transported by hydrodynamic characteristics of the flow and how the eggs' physical properties influence their drifting behavior. To this end, a Lagrangian numerical model, including biotic and abiotic characteristics that affect the transport and dispersion of Asian carp eggs was formulated and used. This model, Fluvial Egg Drift Simulator (FluEgg), not only can be used as a tool to evaluate the transport of Asian carp eggs but also to simulate the transport of eggs of other fish species, or to assess the transport of other passive particles. FluEgg is an Individual Based Model (IBM) that tracks individual virtual eggs as they drift through the current during their first life stages before hatching.

The performance of FluEgg was evaluated using data from published flume experiments previously conducted by Tang et al. (1989). In these laboratory experiments the authors placed water-hardened Asian carp eggs in the upstream portion of a flume and allowed the eggs to drift. Egg vertical concentration distribution was measured using a stratified egg collector sampling device. Egg vertical concentrations obtained from FluEgg simulations of the experimental flume are compared against data collected by Tang et al. (1989). Additionally, an application of the FluEgg model is presented for the Sandusky River in Ohio. This simulation was run with hydrodynamic and water-quality data collected by the U.S. Geological Survey (USGS) in September 2012.

2. Materials and methods

FluEgg is a Lagrangian model developed to study the transport and dispersal patterns of Asian carp eggs. Lagrangian models have been widely used in oceanography with applications of individual-based models in biophysical modeling of the early life history of fish eggs and larvae (Brickman and Smith, 2002; Pedersen et al., 2003; Lett et al., 2008; Parada et al., 2003; Tian et al., 2009; Huret et al., 2007; Davidson and Deyoung, 1995). FluEgg uses random walk and random displacement techniques to simulate the turbulent diffusion phenomena that contribute to eggs movement. Changes in the biological characteristics of eggs (e.g., diameter and egg density) are embedded into the model through a user-defined growth function. FluEgg treats the mass of eggs as discrete particles. At each time step the movement of each particle consists of an advective, deterministic component and a diffusive, stochastic component. This approach is an effective way to describe the movements of Asian carps eggs because the eggs are live particles that move with the turbulent flow field. FluEgg is a tool for prediction, control and management of early life stages of Asian carp eggs. The model description follows the ODD (Overview, Design concepts and Details) protocol (Grimm et al., 2006).

2.1. Purpose

The purpose of FluEgg is to understand how the transport of eggs is influenced not only by biological characteristics such as growth rate, diameter and density, but also by the hydrodynamics and environmental characteristics of the waterbody in which they are drifting. The most important environmental and hydrodynamic variables that drive egg transport processes are advection, shear dispersion, and turbulent diffusion. FluEgg can be used to evaluate how these variables will affect the concentration distribution of the eggs, and provide information regarding the longitudinal, lateral and vertical concentration distribution of eggs downstream of spawning grounds. This information may give insight into the potential recruitment success of eggs. Higher percentage of eggs in suspension are associated with higher probability of survival and recruitment success. The knowledge gained from this study will enable the identification of critical hydrodynamic conditions under which the eggs at different developmental stages remain in suspension, including shear velocities, residence time and travel lengths required for successful egg development.

2.2. State variables and scales

FluEgg includes virtual individuals (eggs) and fluvial environmental and hydraulic characteristics. Virtual eggs are characterized by the state variables: age [h], diameter [mm], egg density [kg/m^3], and location (x, y and z) all in [m]. The fluvial environmental and hydraulic state variables include: water temperature [$^\circ$C], flow discharge [m^3/s], water depth [m], shear velocity [m/s], lateral velocity [m/s], and vertical velocity [m/s]. The fluvial environmental and hydraulic state variables are prescribed in the model by the user with a one-dimensional discrete series of cells. Cell dimensions are defined by the cell hydraulic width, length and water depth. Cell length depends on the availability of data for the water body and on the complexity of the system (see Fig. 1). Fluvial state variables