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 percent 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.

Keywords: FluEgg, Saint Joseph River, Invasive species, Asian carp eggs, Spawning, Hatching Risk, Great Lakes

1. 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

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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, 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.

2. 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 eggs movements in the streamwise (x), transverse (y) and vertical direction (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.

2.1. *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 eggs 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.

$$\rho_{Egg}^{t,T} = \rho_{Egg,ref}^{t,T_{ref}} + \eta(T_{ref} - T) \quad (R^2 = 0.82) \quad (1)$$

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 equation 2). These time-dependent relations were found by fitting experimental data by Chapman and George (2011b) on cultured silver (*Hypophthalmichthys molitrix*) and bighead (*Hypophthalmichthys nobilis*) carp and then correcting to the reference temperature.

$$\rho_{Egg}(t) = \begin{cases} 24.98 \exp\left(-\frac{t}{1570.1}\right) + 999.5 & (R^2 = 0.99) \text{ for silver carp eggs} \\ 23.12 \exp\left(-\frac{t}{2164.9}\right) + 999.2 & (R^2 = 0.99) \text{ for bighead carp eggs} \end{cases} \quad (2)$$

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

2.2. Egg hatching time

Hatching time is an important parameter in the evaluation of egg development and potential recruitment success. Chapman and George (2011) showed with experimental data that small changes in water temperature (2 to 3°C) can result in considerable changes in hatching time. In the new version of FluEgg, the approximate hatching time is calculated based on the temperature averaged over all the cells. FluEgg uses an empirical function derived from the compilation completed by Murphy and Jackson (2013) on hatching times as a function of temperature. For a given species the hatching time is calculated based on the temperature averaged over all the cells as follows:

$$T_H(T_{avg}) = \begin{cases} (1.2087 \times 10^7) T_{avg}^{-4.2664} + 10.242 & (R^2 = 0.96) \text{ for silver carp eggs} \\ 35703 T_{avg}^{-2.223} & (R^2 = 0.93) \text{ for bighead carp eggs} \end{cases} \quad (3)$$

where T_H is the hatching time [hours], T_{avg} is the temperature averaged over all the cells [°C], and R^2 is the coefficient of determination.

2.3. River bed composite roughness

In the new version of the FluEgg model, the characterization of the bed substrate is no longer a user-input variable, but rather is estimated based on the river hydrodynamics. In this way, the river bed is characterized as a composite roughness. The composite roughness includes more features that contribute to the river roughness in addition to the local roughness caused by the size of the sediment in the river substrate. The composite roughness is an important variable because it directly affects the magnitude of the shear velocity. As the shear velocity is a measure of the turbulence intensity, it also directly affects the transport and dispersion of the eggs. The composite roughness height (k_c) is calculated using Keulegan's law, which is the integrated version of the log-law over the water column (Garcia, 2008):

$$k_c = \frac{11h}{\exp\left(\frac{u\kappa}{u_*}\right)} \quad (4)$$

where h is the water depth of the cell where the egg is located [m], u is the streamwise water velocity (x direction) [m/s], $\kappa = 0.41$ is the von Karman's constant, and u_* is the shear velocity [m/s] in the corresponding cell.

2.4. Streamwise velocity variation along the transverse direction

The estimation of the variability of streamwise velocity along the transverse direction is an important feature that improves predicted shear dispersion in the model. The previous version of the FluEgg model treated the streamwise velocity in the transverse direction as a constant. However, the banks of the river (lateral walls) affect the transverse velocity distribution with the velocity tending toward zero at the banks. As a result, the previous version of the model underestimated the streamwise dispersion of the eggs.

The enhanced version of the FluEgg model estimates the streamwise velocity in the lateral direction by using the lateral velocity profile proposed by Seo and Baek (2004). The velocity profile is calculated based on a beta probability density function. This function represents, in a more accurate way, the characteristics of the streamwise velocity in the transverse direction in natural streams. A general form of the transverse velocity distribution using the beta probability density function is described as follows (Seo and Baek, 2004):

$$u(y') = U \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} (y')^{\alpha-1} (1 - y')^{\beta-1}, \quad 0 < y' < 1 \quad (5)$$

where $u(y')$ is the streamwise water velocity [m/s], $y' = \frac{y}{W}$ [unitless], y is the lateral coordinate measured from right bank of the stream [m], U is the cross-sectional mean velocity [m/s], α and β are parameters describing the shape of the distribution function estimated from hydraulic data [unitless], and W is the stream width [m]. Parameters α and β can be estimated by regression analysis using the transverse velocity distribution of the river. For the convenience of the user, the model uses as default values $\alpha = 1.9$ and $\beta = 1.8$, which correspond to the average values computed from eight river datasets provided by Seo and Baek (2004).

By including the lateral velocity profile, the FluEgg model more realistically simulates the streamwise dispersion of the eggs resulting from the shear induced by the river banks. This improvement allows for a better representation of the trailing edge of the drifting egg distribution curve.

3. A GUI for the Fluvial Egg Drift Simulator (FluEgg)

Upon opening FluEgg, the main user interface window will appear (Figure 1). This window guides the user through the different steps required to setup and run the model and analyze the results. The main GUI consists of four

input panels: River input data, spawning event, egg characteristics, and simulation setup. The input parameters must be provided in metric units. After the user inputs the required data and runs the model, he or she can visualize the results using the post-processing tools linked through the "Analyze results" push-button. The figures in this section illustrate the input data used to simulate egg development and transport on the Saint Joseph River and to produce the results discussed in Section 4.

As discussed above, FluEgg and its GUI were coded in MATLAB®. Executable versions and installation instructions for 32 and 64 bit Windows platforms are freely available from <<http://asiancarp.illinois.edu/FluEgg.html>>.

3.1. River input data

In the "River input data" panel, the user specifies the river hydrodynamic and environmental characteristics discretized by cells or reaches. River characteristics are entered into the River input file sub-interface (Figure 2). Users are allowed to input the river characteristics directly into the table embedded in the GUI, or by loading an input file. The supported formats include: Microsoft Excel® (*.xls), comma-separated values (*.csv), and text (*.txt). The input river parameters are: cell number [unitless], cumulative distance [km] (most upstream point is generally considered 0 km), water depth [m], discharge [$\frac{m^3}{s}$], velocity magnitude [$\frac{m}{s}$], vertical velocity [$\frac{m}{s}$], lateral velocity [$\frac{m}{s}$], shear velocity [$\frac{m}{s}$], and water temperature [$^{\circ}C$]. For convenience, plots of the river input parameters are provided in the right-hand side of the sub-interface. If the user creates or modifies the river input table in the GUI, the user has the option of saving it for later use.

Once the river input data are loaded, the user is required to specify the vertical eddy diffusivity function that describes the vertical diffusion of fluid momentum. The default option is the parabolic-constant eddy diffusivity function. The user selects this function from a drop-down menu that displays the three predetermined profile functions for the calculation of the fluid eddy viscosity as stated by Garcia et al. (2013): parabolic-constant turbulent diffusivity, constant turbulent diffusivity, and parabolic turbulent diffusivity. Finally, the user selects the method to calculate changes in the streamwise velocity in the vertical direction. The user can choose from two methods: log-law rough bottom boundary (for rivers; default in FluEgg) or log-law smooth bottom boundary (for flumes). After the river input file is loaded, a panel containing a summary of the river geometry is enabled (Figure 1). This summary contains the minimum and maximum cumulative distance along the simulation reach, water depth, and width. This information is displayed to help the user select a location of spawning.

3.2. Spawning event

The input parameters required in the "Spawning event" panel include the number of eggs to be released in the spawning event and the three-dimensional virtual spawning location (X_i, Y_i, Z_i) (Figure 1). The default spawning

location is set to the most upstream point ($X_i = 0$ m), at the middle of the cross-section ($Y_i = \frac{w}{2}$ m), and at the water surface ($Z_i = 0$ m).

3.3. Egg characteristics

The characteristics of the egg are described in the FluEgg model in terms of diameter and density. In the "Egg characteristics" panel (Figure 1), the user can choose the desired method to describe the egg characteristics from a drop-down menu. Two options are available: (i) constant egg diameter and density (Figure 1A) and (ii) time-dependent relation following the experimental data from Chapman and George (2011b) as described by Garcia et al. (2013) (Figure 1B). The user must specify the diameter of the eggs, the density of eggs, and the temperature at which the density of the eggs was measured if the constant method is used (Figure 1A). Whether the user chooses to treat the egg characteristics as constant or as a function of time, he or she is required to select the desired species to simulate. The user can select from a radio button: silver carp or bighead carp. The selection of the species is required for two purposes: (i) to estimate the hatching time (see Section 2) and (ii) to calculate the changes over time of the diameter and density of eggs based on the time series proposed by Chapman and George (2011b).

3.4. Simulation setup

In the "Simulation setup" panel (Figure 1), the user specifies the simulation time and the time step. These parameters determine the duration and the stability of the simulation. The maximum simulation time corresponds to the hatching time, which depends on temperature and species. After hatching the egg transport equations used in FluEgg are no longer valid. This results from the fact larval Asian carp exhibit vertical swimming and can influence their position in the water column (George and Chapman, 2013). The simulation time step must fulfill the stability criteria established by Garcia et al. (2013). The required minimum time step depends on the selected species, water temperature, shear velocity, and water depth.

3.5. Post-processing tools

Once the user sets up and successfully runs the model, the "ANALYZE RESULTS" push-button is enabled (Figure 1B). A sub-interface containing the list of post-processing tools to visualize the results will appear upon pressing the button. This interface facilitates the analysis and interpretation of the FluEgg model results. Nine post-processing visualization options are available: (i) Evolution of a mass of Asian carp eggs, (ii) Vertical position of the centroid of the egg mass as a function of distance, (iii) Summary of temporal and spatial evolution of the egg mass, (iv) Egg vertical concentration distribution, (v) Distribution of eggs over the water column at a given downstream distance,

(vi) Egg travel-time distribution, (vii) Distribution of eggs over the water column at hatching time, (viii) Longitudinal distribution of the eggs at a given time and eggs at risk of hatching, and (ix) 3D animation of egg transport.

These post-processing visualization tools were designed to help answer questions regarding the prevention, management and control strategies for Asian carp in early life stages. Examples of questions include: (i) What is the likelihood of a river to be suitable for spawning? (ii) What potential does the river have to transport Asian carp eggs in suspension until hatching? (iii) Where is the location of Asian carp eggs at different developmental stages and at different periods of elapsed time? (vi) What scenarios decrease the likelihood of a river to be a suitable habitat for egg development before the eggs hatch and develop the ability to swim? The visualization tools and their usefulness in answering such questions are explored in more detail in the next section through a case study of the simulation of transport of Asian carp (silver carp) eggs in the Lower Saint Joseph River in Michigan.

4. Application to the Saint Joseph River

The FluEgg model was applied to simulate the transport of silver carp eggs in the lower 40.1 km of the Saint Joseph River (Figure 3), from Berrien Springs Dam to the rivermouth at Lake Michigan. The Lower Saint Joseph River downstream of Berrien Springs Dam is a narrow, free-flowing, meandering reach confined within a glacial valley, with the exception of the lower 8 miles which meanders unconfined through a glacial lake plain and divides the towns of Saint Joseph and Benton Harbor before entering Lake Michigan. The lower 8 miles of the river is considered the rivermouth segment (Wesley and Duffy, 1999) and is characterized by a low gradient and affected by backwater from Lake Michigan (Murphy and Jackson, 2013). Depths in the Lower Saint Joseph River are generally less than 3 m except for the section nearest Lake Michigan where the depth increases to over 6 m. Several tributaries including Farmers, Lemon, Love, Pipestone and Hickory Creeks and the Paw Paw River join the Saint Joseph River in the lower 40.1 km. The substrate in the Lower Saint Joseph River is mostly sand, gravel, and cobble, with finer sediments (sand and silt) dominating the substrate close to the rivermouth (Wesley and Duffy, 1999). FluEgg was used to simulate and analyze the results of silver carp egg transport using the post-processing tools available in the GUI. This example provides insights about potential Asian carp spawning behavior and egg development in the Lower Saint Joseph River. This information can then be used to develop prevention, management and control strategies. The transport and dispersion of silver carp eggs were simulated using two data sources. The first uses detailed observed hydraulic data from the Lower Saint Joseph River, and the second uses simulated hydraulic data from a HEC-RAS model. These two different approaches demonstrate the model flexibility and its potential use as a decision-making tool. From the user perspective, a significant advantage of using a hydrodynamic model to generate a range of flow conditions with FluEgg compared to a synoptic field survey is the ability to simulate different hydrodynamic and temperature

conditions not observed during the field survey. The field surveys can provide ground truth data for calibration of the hydraulic model if necessary.

4.1. Materials and methods

The Chicago Area Waterway System (CAWS) has been identified as a potential connection between the Mississippi River Basin and the Great Lakes Basin (U.S. Army Corps of Engineers, 2012). If Asian carps use the CAWS to reach Lake Michigan, they will likely search for tributaries with fast-moving water in which to spawn. In this case, the Saint Joseph River would be an attractive spawning habitat for these species, because it is the closest major river on the east coast of Lake Michigan and has been predicted to be a potential suitable habitat for Asian carp reproduction (Murphy and Jackson, 2013; Kolar et al., 2005).

Murphy and Jackson (2013) analyzed the potential of the Saint Joseph River as a viable spawning ground using observed hydraulic and water-quality data. The authors compared egg settling zones and egg travel times against hatching time to determine the possibility of hatching. The reported peak transport time from the Berrien Springs Dam to the settling zone where the Saint Joseph River transitions to backwater conditions from Lake Michigan (36.8 km downstream from Berrien Springs Dam) was approximately 16 hours with leading and trailing edge transport times of 15 and 20 hours, respectively (Murphy and Jackson, 2013). Comparing the egg travel times with the estimated hatching time for silver carp at typical summertime water temperatures (18.7 hours at 26.5°C), Murphy and Jackson (2013) concluded that only a small fraction of the eggs might hatch before reaching the lake. However, the authors suggested that lower flow rates and higher water temperatures may increase the fraction of the eggs that could potentially hatch before reaching Lake Michigan (Murphy and Jackson, 2013).

Using FluEgg, we simulated the transport of silver carp eggs in the Lower Saint Joseph River and compared the results of this simulation with the statements made by Murphy and Jackson (2013) regarding the hatching possibility of silver carp eggs. A major advantage of the FluEgg model over the field-based analysis of Murphy and Jackson (2013) is the ability to model the three-dimensional position of individual eggs at every time step. Therefore, FluEgg provides high order analyses where the entire egg plume distribution can be estimated at the predicted hatching time or at a distance downstream from the virtual spawning location or plotted as an egg concentration breakthrough curve at a given downstream distance from the virtual spawning location. Physical studies cannot provide this level of insight. Moreover, FluEgg results provide additional information about both egg transport behavior and hatching suitability. Additional information can be derived from the FluEgg output using the post-processing tools included in the GUI (see sub-section 3.5).

The first approach used to analyze the transport and dispersion of Asian carp eggs in the lower 40.1 km of the Saint Joseph River used observed hydraulic input data. The environmental and hydrodynamic data, analyzed by Murphy

and Jackson (2013), were used to simulate the transport of the eggs. This simulation provided a base case scenario, and more importantly a reference case to compare with results obtained using the simulated hydraulic data from the HEC-RAS model (second approach).

Observed hydraulic and water-quality data from Murphy and Jackson (2013) were used to create the river input file (Figure 2). The simulated river reach is about 40 km long and was divided into 127 cells. The last cell corresponds to Lake Michigan. This cell was input as an extension of the previous cell, but with a near zero streamwise velocity and shear velocity. The simulated reach for this data set is characterized by an average discharge, water depth, streamwise velocity, and shear velocity of $89.19 \text{ m}^3/\text{s}$, 2.1 m, 0.7 m/s , and 0.06 m/s , respectively. During this data collection, the discharge near the Berrien Springs Dam was equal to $95.96 \text{ m}^3/\text{s}$. The water temperature was set to 26.5°C (July 2011 and July 2012 mean water temperature at USGS streamgage at Niles, MI (Murphy and Jackson, 2013)). Readers are referred to the study of Murphy and Jackson (2013) for detailed information about the observed data.

In the second approach, using simulated hydraulic input data, a simplified 1-D hydraulic model was implemented in the HEC-RAS 4.0 software, developed by the United States Army Corps of Engineers Hydrologic Engineering Center (U.S. Army Corps of Engineers, 2008).

The river input geometry data for the HEC-RAS model was obtained by using HEC-GeoRAS together with a 1-arc second Digital Elevation Model (DEM) (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM)), and orthophotos of the study area. GIS data were downloaded from the U.S. Geological Survey National Geospatial Program (<http://viewer.nationalmap.gov/viewer/>). The cross-section river geometry, extracted using HEC-GeoRAS, is generally shallower because the lack of a detail-high resolution DEM. The cross-section river geometry, extracted using HEC-GeoRAS, was then combined with the geometric shape of the cross-sections, obtained from ADCP measurements by USGS. River bottom elevations and river roughness were adjusted such that the simulated hydraulic conditions were in agreement with the hydraulic measurements obtained by the USGS. Single values of Manning's n coefficients were used to account for both channel and floodplain roughness. Manning's n coefficients varied between 0.024 to 0.08. The downstream boundary condition was set to normal depth with slope equal to 1.5×10^{-6} . Simulated and observed water depth, velocity, and shear velocity data were plotted together and the model was adjusted until the magnitudes were similar. At the end of the adjustment process, we obtained a HEC-RAS model representing the hydraulics of the Lower Saint Joseph River with fairly accurate results based on the comparison of observed and simulated values of water depth and velocities. The average discharge, water depth, streamwise velocity, and shear velocity of the simulated hydraulic data generated by the HEC-RAS model for the conditions analyzed by Murphy and Jackson (2013) was $88.67 \text{ m}^3/\text{s}$, 2.97 m, 0.53 m/s , and 0.07 m/s , respectively.

The effect of discharge and water temperature on the transport and dispersion of the eggs, and ultimately, on the

percentage of eggs at risk of hatching was evaluated in FluEgg using hydraulic river input data from the HEC-RAS model. We used 1 °C incremental water temperatures from 18 °C (minimum spawning temperature (Kolar et al. (2007))) to 27.5 °C (maximum daily temperature for the years 2010 to 2012).

Different hydrodynamic scenarios were simulated using the HEC-RAS model. The first scenario corresponds to the flow event ($95.96 \text{ m}^3/\text{s}$) analyzed by Murphy and Jackson (2013). The last three scenarios correspond to the minimum, mean, and maximum daily flow ($67.7 \text{ m}^3/\text{s}$, $116.5 \text{ m}^3/\text{s}$, and $161.1 \text{ m}^3/\text{s}$) at the USGS streamgage at Niles, Michigan (04101500) during the spawning season (April to July) for the years 2002 to 2013. The flow is assumed to be constant from the streamgage to the Berrien Springs Dam. A total of 52 FluEgg simulations were performed with a combination of hydraulic and water temperature conditions. These simulations are the basis of a holistic analysis of the effect of changes in the hydrodynamics and water temperature of the Lower Saint Joseph River on the transport and dispersion of Asian carp eggs until hatching.

In all FluEgg simulations, 10,000 virtual eggs were spawned at the beginning of the simulation at the start of the first cell at the water surface and in the center of the channel. The vertical diffusivity was simulated using the parabolic-constant option and the log-law for rough boundary conditions. The simulation time was set to the hatching time while the time step used in all FluEgg simulations was equal to 9 seconds, following the stability criteria suggested by Garcia et al. (2013).

4.2. Results and discussion

The transport of silver carp eggs in the Lower Saint Joseph River was simulated using the FluEgg model. These simulations provide insights related to the transport and dispersion of silver carp eggs and to the risk of eggs hatching under different water temperatures and hydraulic conditions. Additionally, the majority of the figures presented in this manuscript were generated using the FluEgg post-processing tools.

4.2.1. FluEgg simulations using observed data

The hydraulic and water-quality data collected by the USGS were used as river input data to simulate the transport of silver carp eggs in the Lower Saint Joseph River for the flow event analyzed by Murphy and Jackson (2013). Results from this simulation are summarized in Figure 4.

The snapshot of eggs drifting in the vertical-longitudinal space in the Lower Saint Joseph River was generated by the tool "Evolution of a mass of Asian carp eggs" (Figure 4A). In Figure 4A, snapshots are recorded at 0, 1, 10 and 20 hours after the spawning event. Note the user can adjust the periodicity of the snapshots. Different colors were employed to represent the cloud of eggs at different post-spawning times. While this figure is generally qualitative, it shows several important aspects of the evolution of the egg plume. First, as the eggs advect downstream, the mass

of eggs disperses in the streamwise direction due to shear dispersion. Second, shortly after the spawning event, and within the entire study reach, the eggs are distributed throughout the water column.

A more quantitative analysis examines the temporal and spatial evolution of the egg mass. The spatial characteristics of the plume in the three-dimensional space at any time during the simulation (Figure 4B, 4C, and 4D) are illustrated using the post-processing tool, “Summary of temporal and spatial evolution of the egg mass”. Travel times for the mean location of the egg mass (centroid), the mean location $\pm$ one standard deviation, and the minimum and maximum egg location for the Lower Saint Joseph River are depicted in Figure 4B, 4C, and 4D. During the first two to four hours, the longitudinal dispersion (x direction) increases slowly, then it increases at a much faster rate. The greatest dispersion of eggs occurs nearly 12 hours after the spawning event. At the end of the simulation time, the centroid of the eggs is located 36.7 km downstream from the spawning location.

In FluEgg, all the cells are aligned in the lateral direction to the right bank ($\frac{Y}{W} = 0$, Figure 4B). Drastic reductions in hydraulic width between adjacent cells cause the centroid of the egg mass to shift to the left bank ($\frac{Y}{W} = 0$). The opposite, an increase in cell width, shifts the centroid of the egg mass in the lateral direction to the right bank. This phenomenon accounts for the lag-time caused by temporal storage of eggs in sides of the channel where the magnitude of the streamwise velocity is less than the middle of the channel cross-section. In a perfectly straight channel, with constant width, the centroid of the egg mass will be located in the middle of the cross section, shortly after spawning. In the Lower Saint Joseph River, the temporal evolution of the centroid of the lateral position of the eggs (Figure 4B), indicates that within the first six minutes after spawning, the eggs mixed in the lateral direction, placing the centroid of the egg mass in the middle of the cross section. During the next four hours the centroid first shifts from the middle of the cross-section near to the left bank. The centroid then moves near to the right bank. Four hours after spawning the centroid is located near the right 40 percent section of the channel where it remains approximately constant during the rest of the simulation period. It should be noted that the FluEgg model does not use true planform geometry of the river and therefore, analysis of lateral dispersion is limited. Figure 4B provides a check that the eggs are fully distributed across the channel.

At the beginning of the simulation, eggs were placed at the water surface. Vertical mixing occurred rapidly, thereafter. After the first six minutes of the simulation, the centroid of the vertical location of the eggs is located in the lowest 30 percent of the water depth (Figure 4D). As the eggs travel downstream to cells with higher flow velocities and higher turbulence, they distribute more uniformly through the water column. Consequently, the vertical centroid of the mass of eggs is located near the middle of the water column starting about 2 hours after spawning. The backwater effect from Lake Michigan impacts the last 10 km of the simulated river reach, where the flow begins to decelerate. Once the majority of the eggs enter the backwater zone, the normalized centroid of the eggs’ vertical

location decreases from 0.5 to 0.3, resulting in a large portion of the eggs in the lower 30 percent of the water column. These eggs are at risk of settling out of suspension.

This analysis was applied to a tributary of Lake Michigan where Asian carp have yet to inhabit. However, the analysis of the temporal and spatial evolution of the egg mass is also useful when planning egg sampling in a stream with well established Asian carp populations. For example, it helps determine the downstream distance from a known spawning location at which to measure and collect egg samples. It also provides data about the dispersion of the egg mass in the lateral and vertical direction. When sampling, the vertical location of the egg mass is important. For example, if sampling nets are placed in the upper 50 percent of the water depth but eggs are located in the lower 50 percent, the egg samples will report few or no eggs in that particular area.

The egg travel time to a specific downstream distance is explored in more detail using FluEgg's post-processing tools. We used the "Egg travel-time distribution tool" to calculate egg travel times from the Berrien Springs Dam to the beginning of the last settling zone, defined by Murphy and Jackson (2013), of the Lower Saint Joseph River, located approximately 36.8 km downstream of the dam. We used the same hydraulic conditions (discharge at the dam equal to 95.96 m³/s and a water temperature equal to 26.5 °C) as Murphy and Jackson (2013). However, at this temperature the hatching time is approximately 20 hours, not enough time for all eggs to drift and reach the settling zone. At the end of the simulation (hatching time) slightly more than 50 percent of eggs reached the settling zone. Therefore, a new travel-time analysis was performed using a temperature equal to 18 °C (minimum temperature for Asian carp spawning), allowing the eggs to drift long enough to reach the settling zone (Figure 5). As expected, the travel-time distributions exhibit a long tail caused by dispersion due to shear generated by the river bed and banks (Figure 5A). At the end of the simulation 100 percent of the eggs reached the settling zone.

Results from FluEgg simulations show a peak transport time, from the Berrien Springs Dam to the settling zone (36.8 km), equal to 18 hours with leading and trailing edge (10 percent of the peak percentage of eggs) transport times of 14 and 29 hours respectively (Figure 5A). Results indicate the mass of eggs moves slower than predicted by Murphy and Jackson (2013), who estimated transport time based on mean streamwise velocity. This difference is due to the effect of the egg settling velocity, and the vertical and lateral velocity gradients caused by shear. Unlike a well-mixed system (e.g. dye, pollutant) where scalars are distributed uniformly throughout the water column, the eggs are subject to a settling velocity which can lead to higher concentrations near the bed and the vertical centroid of the eggs in the lower half of the water column along most of the simulated river reach. Murphy and Jackson (2013) assume that the egg mass is uniformly mixed over the water column much like a passive dye. However, as the centroid of the egg mass moves closer to the bed due to settling, the mass of eggs is subject to lower velocities and rate of downstream transport of the centroid of the plume decreases compared to a fully-mixed passive dye which is subject to higher velocities.

Therefore, the slower advection rate of the egg plume predicted by FluEgg is justified and proves that assumptions made in traditional river mixing and transport theory (e.g. a vertically mixed water column) may be violated in the case of transport of dense particles (such as eggs or sediment) in rivers.

The percentage of eggs near the bottom is particularly important if analyzing the risk of eggs hatching. When analyzing hatching risk, suspension and settlement processes are important because it is thought eggs are required to remain in suspension to hatch (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). The vertical distribution of the eggs over the water column is a powerful tool to analyze Asian carp transport in tributaries. Moreover, it can be employed to great effect to perform egg sampling and develop control strategies targeting Asian carp at early life stages. The vertical distribution of the eggs can be generated at different downstream locations from the virtual spawning point. Locations of interest include, but are not limited to, downstream of dams, egg or larvae sampling sites, or near a major ecosystem (e.g., the Great Lakes).

Figure 5B shows the percentage of eggs distributed vertically in different sections of the water column, downstream from the Berrien Springs Dam. This figure, was created using the “Distribution of eggs over the water column at a given downstream distance” post-processing tool. Results indicate that at the start of the settling zone 36.8 km downstream of the Berrien Springs Dam, approximately 8 percent of the eggs are in the lower 5 percent of the water column and at risk of perishing. However, if we calculate the vertical distribution of the eggs at the mouth of the Saint Joseph River at Lake Michigan (end of the jetty-not shown), the number of eggs in the lower 5 percent of the water depth increases to 25 percent, thus putting more eggs at risk of settling and perishing. The increase in the near bottom percentage of eggs is consistent with the settling zone defined by Murphy and Jackson (2013).

The use of observed hydrodynamic data collected at a relatively high flow with FluEgg provides knowledge about transport, dispersion and hatching dynamics of Asian carp eggs under a specific flow event. Different scenarios can be simulated to analyze the effect of water temperature on the transport and dispersion of carp eggs until hatching. However, the analysis of the effect of water temperature, performed using this approach, is restricted to a particular flow event. However, the use of simulated hydraulic river input data (e.g., using a HEC-RAS model), provides a more holistic approach, allowing the user to examine a wide range of temperature and hydrodynamic scenarios.

4.2.2. Comparison of FluEgg simulations using simulated and observed hydraulic data

In addition to using observed hydraulic data in the Lower Saint Joseph River, the FluEgg model was run with input data calculated from a HEC-RAS model to simulate the flow event and water-quality conditions (discharge at the dam equal to $95.96 \text{ m}^3/\text{s}$ and a water temperature equal to $26.5 \text{ }^\circ\text{C}$), like Murphy and Jackson (2013). A comparison of FluEgg simulation results for the two approaches under the same hydraulic and water-quality conditions is shown

in Figure 6.

The mean travel path of the eggs in the vertical-longitudinal space using the two different sources of input hydraulic data for FluEgg is illustrated in Figure 6A. FluEgg was used to generate a plot of the location (x, z) of the centroid of the eggs' mass at every time step. The vertical location of the centroid is normalized by the water depth to facilitate analysis of egg settling zones. Results showed agreement between simulations using the two different approaches.

The longitudinal distribution of the eggs and the risk of hatching can be visualized by employing the “Longitudinal distribution of the eggs at a given time and eggs at risk of hatching” post-processing tool. This tool allows the user to generate a plot of the distribution of the downstream location of the eggs at a given post-spawning time up to the hatching time. In the plot generated by this tool, eggs in suspension are differentiated from those near the bottom. The eggs in suspension correspond to those drifting in the upper 95% of the water column while those in the lower 5% of the water column are considered settled. This plot also includes the cumulative percentage of eggs (CPE) in suspension and the corresponding percentage of eggs at risk of hatching (rounded to the nearest 5% to account for uncertainty). The cumulative sum of the percentage of eggs in suspension at hatching time is a proxy for hatching risk.

The longitudinal distribution of the eggs at hatching time and the percentage of eggs at risk of hatching using the two different approaches to input hydraulic data into FluEgg are illustrated in Figures 6B and 6C. The peak percentage of eggs in Figure 6C (HEC-RAS simulated hydraulic river input data) is slightly higher and farther downstream (less than 1 km) than in Figure 6B (observed hydraulic river input data). Although the distribution generated using the simulated hydrodynamic river input data fails to capture a small percentage of slow moving and a minor percentage of the fast moving eggs, the overall longitudinal distribution of the eggs using the two different approaches are in agreement. Moreover, the percentage of eggs at risk of hatching (cumulative percentage of eggs in suspension at hatching time) from both approaches are consistent.

4.2.3. *Effect of discharge and water temperature on the transport and dispersion of silver carp eggs*

Using simulated hydraulic data for a range of flow events at different water temperatures into FluEgg provides a more holistic analysis. We simulated the river hydrodynamics for a range of flow regimes. In Table 1 there is a summary of results from HEC-RAS simulations. The headwater discharge (Q^* at Berrien Spring Dam) was assumed to be constant from the USGS streamgage at Niles. Mean values of discharge ($\overline{Q}$), water depth ($\overline{H}$), streamwise velocity ($\overline{u}$), and shear velocity ($\overline{u}_*$) for the four different flow regimes studied are reported in Table 1.

Figure 7 illustrates results from 52 FluEgg-simulations run under different water temperatures and discharges. Assuming silver carp eggs were spawned at Berrien Springs Dam, and water temperature and discharge are known, then both the downstream location of the eggs and the percentage of eggs at risk of hatching can be derived from

Figures 7A and 7B. Figure 7A illustrates the downstream longitudinal location of viable eggs (suspended) and 7B illustrates the percentage of eggs at risk of hatching for a range of water temperature and discharge (at Berrien Springs Dam). Figure 7C illustrates the changes in hatching time as a function of temperature, as described in section 2.2.

The risk of hatching is a major factor impacting recruitment success. The percentage of eggs in suspension, the drifting time, and the hatching time affect the risk of hatching. These three factors are influenced by water temperature and the hydraulic characteristics of the river in which the eggs are drifting. As indicated above, the buoyancy of the eggs and the density of the water are both affected by the water temperature. The greatest impact of the water temperature is not on the settlement of the eggs, but rather on hatching time. Higher temperatures correspond to shorter times required for hatching. Therefore, eggs need to travel shorter distances to hatch, which increases the hatching risk. The velocity of the river also plays an important role when assessing hatching risk. An egg's drifting time increases at lower velocities, which increases the risk of hatching. However, velocity must remain high enough to maintain the eggs in suspension.

The relation between water temperature and discharge illustrated in Figure 7A and 7B, together with 7C, may be useful in making predictions about the likelihood that silver carp would be able to hatch in the Lower Saint Joseph River. Stakeholders can use this information to estimate and/or assess: the downstream location of Asian carp eggs at hatching time, the amount of eggs at risk of hatching, the potential of the river to transport Asian carp eggs in suspension until hatching, and a diversity of scenarios that might increase or decrease the percentage of eggs at risk of hatching.

In the past, researchers evaluated minimum river length required for hatching of Asian carp eggs (e.g., Kolar et al. (2007); Kocovsky et al. (2012)). This single distance was used to assess the likelihood of a river to support Asian carp reproduction by comparing it against undammed river length. However, Figure 7A and 7B illustrate the complex interaction between the biological and physical systems. This relation will change among rivers because the hydrodynamic characteristics and water-quality characteristics of every river will lead to different dispersion patterns of eggs, and therefore to different amounts of viable hatching eggs (in suspension). Even when analyzing one particular river, the likelihood a river is viable for reproduction will vary depending on the water temperature and the hydraulic characteristics of the river (Figure 7B).

The Lower Saint Joseph River exhibits interesting patterns over the range of flows. The overall streamwise velocity along the most upstream 30 km of the Lower Saint Joseph River increases as flow increases among different scenarios. However, in the lower 10 km there is a backwater zone, where the flow decelerates with distance as it meets Lake Michigan. In this last region, the streamwise velocity is higher for lower flow scenarios than for higher flows. At high flows the water depth increases greatly in the backwater zone causing the energy slope to decrease considerably, and

therefore the streamwise velocity decreases. For example, along the upstream 30 km of the river, the flow velocities are higher in the scenario where the upstream discharge is equal to $161.1 \text{ m}^3/\text{s}$ compared to the case at which the upstream discharge is equal to $67.7 \text{ m}^3/\text{s}$. On the contrary, along the downstream 10 km of the river, the flow velocities are higher for the upstream discharge equal to $67.7 \text{ m}^3/\text{s}$ than for the upstream discharge equal to $161.1 \text{ m}^3/\text{s}$.

At hatching time, the majority of the eggs are located in the downstream 10 km of the simulated reach (Figure 7A). For the majority of the simulated scenarios, the median location of the eggs moved farther downstream as the discharge decreased (velocity increased) in the different scenarios. However, for the low flow scenario and temperatures ranging from 26 to 27.5°C , the median of the location of the eggs was located slightly upstream as compared to the median of the location of the eggs for the rest of the flow scenarios for a particular temperature group. This occurred because the simulation time (hatching time) was small enough that the upstream effect of low flow velocities in the upstream 30 km delayed the egg mass in comparison to higher flow scenarios.

We analyzed changes in the centroid of the vertical location of the eggs as a function of distance for the different case scenarios (various water temperature and flow regimes). In terms of egg suspension, FluEgg results showed that independent of the flow fields, the centroid of the vertical location of the eggs was located deeper in the water column at higher temperatures. This occurred because at high temperatures, the density of the water decreases and therefore the fall velocity of the eggs increases. To understand this phenomenon in more detail, we isolated the effect of water temperature from the effect of the river hydrodynamics (Figure 8). Egg settling velocities in stagnant water were calculated using FluEgg subroutines for a range of water temperatures and for different post-spawning times. In addition, we took into account changes in egg diameter and egg density as a function of time. After spawning, egg diameter increases with time while egg density decreases with time up-to four hours post-fertilization, at which time the egg diameter and density remain approximately constant (Chapman and George, 2011a). Figure 8 illustrates a family of curves showing an inversely proportional relation between post-fertilization time and settling velocity. Moreover, Figure 8 shows a directly proportional relation between temperature and settling velocity. Therefore, for flows analyzed in this study and along the simulated river stretch, lower temperatures exhibited higher suspension rates than higher temperatures for a particular scenario.

The majority of the simulations showed an increase in the percentage of eggs at risk of hatching with increased temperature. For temperatures above the mean daily temperature (24.6°C) the percentage of eggs at risk of hatching was inversely proportional to the flow characteristics. The critical condition at which there is a higher percentage of eggs at risk of hatching occurred at the lowest discharge and at the highest temperature (Figure 7B). However, for temperatures lower than the mean daily temperature this effect is reversed, the percentage of eggs at risk of hatching increases with flow (corresponding to lower velocities in the downstream 10 km). This is due to both the

variability in hatching time as a function of temperature and the local hydrodynamics of the river. In addition, for lower temperatures, the river length plays an important role because of the longer required hatching times. Even though at lower temperatures the eggs were located farther from the bottom than at higher temperatures, they required longer drifting times (distances). Therefore, for the majority of simulations with temperatures lower than 23 °C, the centroid of the egg plume had reached Lake Michigan. This result indicates that for this range of temperatures (18 to 23 °C) the river length is short enough and the velocity high enough that the centroid of the egg plume reaches the lake before the predicted hatching time. Eggs that reach the lake before hatching are likely to settle and perish. Therefore, for these scenarios, a majority of the eggs spawned will not hatch despite remaining in suspension through the Lower Saint Joseph River. Figure 7 demonstrates that river characteristics, including water temperature and hydraulic characteristics can lead to significant changes to eggs' risk of hatching.

A video of the animation of FluEgg results using the HEC-RAS simulated hydraulic river input data, an upstream discharge equal to 67.7 m³/s, and a water temperature equal to 27.5 °C is provided in the supplemental material of this paper. A three-dimensional animation of the egg transport in the river system can be generated using the "3D animation of eggs transport (video)" tool available in the GUI. The user can generate a video of eggs drifting in the cells-discretized river in a three-dimensional space. The river cells are displayed with a color code indicating the magnitude of the streamwise velocity.

5. Summary and Conclusions

The lower portion of the Saint Joseph River, a tributary of Lake Michigan, was simulated with FluEgg to estimate the transport and risk of hatching of Asian carp eggs under various water temperatures and hydrodynamic conditions. Two sources of hydraulic input data were used for FluEgg: ADCP data collected by the USGS, and simulated hydraulic data using a HEC-RAS model. Eggs were spawned below Berrien Springs Dam (Berrien Springs, Michigan) under a relatively high flow (upstream discharge equal to 95.96 m³/s) and typical summertime water temperatures (26.5°C). Results using the two different approaches were in agreement.

We analyzed the effect of the dynamic relation between the physical characteristics of the flow and water temperature using FluEgg and a HEC-RAS model (used to simulate a range of flow regimes) on egg dispersion and egg-hatching risk. We analyzed 52 simulations of the transport and dispersion of silver carp covering a range of flow regimes (upstream discharges ranging from 67.7 m³/s and 161.1 m³/s) and water temperatures (18 to 27.5°C). Results showed that the eggs at risk of hatching in the Lower Saint Joseph River varied from zero to 93 percent depending on the river hydrodynamic and temperature conditions. FluEgg simulations illustrated that the most critical condition (highest percentage of eggs at risk of hatching) occurred at the lowest discharge and at peak water temperatures. In

summary, simulation results showed Asian carp eggs can hatch successfully (eggs at risk of hatching greater than 27 percent) in the Lower Saint Joseph River under a broad range of hydrodynamic conditions for temperatures greater than 23°C in a river reach that is about 40 km long. This is much shorter than the 100 km previously assumed to be adequate based on the observation of native spawning rivers (Kolar et al. (2007) as cited in Gorbach and Krykhtin (1980)). However, for temperatures lower than 23°C, a longer river stretch is required.

New features were included in the FluEgg model to better capture the dispersion and hatching dynamics of Asian carp eggs. The features include the ability to simulate the streamwise velocity variations in the transverse direction, the effect of ambient water temperature on the density of the eggs, the internal calculation of the river bed composite roughness, and the estimation of hatching time. The MATLAB®-based graphical user interface for FluEgg was developed to not only support simple, fast, and efficient user interaction, but also to minimize input errors and reduce set-up time. The GUI encourages the use of FluEgg by a larger group of users from different disciplines and backgrounds. FluEgg results provide valuable information necessary to determine whether or not a river can support Asian carp reproduction, egg development, and hatching.

In this paper, the flexibility of FluEgg to simulate a wide range of conditions is demonstrated. The FluEgg model is not only able to characterize in detail the transport and dispersion of Asian carp eggs but also to quantify the percentage of eggs at risk of hatching. The use of a hydraulic model to input the characteristics of the flow into FluEgg allows managers to perform a more holistic analysis of the transport and dispersion of the eggs. FluEgg results demonstrate that the hatching suitability assessment is not a linear problem where the length of the river, velocity, or water temperatures can be assessed individually in order to conclude whether a tributary is suitable for Asian carp reproduction. Rather, a complex analysis is required, one where egg development dynamics, water-quality characteristics, and the hydrodynamics of the river play an important role.

The enhanced FluEgg model is a powerful tool that provides a better understanding of egg transport, dispersion, development, and hatching dynamics in potential spawning rivers. This tool can help managers develop control strategies in rivers with existing Asian carp populations and to prevent their establishment in new ecosystems.

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- 4 Temporal and spatial evolution of the simulated egg mass in the Lower Saint Joseph River using longitudinal ADCP measurements as FluEgg input-hydrodynamic data after Murphy and Jackson (2013). Shown are snapshots with egg position in vertical-longitudinal space (A). Snapshots were taken at 0, 1, 10 and 20 hours post-spawning. Sphere colors represent the post-spawning time at which egg location was captured. Summary of the evolution of the egg mass in the longitudinal (x-direction, B), lateral (y-direction normalized by the water depth, C), and vertical (z-direction normalized by the water depth, D) direction. The solid lines indicate the mean location of the egg mass at different post-spawning times (in red-x, pink-y, and purple-z directions), the colored shaded area delimited by dash lines represents the mean $\pm$ one standard deviation, and the gray solid lines represent the minimum and maximum location of the eggs. 29
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- 6 Comparison of two different approaches to input hydrodynamic data into FluEgg. Normalized vertical position $\left(1 + \frac{z}{H}\right)$ of the centroid of the simulated egg mass as a function of the average downstream distance from Berrien Springs Dam (streamwise position of the centroid) (A) using longitudinal ADCP measurements (in pink) and a HEC-RAS model (in blue). The vertical centroid of the egg mass is normalized by the water depth to facilitate analysis between river-cells. Longitudinal distribution of the eggs at hatching time using longitudinal ADCP measurements (B) and a HEC-RAS model (C) to input the hydrodynamic characteristics of the River into FluEgg. Light blue bars represent the percentage of eggs in suspension at hatching time. Grey bars indicate the percentage of eggs in the lower 5% of the water column; eggs at risk of hatching (E_{RH}) is calculated as the total percentage of eggs in suspension. The right axis represents the cumulative percentage of eggs (CPE) in suspension (solid-black line). Light blue solid lines represent the location of Lake Michigan. 30
- 7 Box-plot of the longitudinal location of the eggs at hatching time at different discharge, as a function of water temperature (A) based on 52 FluEgg-simulations of the Lower Saint Joseph River. The x-axis indicates the distance downstream Berrien Springs Dam (0.0 km - spawning location). Colored boxes represent the middle 50% of the distribution (from the 25th to 75th percentile); shown are the median (solid black lines), error bars show 10th and 90th percentiles (colored lines), and outliers (colored dots). The intensity of the color of the boxes in (A) increases with discharge. Solid gray lines separate groups of simulations with different discharge for a particular temperature. Eggs at risk of hatching (E_{RH}) at different discharge (circles-67.7 m³/s, diamonds-95.96 m³/s, squares-116.5 m³/s, and triangles-161.1 m³/s) as a function of water temperature (B). Hatching time (T_H) as a function of water temperature. 31
- 8 Egg settling velocity in stagnant water calculated using FluEgg subroutines at different post-spawning times for a range of water temperatures. Post-spawning times were used to calculate egg diameter and density based on growth time-dependent relations after Chapman and George (2011b) and Garcia et al. (2013) corrected by temperature. Regression equations for each curve are provided. Coefficient of determination (R^2) for all the equations equal to 1.00. 32

Figure 1: FluEgg main graphical user interface. Input parameters shown in this window correspond to those of the Lower Saint Joseph river simulation. User is guided through a series of steps to setup and run the model. Four main input panels are embedded in the main GUI: (1) River input data, (2) spawning event, (3) egg characteristics, and (4) simulation setup. Two options are available to input the egg characteristics: Using constant egg diameter and density (A) or using diameter and egg density time series after Chapman and George (2011b) (B). View of the FluEgg main graphical user interface after the model has been setup and the simulation run (B). Two new push-buttons are enabled: "New simulation" and "Analyze results".

Figure 2: View of the FluEgg River input file graphical user sub-interface. River Input parameters include: cell number (*Cell*) [unitless], cumulative distance (*CumDistance_km*) [km] (most upstream point is generally considered 0 km), water depth (*Depth_m*) [m], discharge (*Q_cms*) $\left[\frac{m^3}{s}\right]$, streamwise velocity (*Vmag_mps*) $\left[\frac{m}{s}\right]$, lateral velocity (*Vy_mps*) $\left[\frac{m}{s}\right]$, vertical velocity (*Vz_mps*) $\left[\frac{m}{s}\right]$, shear velocity (*Ustar_mps*) $\left[\frac{m}{s}\right]$, and water temperature (*Temp_C*) [°C].

Figure 3: Map of the Lower Saint Joseph River in Michigan.

Figure 4: Temporal and spatial evolution of the simulated egg mass in the Lower Saint Joseph River using longitudinal ADCP measurements as FluEgg input-hydrodynamic data after Murphy and Jackson (2013). Shown are snapshots with egg position in vertical-longitudinal space (A). Snapshots were taken at 0, 1, 10 and 20 hours post-spawning. Sphere colors represent the post-spawning time at which egg location was captured. Summary of the evolution of the egg mass in the longitudinal (x-direction, B), lateral (y-direction normalized by the water depth, C), and vertical (z-direction normalized by the water depth, D) direction. The solid lines indicate the mean location of the egg mass at different post-spawning times (in red-x, pink-y, and purple-z directions), the colored shaded area delimited by dash lines represents the mean $\pm$ one standard deviation, and the gray solid lines represent the minimum and maximum location of the eggs.

Figure 5: Travel time distribution 36.8 km downstream from Berrien Springs Dam (A). Light blue bars represent the percentage of eggs in suspension at hatching time. Grey bars indicate the percentage of eggs in the lower 5% of the water column. Distribution of eggs over the water column at 36.8 km downstream from Berrien Springs Dam (B). Results from FluEgg simulations using a discharge at Berrien Spring Dam equal to $95.95 \text{ m}^3/\text{s}$ and a water temperature equal to 18°C (A,B).

Figure 6: Comparison of two different approaches to input hydrodynamic data into FluEgg. Normalized vertical position $\left(1 + \frac{\bar{z}}{H}\right)$ of the centroid of the simulated egg mass as a function of the average downstream distance from Berrien Springs Dam (streamwise position of the centroid) (A) using longitudinal ADCP measurements (in pink) and a HEC-RAS model (in blue). The vertical centroid of the egg mass is normalized by the water depth to facilitate analysis between river-cells. Longitudinal distribution of the eggs at hatching time using longitudinal ADCP measurements (B) and a HEC-RAS model (C) to input the hydrodynamic characteristics of the River into FluEgg. Light blue bars represent the percentage of eggs in suspension at hatching time. Grey bars indicate the percentage of eggs in the lower 5% of the water column; eggs at risk of hatching (E_{RH}) is calculated as the total percentage of eggs in suspension. The right axis represents the cumulative percentage of eggs (CPE) in suspension (solid-black line). Light blue solid lines represent the location of Lake Michigan.

Figure 7: Box-plot of the longitudinal location of the eggs at hatching time at different discharge, as a function of water temperature (A) based on 52 FluEgg-simulations of the Lower Saint Joseph River. The x-axis indicates the distance downstream Berrien Springs Dam (0.0 km - spawning location). Colored boxes represent the middle 50% of the distribution (from the 25th to 75th percentile); shown are the median (solid black lines), error bars show 10th and 90th percentiles (colored lines), and outliers (colored dots). The intensity of the color of the boxes in (A) increases with discharge. Solid gray lines separate groups of simulations with different discharge for a particular temperature. Eggs at risk of hatching (E_{RH}) at different discharge (circles- $67.7 \text{ m}^3/\text{s}$, diamonds- $95.96 \text{ m}^3/\text{s}$, squares- $116.5 \text{ m}^3/\text{s}$, and triangles- $161.1 \text{ m}^3/\text{s}$) as a function of water temperature (B). Hatching time (T_H) as a function of water temperature.

Figure 8: Egg settling velocity in stagnant water calculated using FluEgg subroutines at different post-spawning times for a range of water temperatures. Post-spawning times were used to calculate egg diameter and density based on growth time-dependent relations after Chapman and George (2011b) and Garcia et al. (2013) corrected by temperature. Regression equations for each curve are provided. Coefficient of determination (R^2) for all the equations equal to 1.00.

Table 1: Summary of simulated hydrodynamic characteristics of the Lower Saint Joseph River for a range of flow regimes obtained from HEC-RAS simulations. Where, Q^* is the headwater-discharge at Berrien Spring Dam, $\bar{Q}$ is the mean discharge, $\bar{H}$ is the mean water depth, $\bar{u}$ is the mean streamwise velocity, and $\bar{u}_*$ is the mean shear velocity corresponding to each of the four flow regimes at Berrien Springs Dam.

Q^* [m ³ /s]	$\bar{Q}$ [m ³ /s]	$\bar{H}$ [m]	$\bar{u}$ [m/s]	$\bar{u}_*$ [m/s]
67.7	62.5	2.5	0.49	0.064
95.96	88.7	3.0	0.53	0.066
116.5	107.7	3.4	0.55	0.067
161.1	148.9	4.2	0.56	0.067

Inside FluEgg

Adapted from Garcia et al. (2013)