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Application of the FluEgg model to predict transport of Asian carp eggs in the Saint Joseph River (Great Lakes tributary)

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ABSTRACT

The Fluvial Egg Drift Simulator (FluEgg) is a three-dimensional Lagrangian model that simulates the movement and development of Asian carp eggs until hatching based on the physical characteristics of the flow field and the physical and biological characteristics of the eggs. This tool provides information concerning egg development and spawning habitat suitability including: egg plume location, egg vertical and travel time distribution, and egg-hatching risk. A case study of the simulation of Asian carp eggs in the Lower Saint Joseph River, a tributary of Lake Michigan, is presented. The river hydrodynamic input for FluEgg was generated in two ways — using hydroacoustic data and using HEC-RAS model data. The HEC-RAS model hydrodynamic input data were used to simulate 52 scenarios covering a broad range of flows and water temperatures with the eggs at risk of hatching ranging from 0 to 93% depending on river conditions. FluEgg simulations depict the highest percentage of eggs at risk of hatching occurs at the lowest discharge and at peak water temperatures. Analysis of these scenarios illustrates how the interactive relation among river length, hydrodynamics, and water temperature influence egg transport and hatching risk. An improved version of FluEgg, which more realistically simulates dispersion and egg development, is presented. Also presented is a graphical user interface that facilitates the use of FluEgg and provides a set of post-processing analysis tools to support management decision-making regarding the prevention and control of Asian carp reproduction in rivers with or without Asian carp populations.

Introduction

Asian carp (primarily silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*)) continue to cause ecological and economic damage throughout the Mississippi River Basin. Because of encroaching migration, it is feared that they could enter and establish a population in the Great Lakes Basin. To prevent Asian carp from establishing a breeding population, it is important to identify tributaries that are suitable to support Asian carp reproduction and potential recruitment. The number of suitable spawning tributaries is one of the important factors in increasing the probability of Asian carp establishment in the Great Lakes (Cuddington et al., 2013). The number of suitable spawning tributaries affects the probability of fish finding both mates and a tributary with sufficient turbulence and water temperature to support successful recruitment (Cuddington et al., 2013). Previous studies have identified suitable spawning rivers with a first-order assessment based on estimated river temperature and velocity, and undammed river length (Kolar et al., 2007; Kocovsky et al., 2012). Murphy and Jackson (2013) evaluated the shear velocity (an indicator of turbulence) and the egg settling velocity and travel times to assess the potential of Asian carp spawning and successful recruitment in four tributaries of the Great Lakes (Milwaukee, Saint Joseph, Maumee, and Sandusky Rivers). However, more accurate analyses of tributaries suitable for spawning and successful recruitment should be based on predictions made from a holistic assessment incorporating river hydrodynamics, water temperature, and egg development dynamics (Garcia et al., 2013).

The transport of eggs and fish in early life stages is considered an important factor in the life history and recruitment success of many species (Hinckley et al., 1996; Parada et al., 2003). Therefore, predicting the transport and dispersal patterns of Asian carp eggs is imperative for assessing Asian carp reproduction and potential recruitment. For example, understanding the transport of Asian carp eggs is critical to predict whether Asian carp can recruit in tributaries of the Great Lakes. In addition, egg-drifting dynamics contribute valuable information for use in streams where these species are well established (e.g., Mississippi River Basin) that can aid in the development of management and control strategies targeting Asian carp in early life stages.

A three-dimensional Lagrangian numerical model, FluEgg (Fluvial Egg Drift Simulator), was developed by Garcia et al. (2013) to simulate the transport dynamics of Asian carp eggs. The FluEgg model is written in the MATLAB® programming language (Mathworks, Natick, MA,

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USA). FluEgg is an assessment tool capable of evaluating the influence of flow velocity, shear velocity, and turbulent diffusion on the transport and dispersal patterns of Asian carp eggs. The model incorporates information about Asian carp egg development and river hydrodynamics to provide insights regarding: (i) the likelihood of a river to be suitable for spawning, (ii) the potential of a river to transport Asian carp eggs in suspension until hatching, and (iii) the identification of the location of Asian carp eggs at different developmental stages. This information is valuable to the development of prevention, management, and control strategies before the eggs hatch and develop the ability to swim. For instance, the generally held belief that Asian carp eggs must be in suspension in order to hatch can be used together with FluEgg simulation results to create control strategies at a specific life stage (Peh-Lu et al., 1964; Jennings, 1988; Schrank et al., 2001; Kolar et al., 2007; Aitkin et al., 2008; Chapman and Deters, 2009; Rach et al., 2010; Yi et al., 2010). FluEgg is a useful tool for scientists, managers, and stakeholders both to improve their understanding of drifting behavior of Asian carp in early life stages and to improve their decision-making processes for controlling Asian carp in early life stages.

The primary objective of this article is to describe how the FluEgg model was used to simulate the transport and dispersion of silver carp eggs in the Lower Saint Joseph River, a Great Lakes tributary identified by Murphy and Jackson (2013) as potentially at risk for Asian carp spawning and recruitment. Two approaches to input the river hydraulic data into FluEgg were explored: one uses observed acoustic Doppler current profiler (ADCP) data collected by the U.S. Geological Survey (USGS), and the other uses simulated hydraulic data. This article investigates the interdependencies between water temperature and the physical characteristics of the river and its flow field and the dispersion and hatching risk of silver carp eggs in the Saint Joseph River.

An additional outcome of this study was improvements to the FluEgg model. This enhanced version of FluEgg includes three new features: (i) the effect of ambient water temperature on the density of the eggs, (ii) the estimation of egg hatching time, (iii) the calculation of the river's bed composite roughness, and (iv) the inclusion of variations in the streamwise velocity along the transverse direction thereby allowing a more accurate representation of shear dispersion caused by the river banks. FluEgg now includes a MATLAB®-based graphical user interface (GUI) and a free executable version of the model to make the user's interaction with the model simple, fast, and efficient. In this way, users from different disciplines and different backgrounds will be able to simulate scenarios that enable informed decisions based on model results. The user interface includes a set of post-processing tools that allows the user to visualize and perform analysis on the output of FluEgg simulations.

Software overview and model improvements

The FluEgg model (Garcia et al., 2013) was developed primarily as a tributary assessment tool to study the transport and dispersal patterns of Asian carp eggs in tributaries of the Great Lakes. However, this model can be used to simulate the transport of Asian carp eggs in other water bodies, including those with established Asian carp populations. FluEgg is a three-dimensional Lagrangian model that uses: (i) the biological characteristics of the eggs, such as growth rate and changes in egg density, (ii) the hydrodynamic characteristics of the flow, and (iii) the water temperature to simulate the turbulent diffusion phenomena that contribute to egg movement. Water temperature is an important parameter due to the role it plays in both egg development (Chapman and George, 2011a; George and Chapman, 2013) and egg buoyancy. In FluEgg, the river is discretized into a series of cells and the egg mass is simulated as discrete particles. The model predicts the advective, deterministic component and the diffusive, stochastic component of individual egg movements in the streamwise (x), transverse (y) and vertical directions (z) at every time step. The main limitations of FluEgg are (i) the assumption of steady-state and homogeneous hydrodynamic characteristics within a river cell, (ii) the absence of egg traps in dams and hydraulic structures, and (iii) the lack of a mortality model. A complete description of the FluEgg model was presented by Garcia et al. (2013); users can refer to this paper for detailed information on both the mathematical model and the performance of the model.

The remainder of this section discusses the four new features of the FluEgg model: changes in the density of the eggs due to the influence of ambient water temperature, the estimation of egg hatching time, the internal calculation of the river bed composite roughness, and changes in streamwise velocity in the transverse direction.

Effect of ambient water temperature on the density of the eggs

This feature improves upon how the density of the eggs under different ambient water temperatures is simulated in FluEgg. In the previous version of the model, the density of the eggs was assumed to be constant at different temperatures. In reality, changes in the density of the eggs with respect to ambient water temperature are expected. These changes occur both because the egg membrane absorbs water at a different temperature during the water hardening process, and because there are changes in temperature gradient between ambient water and water contained inside the egg.

There are no detailed experiments that show how the density of the egg changes with temperature. However, the experimental data from Tang et al. (1989) on water-hardened eggs include values for specific gravity of the four species of Asian carp for a range of temperatures (18.5 °C to 32.5 °C). A generic function relating the density of the eggs as a function of ambient temperature is obtained from these data.

$$\rho_{Egg}^{t,T} = \rho_{Egg_{ref}}^{t,T_{ref}} + \eta\left(T_{ref} - T\right) \qquad \left(R^2 = 0.82\right) \tag{1}$$

where $\rho_{Egg}^{t,T}$ is the density of the eggs $\left[\frac{kg}{m^3}\right]$ at both developmental stage t [seconds] and ambient water temperature T [°C], $\eta = 0.20646$ is a correction factor for temperature adjustment, $\rho_{Egg_{ref}}^{t,T_{ref}}$ is the density of the eggs $\left[\frac{kg}{m^3}\right]$ at developmental stage t measured at a reference temperature T_{ref} [°C], and R^2 is the coefficient of determination.

There is uncertainty in this function. First, because this empirical equation is based on water-hardened eggs, it does not take into account the process in which eggs absorb ambient water filling the perivitelline space (space between the egg membrane and the embryo, where water is stored) (Tsuchiya, 1980; Sundby, 1997; Chapman and Deters, 2009; Deters et al., 2013). Second, as this is a generic and species-independent function, it does not take into account differences in the volume of the perivitelline space among different species (Kjesbu et al., 1992). For example, for some species like flounder, which have a very small perivitelline space, the density of the eggs will barely change, however, for some other species the density of the eggs is expected to change considerably.

FluEgg uses the time-dependent relations of the density of the eggs at a reference temperature T_{ref} equal to 22 °C (see Eq. (2)). These time-dependent relations were found by fitting experimental data by Chapman and George (2011b) on cultured silver (*H. molitrix*) and bighead (*H. nobilis*) carp and then correcting to the reference temperature.

$$\rho_{Egg}(t) = \begin{cases} 25.2\exp\left(-\dfrac{t}{2259}\right) + 999.3 \quad \left(R^2 = 0.67\right) & \text{for silver carp eggs} \\ 30.58\exp\left(-\dfrac{t}{1716}\right) + 999.4 \quad \left(R^2 = 0.84\right) & \text{for bighead carp eggs} \end{cases} \tag{2}$$

where t is the post-fertilization time [seconds], and R^2 is the coefficient of determination.