HYDRODYNAMIC MODELING TO EVALUATE THE INFLUENCE OF CONSTRUCTED SIDE-CHANNEL HABITAT ON LARVAL DRIFT OF PALLID STURGEON IN THE LOWER MISSOURI RIVER

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Abstract: Larval drift is a critical phase of ontogeny for many species of lotic fishes. Downstream advection and dispersion of drifting larvae or eggs is controlled by the complex interaction of flow regime, channel planform, local channel morphology, and the resulting hydraulic gradients. In many regulated rivers, channel engineering and perturbations to the flow regime may disrupt natural dispersal processes and prevent successful recruitment of native fishes. Here, we explore the influence of flow regime and channel morphology on the downstream transport, dispersion, and retention of free embryos of pallid sturgeon (*Scaphirhychus albus*), an endangered species endemic to the Mississippi River basin and the focus of significant conservation effort on the Missouri River. The transition from drifting free embryo to exogenously feeding larvae has been identified as a potential life stage bottleneck for the pallid sturgeon. We use a two-dimensional hydrodynamic model to evaluate the sensitivity of drift and dispersion to in-channel navigation structures, constructed shallow-water habitat, and flood hydrology. In the simulations, larvae were treated as passively drifting particles and calculated retention times were used as an index of potential for settling and retention within specific environments. During low flows, retention of larvae is promoted by shallow, low velocity conditions provided by constructed side-channel habitats. At higher flows, retention is driven by overbank flows that inundate the floodplain. Based on insights gained from the analysis of field data and modeling outputs, we consider the effects of flow regime modifications or channel re-engineering on the distribution and retention of free embryos within the Lower Missouri River.

INTRODUCTION AND BACKGROUND

The Missouri River has been profoundly transformed by over two centuries of river management and channel alterations (Jacobson and Galat, 2006). The river is the longest river in the United States and has a drainage area of more than 1,300,000 km^2, draining the eastern Rocky Mountains, Great Plains, and a small area of Canada (Figure 1A). Six large mainstem dams have substantially altered the natural flow regime, reducing the magnitude of annual floods and elevating base flows (Galat and Lipkin, 2000). The Lower Missouri River (LMOR) is defined as the 1,300 km of the Missouri River downstream from Gavins Point Dam near Yankton, South Dakota to the confluence with the Mississippi River, near Saint Louis, Missouri. Extensive channelization and construction of training structures (e.g. dikes and bank revetment) in the LMOR have converted the channel from one that was historically a broad, shallow, braided channel to a relatively deep and narrow navigation channel with less morphologic diversity (Jacobson and Galat, 2006).

Ongoing efforts to inform management of the Missouri River as part of Missouri River Recovery Program are focused on the recovery of three endangered or threatened species – the pallid sturgeon (*Scaphirhynchus albus*), piping plover (*Charadrius melodus*), and interior least tern (*Sternula antillarum athalassos*) (U.S. Fish and Wildlife Service, 2000, 2003). Pallid sturgeon are endemic to the Mississippi River basin and are the focus of significant conservation efforts on the Missouri River. Subjected to years of heavy commercial fishing, declining water quality, a highly altered flow regime, and extensive habitat alternations, the pallid sturgeon was formally listed as a federally endangered species in 1990. Current recovery efforts focus on habitat restoration and hatchery augmentation, implemented through an adaptive management framework. However, it remains unclear what factor(s) are primarily responsible for decline of the species and what actions may be most effective in promoting successful recruitment.

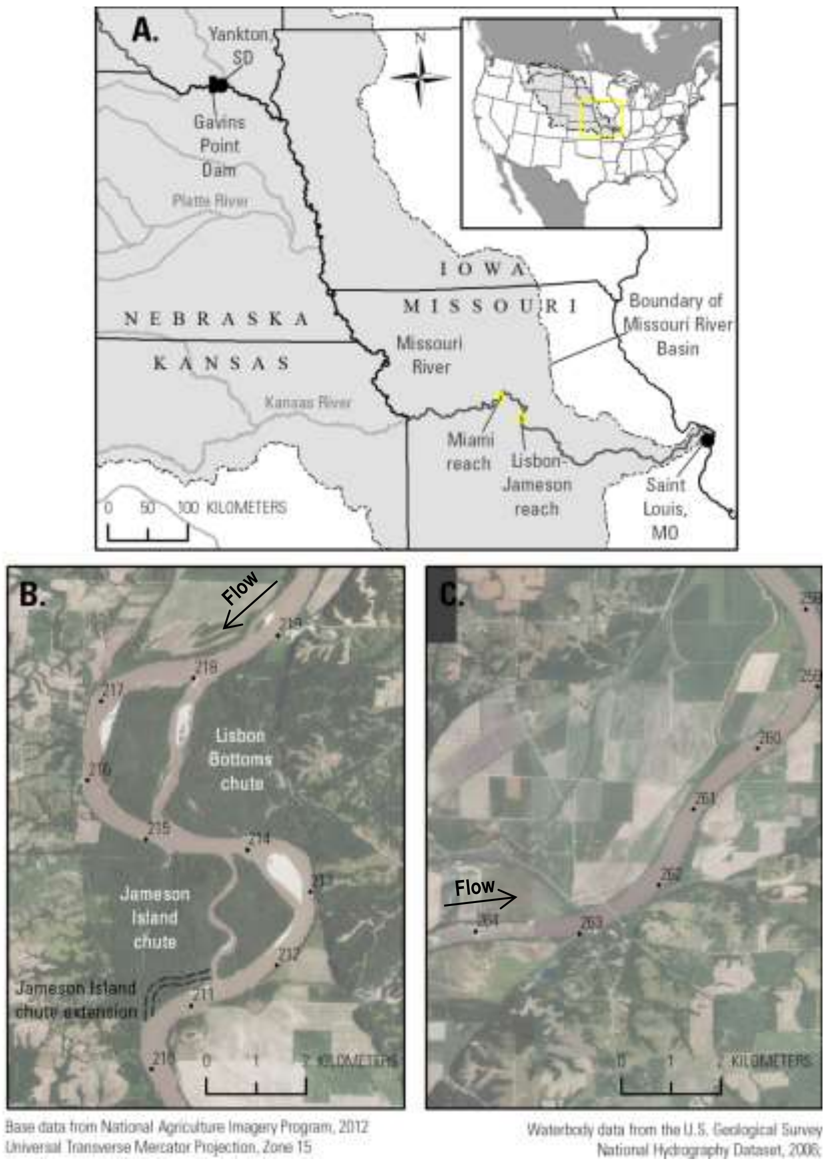

Figure 1 (A) The Lower Missouri River, (B) the Lisbon-Jameson reach (River Mile (RM) 210.0-219.1), and (C) the Miami reach (RM 259.6 – 263.5). River miles are the customary units of longitudinal measurement on the LMOR. They are measured upstream from St. Louis, MO and correspond to the channel position in 1960.

Recent research identifies the transition from drifting free embryo to exogenously feeding larvae as a life stage that may limit successful recruitment of pallid sturgeon in the Missouri River (Kynard and others, 2007; DeLonay and others, 2009a; Braaten and others, 2012). As is common for many lotic fishes (Muth and Schmulbach, 1984; Brown and Armstrong, 1985; Pavlov and others, 2008), pallid sturgeon undergo a period of drift and dispersal post-hatch. During this developmental phase, sturgeon free embryos may be transported several hundred kilometers downstream from the site at which spawning occurred (Kynard and others, 2007). On regulated rivers such as the Missouri River natural patterns of downstream transport and dispersal may be disrupted by extensive channel modifications and flow regulation (Erwin and Jacobson, 2014).

Construction of side-channel chutes has emerged as one of the primary restoration techniques used in the LMOR (Jacobson and others, 2004). The relatively shallow depths and slow velocities provided by such features are thought to increase the retention of drifting larvae within the LMOR, disrupting downstream advection in the channelized portion of the river and providing an environment suitable for foraging when the free embryos transition to exogenous feeding. Here, we present the preliminary results of a hydraulic modeling study designed to explore the influence of flow regime and channel morphology on the downstream transport, dispersion, and retention of larval pallid sturgeon.

STUDY AREA

We constructed two-dimensional hydrodynamic models for two reaches of the LMOR that represent end-member conditions. The Miami (Figure 1C) reach represents a typical channelized and leveed reach of the river, with relatively little in-channel complexity. The Lisbon-Jameson reach (Figure 1B) contains two constructed side-channel chutes and a greater degree of floodplain connectivity than occurs on most of the LMOR.

The 14.6-km Lisbon-Jameson reach is located approximately 22 km upstream from Boonville, MO and encompasses both the Lisbon Bottom and Jameson Island chutes (Figure 1B). The site is located within the U.S. Fish and Wildlife Service's Big Muddy National Fish and Wildlife Refuge and levee setbacks allow floodwater to inundate adjacent floodplains. The Lisbon Bottom chute (upstream chute) was formed as the result of levee breaks during the floods of 1993 and 1995 (Jacobson and others, 2004). The chute was allowed to evolve with minimal intervention until 1999, when a grade-control structure was installed at the downstream end of the chute and a notched hydraulic control structure was installed at the entrance to the chute. The Jameson Island chute (downstream chute) was intentionally constructed by the U.S. Army Corps of Engineers with the objective of creating habitat for pallid sturgeon (U.S. Army Corps of Engineers, 2012). Construction of the pilot channel occurred in 2006-2007 and the channel was subsequently widened during naturally occurring high flows. A chute extension was completed in summer 2014. These channel modifications, coupled with a high degree of floodplain connectivity and a relatively wide mainstem, produce a reach that represents one of the best-available sections of aquatic habitat within the LMOR.

The 8.4-km Miami reach is located at the town of Miami, MO (Figure 1C). Restoration activities in this reach have been limited to some dike notches, and levees restrict access to the floodplain. The reach is characterized by a navigation channel that is typical of the LMOR downstream from the border of Nebraska and Kansas. Both the Miami and Lisbon-Jameson reaches contain extensive bank revetment and regularly spaced river-training structures, or dikes, designed to maintain a self-dredging navigation channel.

METHODS

The Lisbon-Jameson hydrodynamic model was developed following an extensive field campaign in spring and summer 2014. The Miami model was originally developed by USGS in 2006-2007 to evaluate the effects of modifications of releases from Gavins Point Dam on pallid sturgeon habitat dynamics. Methods used in the construction of the Lisbon-Jameson hydrodynamic model are described below, and methods used in the construction of the Miami model are described in detail by Jacobson et al. (2009).

Data Collection: Topographic data for the hydrodynamic models were generated by integrating data from hydroacoustic surveys, topographic ground surveys, and existing aerial LiDAR. Hydroacoustic surveys were performed using methods established by USGS (Reuter and others, 2008; Reuter and others, 2009). Surveys were conducted using a 200 kHz single-beam echo sounder with an 8 degree transducer coupled with real-time kinematic global positioning system (RTK-GPS) equipment to provide precise positioning. The echo sounder was calibrated for draft and sound velocity using a bar check. At Lisbon-Jameson, transects were surveyed at regularly-spaced 50-m increments in the main channel and 20-m increments in the chutes. Hydroacoustic data were supplemented by RTK-GPS ground surveys of sub-aerially exposed sand bars. Floodplain and bank topography was provided by aerial LiDAR collected in 2007 (National Elevation Dataset; http://ned.usgs.gov). Field data for the Miami reach were collected in 2006 and 2007, and transects were surveyed at 20-m intervals throughout the model domain (Jacobson and others, 2009).

Water surface profiles were surveyed over a range of discharges for model calibration. At Lisbon-Jameson, 6 main stem water surface profiles were surveyed at discharges ranging from 1,135 – 5,974 m^3s^{-1}. At Miami, seven water surface profiles were surveyed over discharges ranging from 588 – 3,136 m^3s^{-1}. Velocity data for model validation were acquired using 600 and 1200 kHz Teledyne RDI Rio Grande acoustic Doppler current profiler (ADCP) units, also integrated with RTK-GPS.

Hydrodynamic Modeling: We developed two-dimensional, depth-averaged hydrodynamic models to predict water-surface elevations, depths, and depth-averaged velocity throughout both study areas. Modeling was conducted using TUFLOW (BMT Group Ltd., Brisbane, Australia) and implemented within the Surface-water Modeling System (SMS, Aquaveo, Inc., Provo, Utah). TUFLOW solves the vertically-averaged, two-dimensional shallow water equations by means of finite difference method on a cartesian grid. The Miami model was originally developed and calibrated using an alternate hydrodynamic modeling program (see Jacobson and others, 2009), and was converted to TUFLOW as part of this analysis to facilitate comparison with the Lisbon-Jameson model. For the current application, the Miami model domain was extended to include overbank areas.

Topographic and bathymetric data were used to generate a computational grid for each modeling domain (4x4 m grid for Miami and 10x10 m grid for Lisbon-Jameson). We calibrated the models to measured water-surface elevations by iteratively adjusting channel roughness. Once calibrated, we generated steady-state simulations for discharges ranging from base flow to overbank floods in 200-m^3s^{-1} increments (550 – 6,550 m^3s^{-1} at Miami and 600 – 7,000 m^3s^{-1} at Lisbon-Jameson).

We implemented a particle tracking algorithm within SMS to estimate residence times of passively drifting particles in each model domain (Aquaveo LLC, 2013). On a cell-by-cell basis, velocity vectors and magnitudes were used to generate flow paths through the model domains. Each simulation was seeded with 10,000 particles whose starting positions were uniformly distributed along a cross section perpendicular to flow near the upstream boundary of each reach. Simulations were run for 36 hours, at which point those particles not recirculating in eddies had long since exited the model domain.

RESULTS

Maps of inundation and velocity generated by flow simulations depict markedly different flow patterns in the two reaches. At Miami, simulated depth-averaged velocities during base flows display relatively little cross-stream variability due to the confined flow, relatively uniform channel width, and low sinuosity (Figure 2A). Similar patterns occur during bankfull flows; depth-averaged velocities are greater throughout the model domain, and eddies downstream from dikes become less prominent (Figure 2B). Overbank flows are contained within a relatively narrow corridor along the channel due to extensive levees along the reach (Figure 2C). For the entire range of flows simulated, the primary sources of hydraulic variability within the active channel are dikes used to maintain the navigation channel.

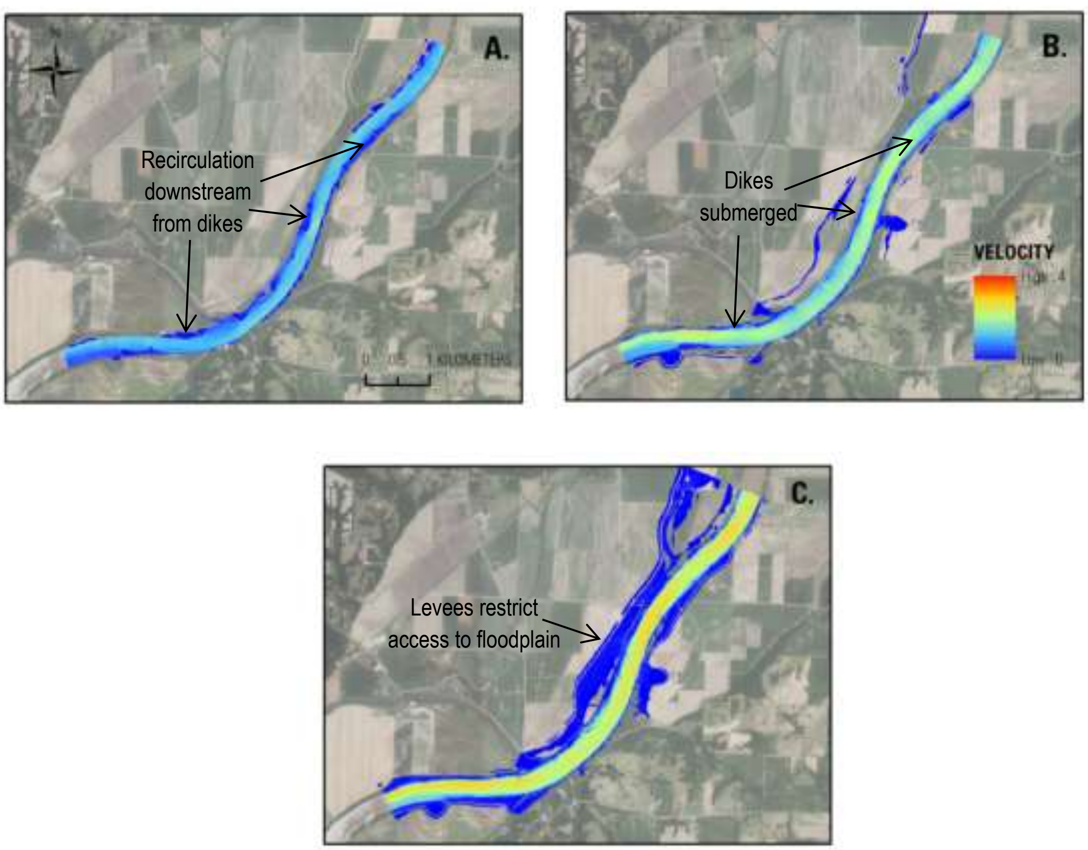

Figure 2 Simulated depth-averaged velocities for a subset of flows in the Miami modeling reach at (A) 950 m^3s^{-1}, (B) 3,750 m^3s^{-1}, and (C) 6,550 m^3s^{-1}.

The Lisbon-Jameson reach is morphologically and hydraulically complex. At base flows, bars, exposed dikes, and constructed side-channel chutes provide areas of low velocity and backwaters (Figure 3A). As discharge approaches bankfull conditions, bar and dikes become inundated but these features still provide substantial zones of hydraulic refugia (Figure 3B). Substantial areas of low velocity occur along the channel margins in the upstream and more developed chute, Lisbon; thus a wide distribution of velocities is maintained during moderate floods (Figure 4). As discharge overtops channel banks, mean velocities in both the main channel and chutes increase, but extensive areas of low velocity occur across the floodplain (Figure 3C).

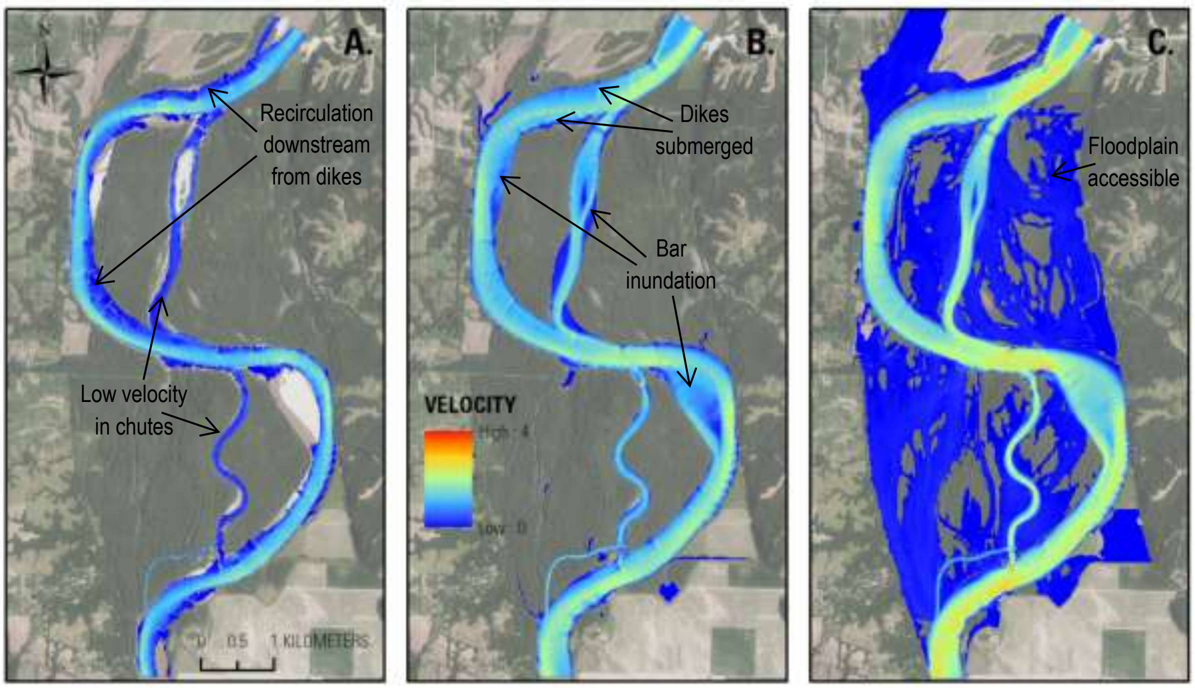

Figure 3 Simulated depth-averaged velocities throughout the Lisbon-Jameson modeling reach at (A) 1,000 m^3s^{-1}, (B) 4,000 m^3s^{-1}, and (C) 7,000 m^3s^{-1}.

The patterns in velocity depicted by the hydrodynamic simulations directly translate into differences in the routing of passively-drifting particles through the model domains. For the full range of discharges evaluated there is much greater variability in particle residence times calculated at Lisbon-Jameson as compared to those in Miami (Figure 5). Mean velocities do not differ substantially between the two reaches because currents in the navigation channel efficiently advect particles downstream. Thus, as flows increase, the median residence time steadily decreases in both reaches. In the Lisbon-Jameson reach, however, there is greater potential for retention within low-velocity environments, thus resulting in the long-tailed distribution of particle residence times observed for all flows (Figure 5A). Additionally, the slight increase in the distribution of residence times at Lisbon-Jameson during large floods reflects the retention of particles on the floodplain that occurs during overbank flows. This effect is not observed at Miami because of the limited floodplain connectivity and the overwhelming ability of the navigation channel to convey water downstream.

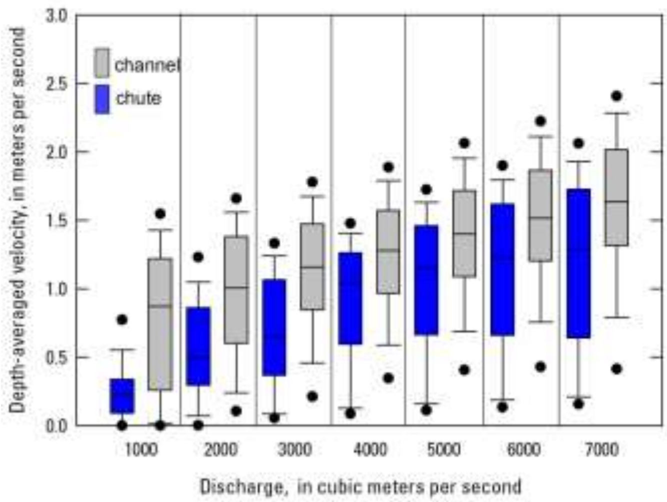

Figure 4 Box plot depicting the distribution of simulated velocities in the Lisbon-Jameson model, calculated for the two chutes and the main channel across a range of discharges.

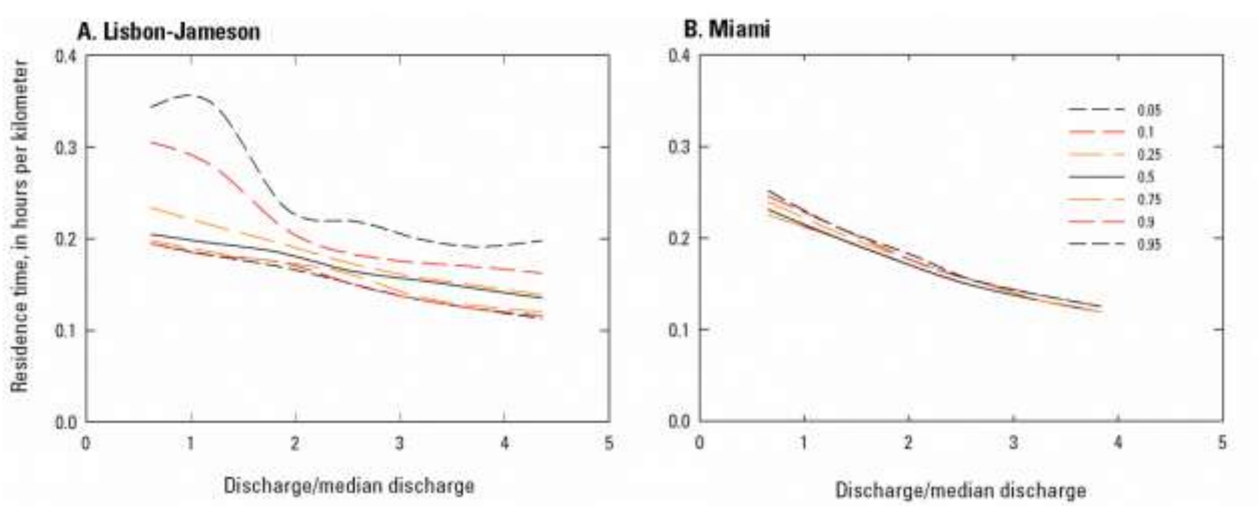

Figure 5 Distribution of particle residence times calculated for the Lisbon-Jameson (A) and Miami (B) modeling reaches. To allow comparison of calculated residence times between the two modeling reaches, values were normalized: (1) discharge was normalized by median discharge for each reach; and (2) residence time was normalized by mean reach length, as measured along the channel centerline throughout the model domain. Lines correspond to percentiles of particles (0.05 – 0.95), as indicated by legend in (B).

DISCUSSION AND SUMMARY

Once hatched, the transport and fate of pallid sturgeon larvae are largely unknown. Free embryos may drift for 9-17 days, depending on temperature-mediated development rate, before using up their yolk sac and transitioning to exogenous feeding (Kynard and others, 2002; Braaten and others, 2008; Braaten and others, 2012). During this time, swimming capabilities increase, and field experiments suggest that they tend to concentrate in the thalweg (Braaten and others, 2010) and drift at velocities slightly slower than mean water velocity (Braaten and others, 2008). Studies in the Upper Missouri River suggest that older larvae tend to drift slower as they settle, or orient to benthic habitats (Braaten and others, 2012), but the degree to which free embryo larvae engage in volitional swimming behaviors in the high velocities of the Lower Missouri River is unknown. Flume studies have begun to address these questions (Kynard and others, 2007; DeLonay and others, in press), but scaling up from experimental settings, where maximum flows have not exceeded 0.30 ms^{-1}, to the LMOR, where typical depth-averaged velocities are greater than 2 ms^{-1}, remains a fundamental challenge. Mean water velocities in the Lower Missouri River suggest larvae may drift hundreds of km per day (DeLonay and others, 2009b), but it is unknown how complex hydraulics along the river may interact with progressive larval development to determine actual drift distances, where larvae may be retained, and whether retention sites provide necessary food resources and protection from predation.

The analysis presented here highlights the geomorphic and channel engineering features that create channel complexity and promote retention of drifting particles within the LMOR. Typical sections of the LMOR, represented by the Miami modeling reach, are characterized by relatively uniform channel widths, low morphologic variability, and limited access to the floodplain. Thus, drifting particles or organisms are efficiently advected downstream and may not be able to exit the thalweg before the point at which they need to transition to the benthos and initiate exogenous feeding. The degree of exchange of free embryos between the thalweg and typical wing-dike structures is unknown. Restored reaches, such as Lisbon-Jameson, provide more complex hydraulic conditions that may transport the larvae into channel-margin habitats. It is hypothesized that such environments provide the food and cover required for survival of juvenile pallid sturgeon.

Several features of the Lisbon-Jameson reach contribute to hydraulic complexity captured by the model outputs and resulting particle tracking simulations. Heterogeneity in the simulated distribution of velocities results from not only the presence of constructed side-channel chutes, however, but also the relatively large channel width, variability in channel width, and sinuosity that lead to the secondary currents which drive the formation of bars. The reach also displays greater floodplain connectivity than much of the LMOR. Together, these characteristics of the Lisbon-Jameson reach increase channel complexity and hydraulic heterogeneity, thus increasing opportunities for drifting free embryos to exit the thalweg and access foraging habitats. Further research is needed to evaluate the relative contributions of these different geomorphic features to the retention of drifting free organisms within the LMOR in order to inform ongoing restoration efforts. Additionally, the presence of hydraulic conditions that are more conducive to retention and settling alone does not indicate that larvae will encounter conditions supportive of foraging or with adequate food resources. Identifying the habitat requirements of pallid sturgeon during these early life stages remains an area of active research.

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