High Resolution Mapping of Aquatic Habitat at the River Corridor Scale Using Hydro-Acoustic Measurements of 3D Current Velocities and River Analyzer Software.

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ABSTRACT

Restoration of sensitive fish species often requires quantifying habitat conditions that change seasonally as water is regulated and supplies vary. Fluid dynamic modeling can provide estimates of flow, whereas high density hydro-acoustic measurements can provide bathymetry, 3D water velocities and current directions spanning the river channel from shore to shore and downstream over hundreds of kilometers using Acoustic Doppler Profilers (ADP). We use an array of boats, each equipped with an ADP and compass-oriented GPS to survey downstream in parallel tracks to map river flows and channel morphology. Data are then interpolated over the entire river using River Analyzer, a specifically-designed data integration software. Hydraulic data are then meshed with floodplain topography and aerial imagery. Repeat surveys spanning observed water levels allow calculating habitat availability at intermediate river stages or reservoir elevations. This data collection and analysis approach allows empirical assessment of river habitat conditions at the resolution needed to examine species' life-cycle requirements. In September 2014 we mapped a 4 km reference reach at a discharge of 170 cms (6000 cfs) and then again in September 2015 we mapped a 50 km reach at a discharge of 127 cms (4,500 cfs). In June 2016, at a discharge of 255 cms (9,000 cfs) we mapped the entire 338 km of the Missouri River downstream of Fort Peck Dam, Montana USA, to the headwaters of Sakakawea Reservoir in just ten days. These studies quantified 3D flow patterns that control the drift speed and dispersal of

endangered pallid sturgeon larvae. Results revealed larval drift speeds and pathways from various hypothetical spawning locations, enabling us to assess if drifting larvae have sufficient river residence time to survive, or if they are swept into Sakakawea Reservoir where they apparently die. The results from the 255 cms discharge over the entire distance demonstrated that less than 1% would drift the entire distance in approximately 6.5 days if the embryos could maintain position high in the water column and in the fastest portion of the thalweg. Embryo drift was thought to occur near the bottom boundary layer. Our analysis demonstrated that bottom boundary drift would take approximately 31 days. The results from the 170 cms reference reach drift concluded that drift for the entire 338 km would take 16 days maintaining a mean drift rate but with similar wide dispersion. Drift analysis at the lowest discharge (127 cms) showed very low dispersion over most of the 50 km mapped due to conversion of drift paths over drift path separation. This was due to confinement of the channel to the thalweg at this low and slow drift condition.

The results from Martoz and Lorang 2017 and these additional reference reach data indicate that drift duration is not the limiting factor for pallid sturgeon recruitment and that maximum dispersal to potential viable shallow water rearing habitat can be achieved by targeted regulated flow from Fort Peck. From a management perspective it is essential to understand the complex flow field and how that controls pallid sturgeon embryos drift and what discharge levels maximizes dispersion to rearing habitats. This can be achieved with new technologies providing empirical data rather than model estimates to support that understanding and subsequent decisions regarding operation of Fort Peck aimed at pallid sturgeon recovery.

INTRODUCTION

Most people are familiar with salmon migrations given the impressive historical numbers of fish that migrate rivers in the northern hemisphere and the cultural and economic impacts those runs have bestowed on humans. Many runs are now nearly extinct and hence these fishes are listed as endangered by US Fish and Wildlife under the endangered species act which requires careful examination of flow regulation aimed at species recovery. The seasonal migration of anadromous adult fishes and subsequent outmigration of juveniles represents a dramatic migration by aquatic species. Many riverine organisms undergo large scale reproductive (spawning) migrations but many others undergo to smaller-scale diel migrations focused around feeding and migration towards hydraulic refugia during flooding or cold-pool migration for temperature refugia during season warm low flow conditions. All of these fish migrations evolve navigating complex channels and flow fields where taking advantage of bottom boundary layers and deep pools provide metabolic advantages and resting habitat. Out migrating juveniles often drift with the currents with many able to swim to and away from less favorable flow and depth environments.

Much of the attention paid to fish migration has been on large fishes including salmonids and sturgeon and relatively little information about the upstream migration of many groups of smaller-bodied fishes such as smelt, minnows, stickleback, catfish, suckers and carp. The disparity is mainly due to the economic value of large species, a focus on sport fisheries and the difficulty in using techniques such as tagging and telemetry on small fishes. Migration frequently involves substantial risks both from natural (e.g., predation, starvation, standing) and anthropogenic (e.g. fishing, barriers) sources hence even small-scale movements on the order of a few kilometers can be parlous on one hand and mandatory on the other for individual survival and to complete critical life-cycles. The hydrodynamics of a river channel are complex due in part to seasonal flow change, regulated flow and interaction of the flow with a complex bathymetry. Hence migrating fish, both upstream migrating adults and downstream out-migrating juveniles in the case of salmonids or drifting embryos associated with sturgeon and other warm water fishes face many challenges related survival and completion of life-cycle stages. To survive as individuals and as a population require that they adapt to a wide range of complex flow hydraulics and adapt in such a way that they use that complexity to their advantage.

Natural reproduction of endangered Pallid Sturgeon (Scaphirhynchus albus) virtually ceased in Montana after dams were constructed on the Missouri River and flow regulation began. High mortality occurs during the first year, predominantly between the fertilized egg stage and when larvae absorb their yolk sac and begin feeding exogenously. Questions remain about the fate of drifting larvae. In June 2016, nearly 700,000 free-embryo pallid sturgeon were released into the Missouri River just downstream of the Milk River confluence (Fig. 1). An intensive netting effort attempted to recapture drifting embryos at incremental points downstream to document their drift speed and dispersal. Unfortunately, only two embryos were recaptured beyond the first downstream netting station. Low recapture rates were expected due to the rapid and broad dispersal of drifting embryos and the extremely small ratio of net aperture to channel cross-sectional area. Consequently, net captures could not account for over 99% of the released embryos.

As part of this experiment, Freshwater Map measured the bathymetry of the Missouri River and the associated complex flow field controlling particle drift throughout the study reach (Marotz and Lorang 2017). We were able to track flow paths along the bottom boundary layer and for the mean water column over the entire 338 km reach and thereby determine potential drift speeds and pathways that would both carry the larvae downstream and disperse them into shallow water habitats along the way. Empirical measurement of the flow field in this manner not only allowed dispersal tracking and identification of probable shallow water habitats for juvenile rearing but also allowed determination of the drift duration. Similar measurement of the flow field at lower discharges, although over much shorter reaches, allowed a first order look at dispersion at different discharge levels. This paper summarizes the results from these shorter reference reaches in light of trying to use such empirical data in a manner that answers pressing flow regulation questions, mainly: what is the “sweet spot” in terms of flow release from Fort Peck reservoir that maximizes larvae dispersal while at the same ensuring sufficient residual time for embryonic development to an exogenously feeding stage and maintain connection to shallow water habits during early stage of juvenile rearing. This go-with-the-flow lagrangian approach to mapping rivers is new to the field of river restoration and flow regulation for which it is more common to use traditional cross-sectional data collection and hydraulic modeling. Given the new technologies in both data collection using ADP's and GPS coupled with robust data processing we can now produce 3D views of both river bathymetry and the complex three-dimensional flow field that is extremely useful for answering important resource management questions at a fraction of the cost of traditional modeling in near real-time and based on empirical data rather than model estimates.

STUDY AREA

Freshwater Map conducted 3D hydraulic mapping throughout 338 km of the Missouri River downstream of Fort Peck Dam in Montana from the Milk River confluence to the headwaters of SAK near Williston, North Dakota (~375 river km Fig. 1).

Figure 1. A location map showing the 335 km reach between Fort Peck dam and Sakakawea Lake.

The riverbed is sandy with infrequent patches of gravel, cobble and bedrock outcrops. The channel thalweg is braided with complex flow patterns and eddies downstream of major channel spanning sandbars, islands and side channel backwaters and another complex off-channel floodplain aquatic habitat. Fort Peck Dam releases cold, clear hypolimnetic water that mixes with warmer and turbid water downstream of the Milk River confluence which is located approximately 15 km below the dam. Dam operations control high flows, which has reduced the river's ability to transport its sediment load. Hydraulic mapping coincided with stabile river flows ranging from 247 cms at the confluence of the Milk River just downstream of Fort Peck Dam, to 287 cms upstream of the confluence of the Yellowstone River, and 612 cms at the bridge in Williston ND (June 19 through June 28, 2016).

The Missouri River, for the most part, has a meandering sand bed channel dominated by very large channel spanning crescentic sand bars that often split the thalweg into two separate shore-attached channels that merge, reorganize, and spit again around bars and islands in the straight reaches between meander bends. Classic point bars dominated the inside of meander bends often extending downstream as channel-crossing transverse bars throughout the reach. Navigation is extremely difficult due to high turbidity and the fact that the channel is choked with sand forming large bars. These bars form islands and shore-attached shelves with backwater channels during lower discharges.

We mapped 225 km of the thalweg using high resolution (2.54 cm) multi-beam sonar and found that it was dominated by large sand “mega-ripples” with amplitudes reaching over a meter and wavelengths up to 10 to 15 m and that the bank was scalloped due to gravity slumping resulting in many large trees with root wads and other large wood debris that had become embedded in the channel bottom and submerged below the water surface (Fig. 2). These large bedforms and wood created complex micro-flow habitat throughout the length of the thalweg resulting in many eddies of zero flow either in the lee of the mega-ripples bedforms or lee of large wood that were recorded by the flow data. These areas become “stall zones” for drifting embryos greatly slowing their downstream drift many of which were identified in the drifter analysis presented below. The thalweg ranged in depth from 6 to 8 meters in the deepest scour holes above the confluence with the Yellowstone River to as shallow as a few centimeters. The average depth of the thalweg was 2 to 3 m. The contribution of flow from the Yellowstone increased the depth of the thalweg for the remaining 38 km of the 338 km study site by nearly a factor of 2.

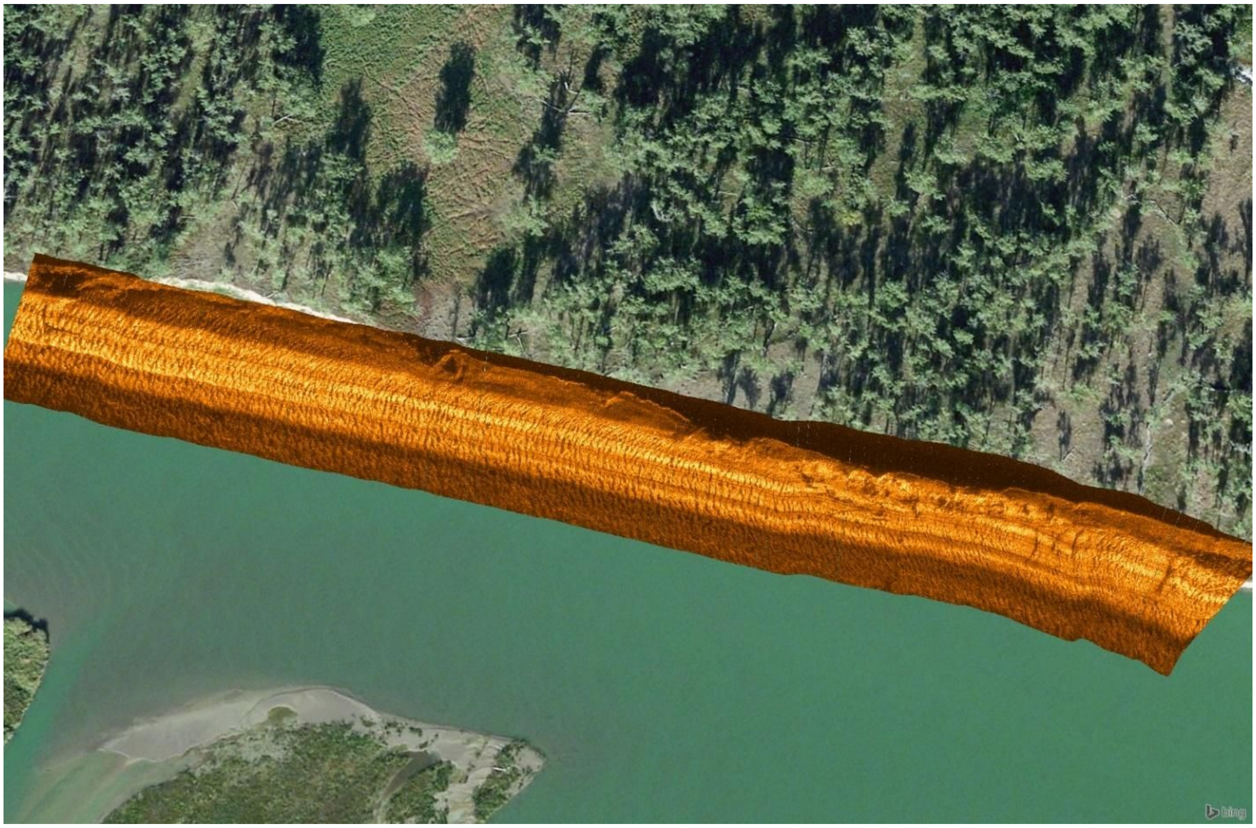

Figure 2. A 60 m wide by 2.5 km long sonar image of the thalweg from the Missouri River embedded onto an aerial image shows a continuous field of “mega-ripple” bedforms composing the sand bed river bottom, as well as complex field of wood debris and gravity slumps along an eroding river bank.

METHODS

An array of eight, one-person pontoon boats floated in parallel tracks, spanning the width of the Missouri River, from the Milk River confluence to the headwaters of SAK (Figs. 3 and 4). Each boat was custom-wired for power and deployed a Teledyne River-Pro Acoustic Doppler Profiler (ADP), a compass-oriented Satellite V 102 GPS unit, and an onboard computer for data storage. GPS Compasses provided 0.5 m position accuracy, maximizing accurate velocity estimates from the acoustic beams compared with the internal backup magnetic compass. Boats had 2.3 HP Honda outboards to maintain progress downstream against wind and over long stretches of slow currents. If a boat lost bottom tracking, the surveyor motored back upstream to resume mapping. Additional mapping tracks were collected for greater data resolution in areas of complex channel and flow features. We averaged 35 km per day with an average spacing of 20 m between transect lines.

Figure 3. A photograph showing the fleet of small rafts from which the hydroacoustic data were collected. The inset shows configuration of the instruments and field tablet.

During data acquisition, hydraulic data from the ADPs and surface temperature were recorded simultaneously with each boat's GPS location at a rate of two measurements per second continuously while floating the river. Water column profiles of flow velocities and current vectors were measured in 10-cm depth increments from the surface to the bottom boundary layer(Fig. 4). Over 16 million data ensembles were collected, resulting in over 256 million spatially dispersed measures of flow velocity and current direction that were compiled into a map of the Missouri River and fed into the drift analysis.

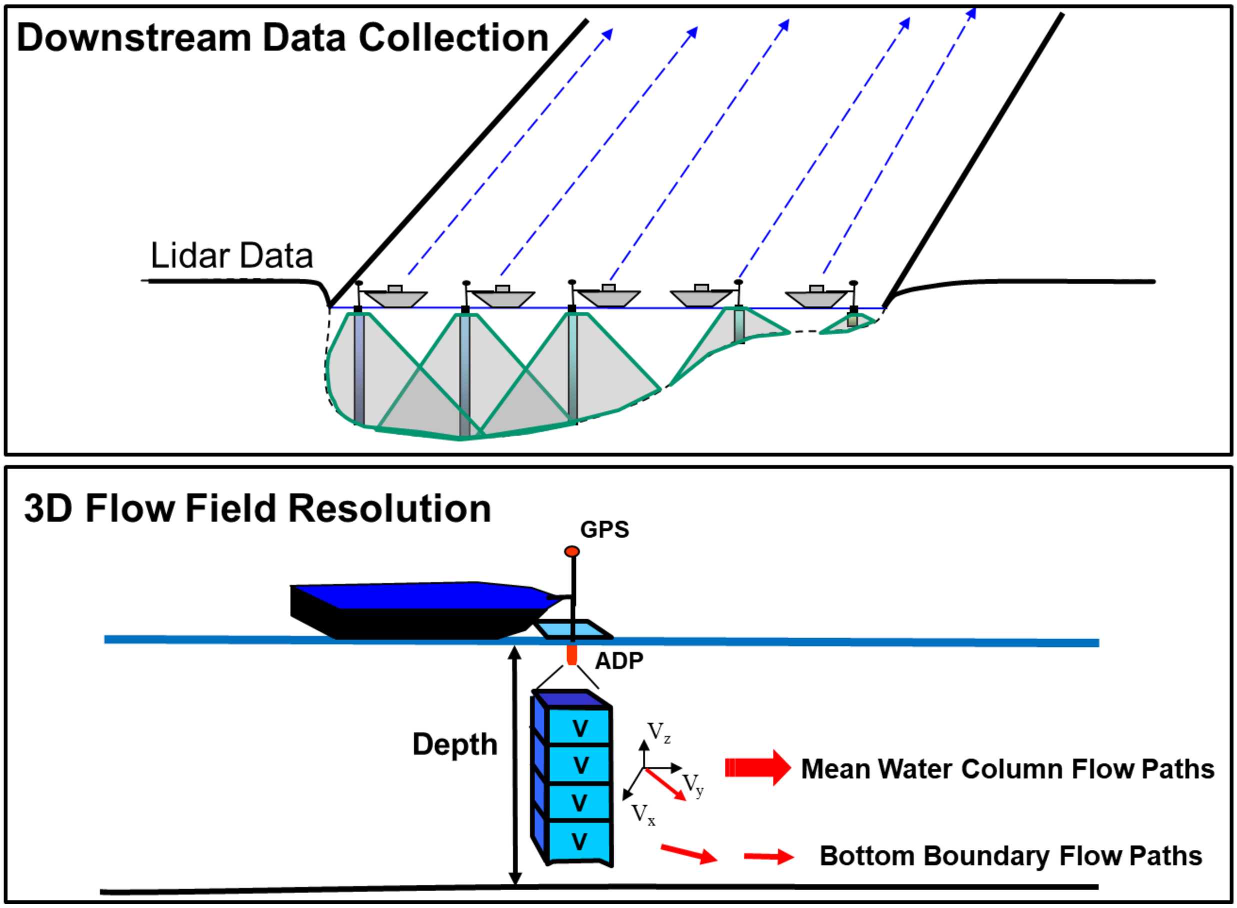

Figure 4. The top schematic depicts boats spread out across a river channel, floating downstream collecting hydroacoustic data with ADP's and position and orientation with GPS compasses. The gray shaded areas depict the spread of acoustic beams with a central bottom looking beam. The bottom schematic shows a stacked array of vertical bins composing a data ensemble. Each bin is 10 cm thick and includes flow velocity and direction information that is collected from a blanking distance from the surface and another from the bottom. Actual depth is determined by the strongest return signal from the center beam. A data ensemble is recorded twice per second from 30 cm to a maximum depth of 30 m. River Analyzer interpolates between the data ensembles to create transect slices of the river channel and flow field and it extracts flow data from user defined bins (e.g. bottom 3 bins or mean for all bins) to determine flow path patterns and velocity from which the drift analysis is conducted.

Field data (bathymetry, 3D velocities and current vectors) were processed using Freshwater Map's patent pending proprietary software, River Analyzer (RA) and associated software components. River maps were overlaid on aerial photographs provided by USDA 2015 National Agriculture Imagery Program, collected at approximately the same river stage as our ADCP data.

RA interpolates linearly between adjacent water column ensembles in 10-cm depth layers, and exponentially between the deepest flow measurement and the river bottom and horizontally from the nearest survey path to the river banks. The mean distance between ADP transects was 20 m and the average data density was 0.25 ensembles per square meter of river surface. Data were displayed in ArcGIS aerial plat maps of river bathymetry, mean water-column flows, and surface water temperatures, in 100 river segments. In addition, RA fuses the bathymetry of the river channel with the topography of the flood plain and the measured 3D flow field (Fig. 5). Multiple measurements of flow at different discharge levels can then be "stacked" on top of each other to examine changes in the velocity field, drift patterns as well as floodplain connectivity with the main channel.

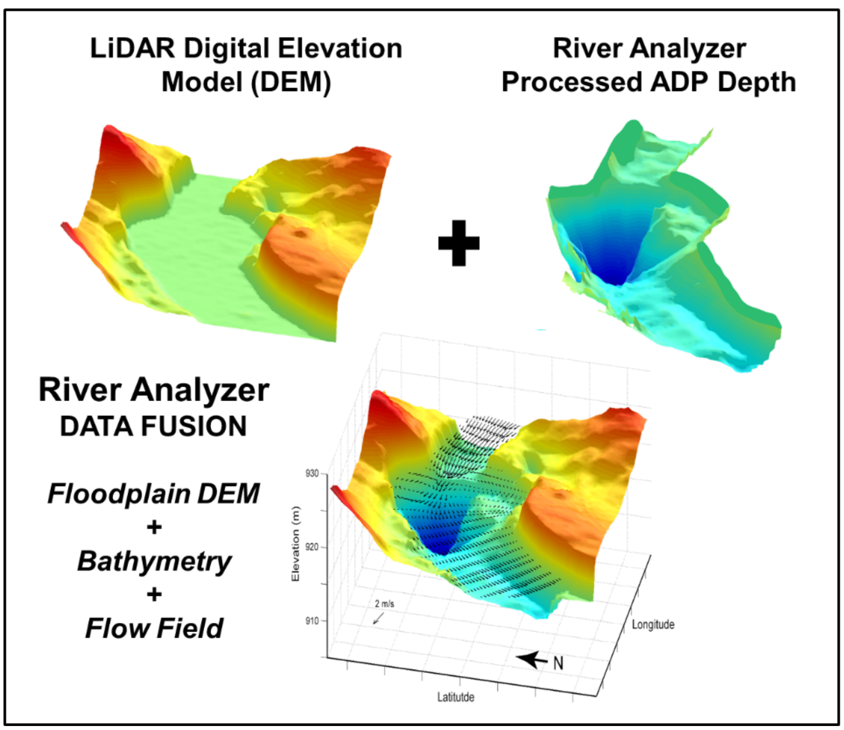

Figure 5. A schematic that illustrates the fusion of three data sources that describe a river floodplain, channel and flow field. LiDAR defines the topography of the floodplain (upper left diagram) while the bathymetry of the channel (upper right diagram) and the flow field (lower diagram) comes from ADP data collected floating the river.

River bathymetry and 3D flow maps were used to conduct 4000 drift simulations using an RA software module called "Drifter". Particle drift speeds and adjective pathways were calculated from various user-specified spawning locations to where drifters entered low velocity habitats and stalled. The 3D hydraulic data set was converted to a 2 m grid using 2D ordinary kriging (Chiles and Delfiner 1999) to calculate horizontal drift paths controlled by the river bathymetry, flow velocity and current direction. In each river segment, the 3D water column data were converted to two 2D layers to compare drift throughout the water column with drift in the bottom 0.5 m where most larvae drift. Flow in the bottom boundary layer was characterized using the bottom three accurate ADP measurements above the bottom (in 10-cm depth layers). This strategy eliminated the use of interpolated data at the river bottom, below the depth that ADPs can accurately measure (~approximately 20 cm on average) and ensured that our calculations did not underestimate drift speed within the bottom 50-cm of the river. Drift is simulated using fourth-order Runge-Kutta with one-minute time intervals and the 2m gridded velocity data (Chiles and Delfiner, 1999).

Another RA module, "Slicer", allows the user to select cross-sectional views of the 3D flow field at 2.5 m intervals throughout the entire river length. This tool enables researchers to view the 3D nature and complexity of the flow and thereby visualize the depth strata inhabited by focal fish species and critical life stages (Fig. 6) Slicer also allows the water surface elevations to be extracted (Fig. 6). A discharge measurement can also be determined from each slice allowing the user to examine groundwater-surface water patterns and trends along the length of the river channel.

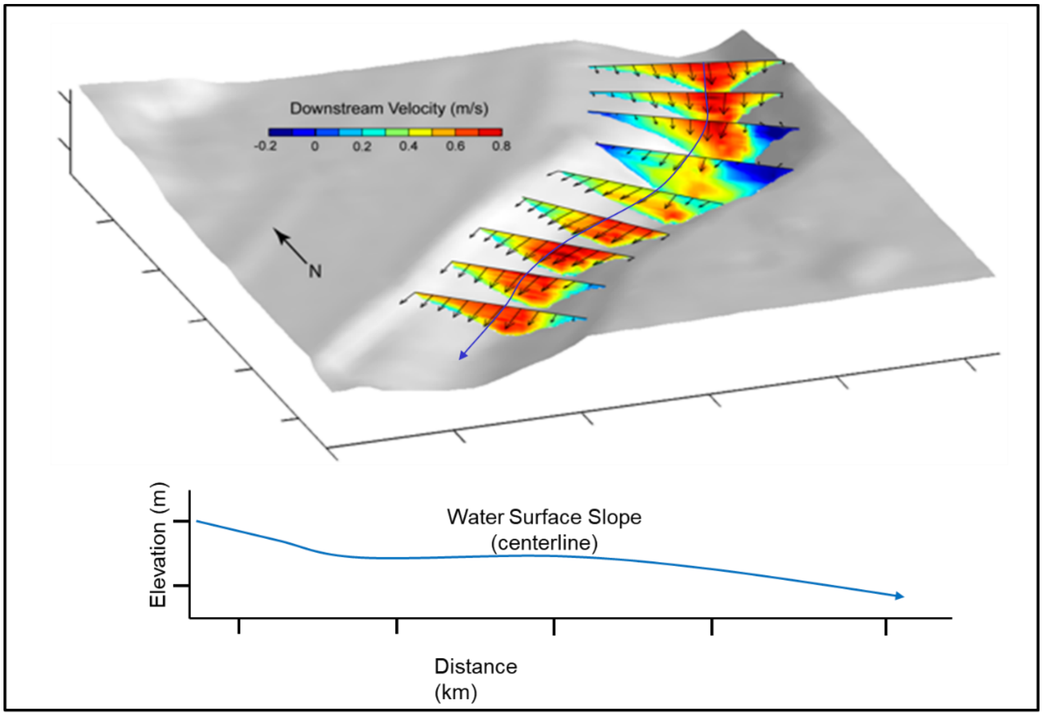

Figure 6. (TOP) A schematic showing a complete Digital Elevation Model of a river channel fused to the floodplain topography (grey area) with a series of cross-sectional slices of the flow field. The arrows on top of each slice represent the average flow direction and velocity for that column of water in the river (note the upstream flow of the river in the large blue eddy). (BOTTOM) A longitudinal plot of river centerline (blue arrow in TOP diagram) versus elevation of the water surface. These are useful pieces of information for initializing computation flow models.

RESULTS and DISCUSSION

ADP data were collected in September 2014 at a discharge of 170 cms (6,000 cfs) on a reference reach on Missouri River 6 km below the confluence with the Milk River. That data was processed in RA and fused with LiDAR data representing the flood plain (Fig. 7). The section of the river is the location where the first nets were deployed (along cross-section 8 in Fig. 7) for the larvae release-recapture study. The river has incised to bedrock in this location which can be visualized in the 3D diagram of the reach with a concentration of flow show in cross-section 3 (Fig. 8). Embryos drifting into this reach would first be distributed to river-left (referenced relative to the direction of flow) side channel, but most would be concentrated into the location of the incised channel (Fig. 9). Some would drift into the lower end of the reach ending up along the river-left shallow water habitats (Fig. 9). There they would either stay and develop to an exogenously feeding stage or just hold up for a few hours or days before slowly drifting further downstream into the river-left shallow water habitats along channels of the next island (Fig. 9). The drift patterns show divergence (Fig. 9) and examining cross-sections 6,7 and 8 (Fig. 8) one can see a similar spread in the flow field throughout the water column and the extensive boundary conditions of very slow-moving water (i.e. < 10 cm/s). Clearly embryos that end up on river-left would have to swim up to 100 m to re-enter the fastest flow within the thalweg. Embryos can dart, up to a meter, but would not know which way to dart repeatedly 100 times because they would not "know" or sense where the thalweg might be relative to their location within the channel. The mean drift duration to reach the backwaters from Sakakawea Lake, based on those drift paths that make it to the bottom of the reach, would be 16 days which is enough time to reach an exogenously feeding stage (Fig. 9).

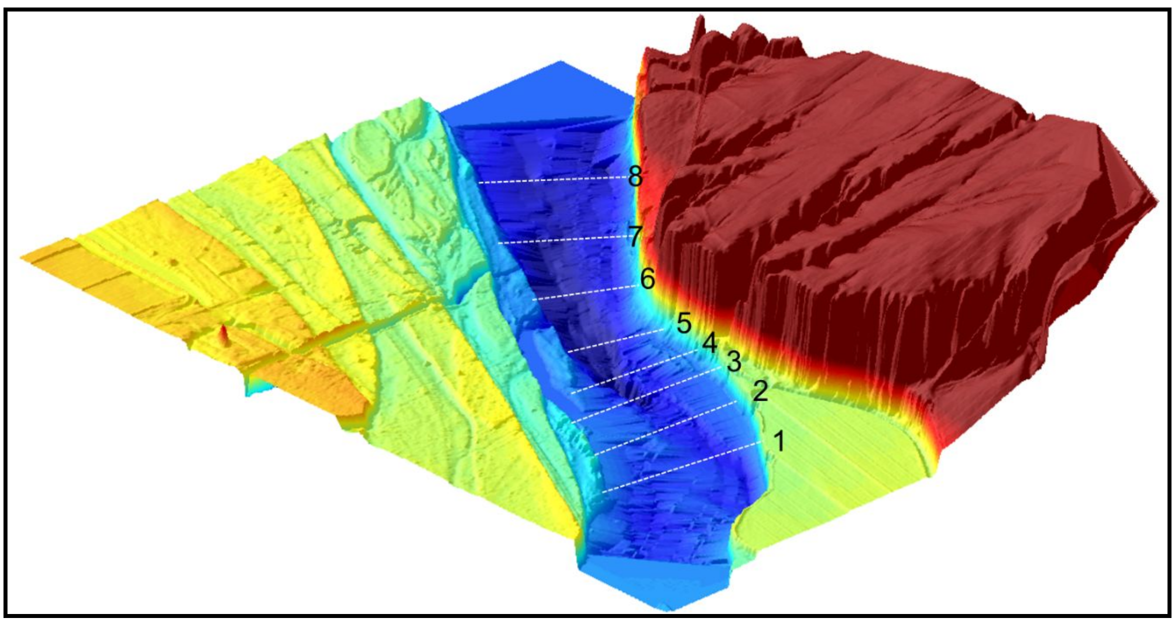

Figure 7. This schematic shows the river channel bathymetry (blue hues) derived from ADP data fused with the floodplain topography (green to red hues) derived from LiDAR data. The white dotted lines show the location of cross-sectional slices depicted in figure 8.

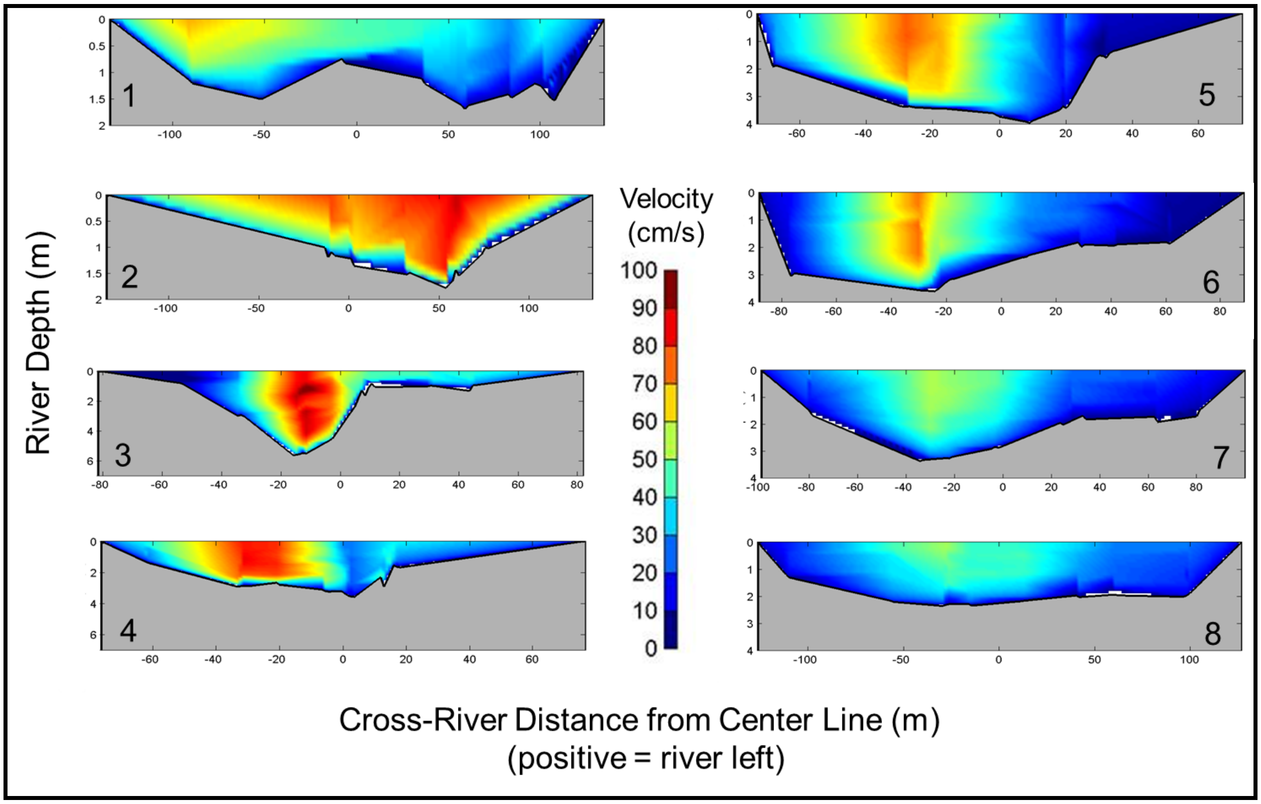

Figure 8. Plots of extracted cross-sectional slices (1-8) showing the channel geometry and flow field at each location.

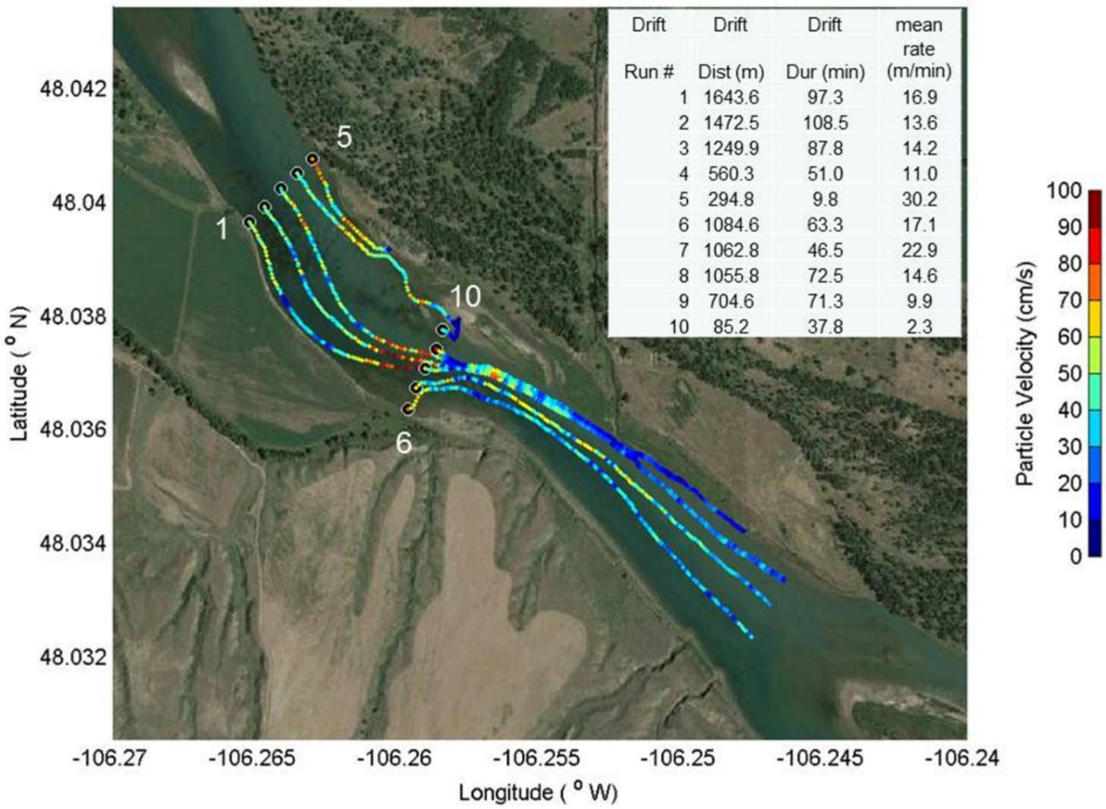

Figure 9. A plot of 10 drift paths through the reference reach based on data collected at a discharge of 170 cms (6,000 cfs). The colors along the drift path depict the drift velocity. The table in the upper right summarizes the basic statistics for each drift path.

We also mapped Missouri River in September 2015 extending from the confluence with the Milk 50 km down river at a discharge of 127 cms (4,500 cfs). At this discharge level the river is at its lowest point and hence most of the major channel crossing bars are exposed as islands with a single or split channel weaving a path through them. Most of the riparian floodplain areas are separated from the river channel. Comparing the mean flow vectors with bottom boundary drift patterns revealed that at this low discharge wide lateral dispersion of drifting embryos is unlikely given most of the flow paths show convergence (Fig. 10). These low flow conditions should be avoided during the embryo drift phase because of the physical disconnection with important shallow water habitats.

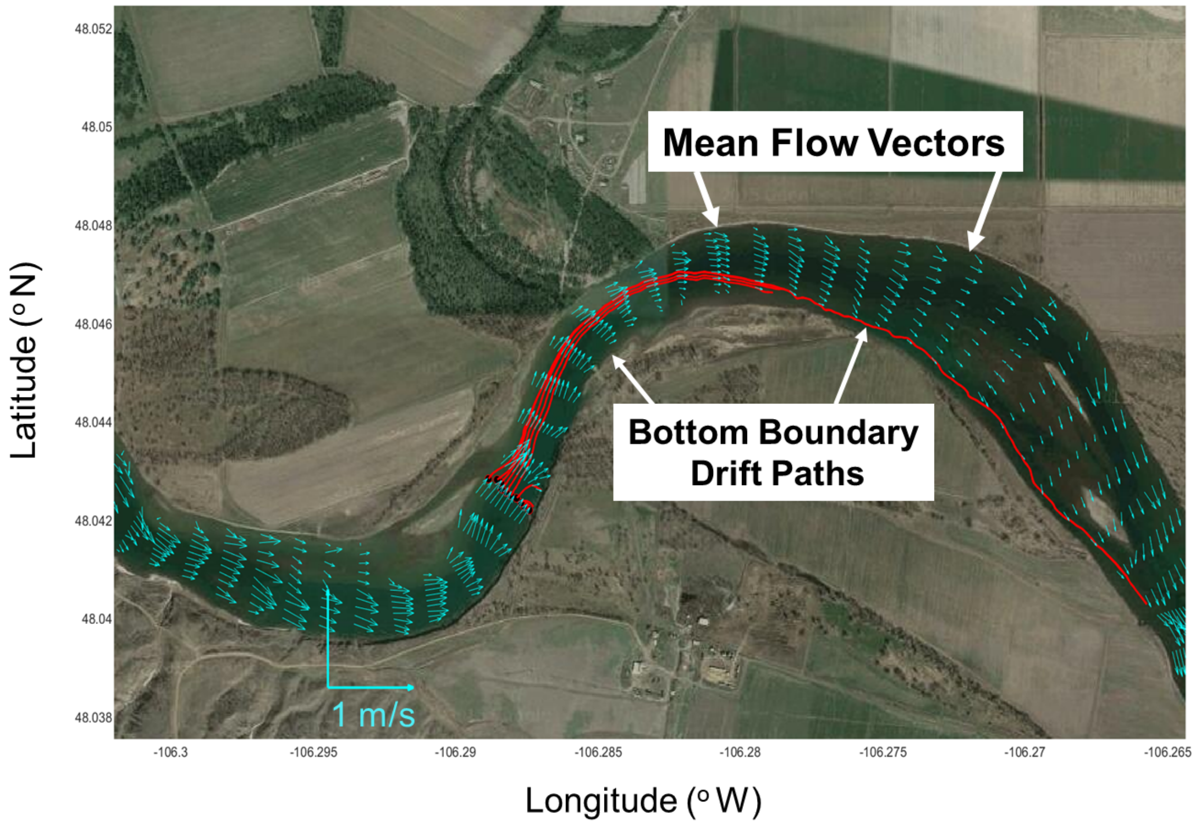

Figure 10. A plot of mean water column flow vectors (light blue arrows) with bottom boundary drift paths (red lines) for a discharge of 127 cms (4,500 cfs). The light blue arrow length indicates 1 m/s velocity.

River maps of the study reach covering the entire 338 km and measured at a discharge held steady by dam operation of 255 cms (9,000 cfs) coupled with drift analysis allowed identification of locations where larvae would drift into low velocity habitats and stall for both mean water column drift (Fig. 11) bottom boundary drift (Fig. 12). Note the wide lateral dispersion at this discharge 255 cms (9,000 cfs) (Figs. 11 & 12) as compare with flow path convergence measured at 127, cms (4,5000) discharge level (Fig. 10). Mapping revealed complex channel forms where the main channel (thalweg) is discontinuous and often abruptly changes position across the channel, providing insight about whether larvae might migrate by actively seeking the fastest currents through darting actions. Unlike passively drifting particles, live free-embryos swim in short random bursts, so they can resuspend and continue drifting downstream, and motility increases with larval development. Flow measurements revealed that water velocities throughout most of the river channel exceed the swimming ability of embryos and larvae, except when they drift into low-velocity areas.

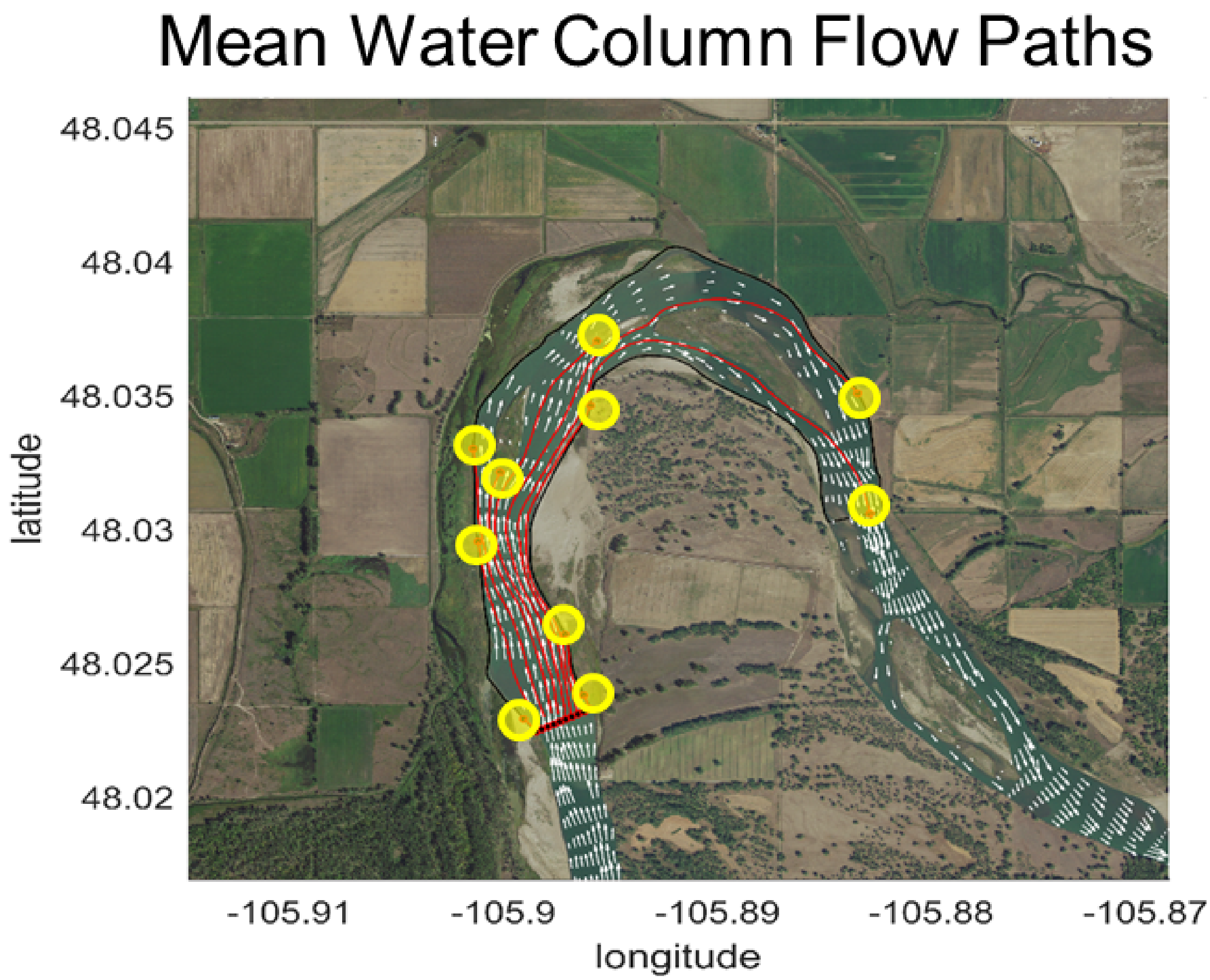

Figure 11. A plot of mean water column flow vectors (white arrows) measured at a discharge of 255 cms (9,000 cfs) compared with mean water column drift paths (red arrows). The yellow circles indicate drift paths that either encounter shallow shoreline habitats on islands and along the river banks or stalls that occur mid-channel due to eddies formed behind submerged sand bars or large wood.

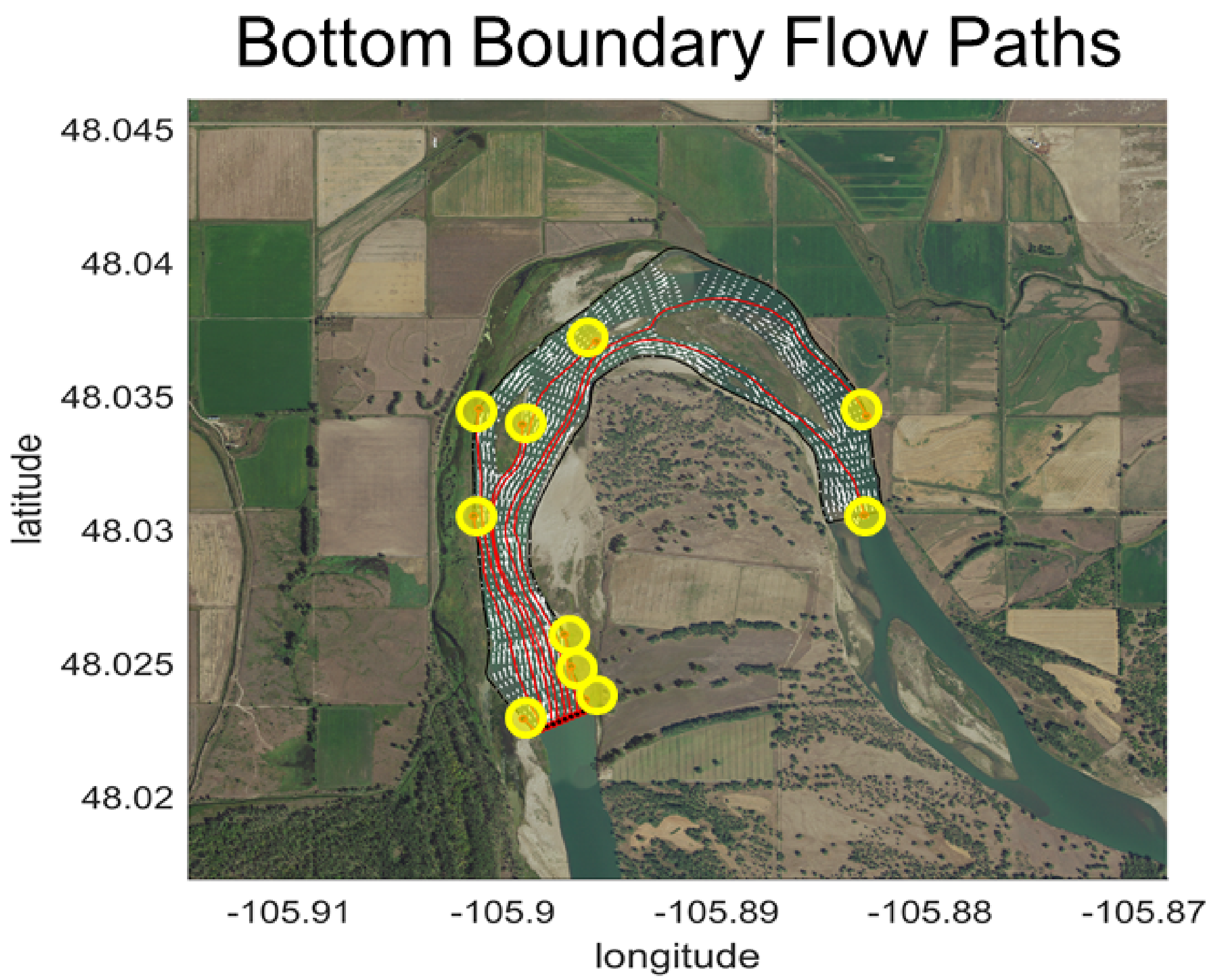

Figure 12. A plot of bottom boundary flow vectors (white arrows) measured at a discharge of 255 cms (9,000 cfs) compared with bottom boundary drift paths (red arrows). The yellow circles indicate drift paths that either encounter shallow shoreline habitats on islands and along the river banks or stalls that occur mid-channel due to eddies formed behind submerged sand bars or large wood.

Evaluation of drift paths relative to channel complexity suggests it is unlikely that drifting larvae can detect and maneuver toward faster currents, especially considering that the thalweg might be hundreds of meters away from their drift path.

CONCLUSIONS

Drift simulations showed that the fastest 10% of drifting particles could reach Sakakawea Reservoir from the release location in 6.56 days (Martoz and Lorang 2107). However, this speed was only possible when drifters remained in the fastest velocities of the thalweg for the entire distance. Rapid dispersal was apparent in drift simulations. Over 90% of simulated drift paths flushed from the thalweg into low velocity habitats, where about half stalled along river margins, islands, channel bars and eddies, increasing river residence time. The longest continual drift distance before stalling was 36.5 km near the river bottom. Simulations revealed that the fastest drifters in the bottom boundary layer would not reach Sakakawea Reservoir for 31 days, which is sufficient time for pallid Sturgeon larvae to residualize in shallow water rearing habitats. These results indicate that if spawning occurs downstream of Fort Peck Dam, drift duration is not a factor limiting pallid sturgeon recruitment. Indeed, if spawning occurs within 150-km downstream of the dam, at least 50% of the embryos would have sufficient river residence time to begin feeding exogenously, assuming that riverine habitat in this dam-influenced reach remains suitable for survival. In October 2017, one individual identified genetically from the 2016 embryo release was recaptured in the river. At the time of recapture, this specimen had grown to 412 mm TL and was in good condition. This single fish had sufficient river residence time to survive, which is consistent with our hydraulic drift simulations.

Evaluations of two different discharge levels demonstrate that dispersion and connection with shallow water rearing habitats varies with discharge. Although only two reference reaches were evaluated, one 2 km long and another 50 km long, it was apparent that there is a preferred discharge or sweet spot in flow regulation where maximum lateral dispersal of embryos coincides with maximum channel connectivity of shallow water floodplain habitats suitable for juvenile rearing. It is not known if discharge levels above 255 cms (9,000 cfs) offer better lateral embryo dispersion and shallow water habitat connection or not. Another complete data collection at a higher discharge and at or near 170 cms would be valuable information in terms of dialing in flow regulation aimed at pallid sturgeon recruitment for a range from dry to moderate to wet water years. It take two weeks to collect each data set and few weeks beyond that to process the data thereby providing resource managers the information they need to make informed decision based on empirical data rather than just modeling reference reaches.

Marotz BL, Lorang MS. Pallid sturgeon
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https://doi.org/10.1111/jai.13569