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# **STURGEON PAPER**



# Pallid sturgeon larvae: The drift dispersion hypothesis

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### Summary

The fate of drifting pallid sturgeon larvae [Scaphirhynchus albus, Forbes and Richardson, 1905] from spawning in the Missouri River below Fort Peck Dam, Montana, USA remains in question. Previous estimates of drift duration used flow modeling and experimental releases of free embryo pallid sturgeon that were recaptured in nets at incremental distances downstream. The recapture studies hypothesized that the released larvae drift along the river bottom in an intact plume that flushes into the downstream reservoir where they die. Results were interpreted that nearly all drifting embryos would reach Sakakawea Reservoir (~375 river km downstream) in just 6 days, suggesting that there is insufficient drift distance for successful reproduction of pallid sturgeon. Those experiments recaptured less than 1% of the released larvae, thus the dispersal fate of the remaining ~99% of drifting larvae remains unknown. We hypothesized that the river is extremely dispersive due to complex channel bathymetry and flow, which spreads the plume of drifting particles bank to bank within a few kilometers downstream of the release location, and that the same would be true for drifting free embryos. This is referred to as the Drift Dispersion Hypothesis. This hypothesis was tested by conducting high-resolution 3D flow and depth mapping, spanning the width of the Missouri River for 338 km in coordination with an embryo release and recapture study conducted in June 2016. Fort Peck Dam discharge was stabilized for the experiment. Hydraulic base maps were used to calculate particle drift paths and estimate drift speeds in (i) the bottom boundary layer (0.5 m) and (ii) the whole water column, as a surrogate for drifting larvae. Drift path patterns indicated wide lateral dispersion across the river, bank to bank. Drift simulations indicated that less than 10% of the fastest drifting embryos could reach Sakakawea Reservoir in just 6.56 days, but only if they remained mid-column and in the channel thalweg the entire distance. However, the fastest drifting particles that remained in the bottom boundary layer would not reach Sakakawea Reservoir for 31 days. Concluded was that most drifting embryos must be swept from the thalweg into low velocity habitats and stall, extending their river residence time. Stall locations were recorded along the entire study reach. The results indicate that drift duration is not the limiting factor for pallid sturgeon recruitment when spawning occurs near the embryo release site downstream of Fort Peck Dam.

## 1 | INTRODUCTION

Aquatic organisms are dependent on specific biophysical space (habitat) to complete their life cycle stages, and riverine species take advantage of the complex spatial array of habitat afforded to them, since discharge varies and causes a shift in that mosaic of habitat (Stanford. Lorang, & Hauer, 2005). Resilience of fish communities often depends on their ability to find and use stage-specific habitat conditions during critical lifecycle phases (Schwartz & Herricks, 2005; Sukhodolov, Bertoldi, Wolter, Surian, & Tubino, 2009; Wolter & Sukhodolov, 2008). Pallid sturgeon (Scaphirhynchus albus) free embryos have limited motility, thus drift with the flow, and hence lateral velocity gradients and turbulence disseminate them broadly throughout the river. It is therefore important to understand complex river flows over long distances, which cannot be achieved by computational fluid dynamic flow modeling alone. One-dimensional models assume average channel velocity, and two-dimensional flow models only segregate water velocity laterally. Three-dimensional models add vertical velocity gradients, but applications have historically been limited to short river reaches. If our goal is to improve flow regulation to recover endangered fish, then field-based, empirical data collection is required to reveal the complexities of flow at the spatial scale that fish require to complete all life stages (Sukhodolov, 2015).

Recruitment failure for endangered pallid sturgeon in Montana is currently hypothesized to be limited by insufficient larval drift distance and time to develop as they drift from spawning areas in the Missouri and Yellowstone rivers into Sakakawea Reservoir (Braaten et al., 2008, 2011) where they apparently die (Guy et al., 2015). Low survival of sub-yearling sturgeon, including the larval drift phase and transition to exogenous feeding, is the most sensitive lifecycle phase limiting natural recruitment. Previous estimates of larval pallid sturgeon drift rates were calculated using a one-dimensional HEC RAS particle transport model that indicated most larvae would drift into Sakakawea Reservoir in just 6 days, providing insufficient river residence time for survival. Drift experiments that were used to calibrate the drift model released 500,000 live larvae and recaptured them in nets at incremental points downstream (Braaten et al., 2008, 2011). Conclusions on flushing rates focused on the first arrivals in the recapture nets, resulting in estimated drift velocities of 0.66 to 0.70 m/s, slightly slower than the average channel velocity of 0.72 m/s observed during the drift experiments. These results yielded estimates that pallid sturgeon require 200-500 km drift distance for successful larval development.

Previous embryo drift experiments accurately measured the dispersal rate of the fastest individuals, but did not focus on the slowestmoving individuals, or account for the vast majority of released larvae. Braaten et al. (2008); Braaten, Fuller, Lott, Ruggles, and Holm, (2010); Braaten, et al. (2011) suggested that some larvae may be delayed by eddies and along channel margins, extending their retention time in the river, and cited the subsequent recapture of over 125 juvenile pallid sturgeon as evidence that some of the embryos released for the drift experiments remained in the river long enough to survive (Braaten, et al., 2012). Pallid sturgeon drift net studies conducted in the upper Missouri (Treanor, Guy, Webb, & Kappenman, 2015) achieved a recapture rate of 0.23%, and found that most of the drifting larvae were captured in the thalweg. They used nets set at multiple depths to determine that nearly all embryos were captured in the bottom 0.5 m of the river, corroborating the findings of Braaten et al. (2008, 2010, 2012), at a maximum drift rate of 0.16 m/s and minimum rate of 0.09 m/s, while velocity measurements at netting locations ranged from 1 to 0.2 m/s. These results indicate that flow in the bottom boundary is much less than higher up in the water column, as would be expected. Also, embryos would have to be resuspended into the water column or actively swim toward higher water velocities to maintain the fastest possible drift speed.

Questions remain about the fate of the slowest drifting larvae and their potential to residualize in suitable river habitat and survive. The Missouri River has complex flow patterns and bathymetry, which led to questions about the pathways in which most of the larvae drift, and what proportion might have sufficient larval development time. Pallid sturgeon egg incubation and embryo development is accelerated by warmer water temperatures (Braaten et al., 2008), demonstrating that water temperature, benthic velocities, channel morphology, and current vectors must be better understood to accurately evaluate the potential for survival from various spawning locations. Moreover, the assumption that most drifting larvae are flushed into downstream reservoirs (Sakakawea from the Missouri downstream of Fort Peck Dam and Yellowstone, and the Fort Peck Reservoir from the isolated upper Missouri RPMA1 population) remains in question, especially when most of the released larvae were not accounted for in the recapture data.

During June 2016, a multi-agency collaboration (USGS, MFWP, North Dakota, U.S. Fish and Wildlife Service and U.S. Army Corps of Engineers) implemented a larval drift experiment downstream of Fort Peck Dam to better understand pallid sturgeon larval drift in the Missouri River (RPMA2). Over 700,000 free embryo pallid sturgeon (<2 days post hatch) were released just downstream of the Milk River confluence (rkm 2835), building upon previous larval drift studies by Braaten et al. (2008, 2010, 2011, 2012). Drift nets were deployed at sites incrementally downstream to capture free embryos as they drifted toward Sakakawea Reservoir. Reporting of the larval drift study will be led by USGS; those results were not available at the time of this writing. Freshwater Map conducted 3D river hydraulic surveys associated with this larval release experiment and empirically mapped the channel bathymetry and 3D flow velocity vectors spanning the entire 338 km of river channel. We then linked measured flow vectors to examine the pathways that drifting particles would follow, and estimated drift speeds from various hypothetical spawning locations from the release site to the headwaters of Sakakawea. These drift pathways were derived from 16 million Acoustic Doppler Current Profile ensembles collected in a series of Lagrangian data transects spanning the river bank-to-bank throughout the study reach.

We hypothesized that that vertical and lateral velocity gradients generated by the complex river bathymetry would disperse a sizable percentage of drifting larvae out of the thalweg into low velocity zones and distribute larvae widely from bank to bank, thereby providing sufficient river residence time for survival (Figure 1, dashed lines). We refer



FIGURE 1 Comparative hypothesis diagram

to this as the Drift Dispersion Hypothesis, which contrasts with an alternative hypothesis that the released embryos remain in a defined plume that drifts in the thalweg throughout the entire river reach. We compare flow pathways in the bottom boundary layer with flow pathways representing mean water-column velocities, allowing us to estimate the fastest drift within each layer. Our flow path approach for estimating the timing of first arrivals at the first netting site matched the empirical net captures (we were anchored alongside a netting boat when the nets began capturing larvae). Similarly, our fastest drift estimate from the release site to SAK in 6.54 days corroborated the arrival time of 6 days reported to us by the netting crew. We believe that measuring the flow field, meter by meter over the entire drift distance, provided a useful surrogate for larval dispersal and drift speed. Drift netting can only sample an extremely small portion of the river, and each net offers an infinitesimally small opening relative to the crosssectional area of the river being sampled. Consequently, netting is biased towards constrained channel geometries, which represent only a fraction of the actual complexity of the river. Given the extremely low recapture percentage (0.14%), netting results cannot support conclusions regarding the fate of all drifting larvae.

#### MATERIALS AND METHODS 2

#### 2.1 Study area

The Upper Missouri Basin encompasses the Missouri River and tributaries upstream from Gavins Point Dam, including Recovery Priority Management Areas (RPMA 1 and 2) described in the first Pallid Sturgeon Recovery Plan (Dryer & Sandvol, 1993). Our study focused on RPMA 2, the Missouri River downstream of Fort Peck Dam in Montana to the headwaters of Sakakawea Reservoir (SAK) in North Dakota (~375 river km; Figure 2). The riverbed is sandy with patches of gravel, cobble and bedrock outcropping mainly associated with two rapids. The channel thalweg is highly dissected and bifurcated due to the formation of large sand dunes that span the width of the river. Dune tops become mid-channel bars and islands at low flows, creating braided channels with complex flow patterns and eddies. This complex river morphology is difficult and dangerous to navigate, even when passively floating, due to repeated groundings. High turbidity obscures the deepest river channels, except in the first 10 km immediately downstream of Fort Peck Dam, which releases cold, clear hypolimnetic water. The thalweg is composed mainly of sand dunes ranging from small 10 cm ripples to dunes, to complex bars several meters in amplitude. The banks are either accreting sand bars or highly unstable vertical bluffs that were constantly collapsing into the river making data collection along riverbanks hazardous. Bank erosion introduces a very high load of fine sediment into a river where natural flood discharges have been largely eliminated by the Fort Peck Dam operation, reducing the river's ability to transport its sediment load.

#### Methods 2.2

Freshwater Map conducted 3D hydraulic mapping of 338 km of the Missouri River from the Milk River confluence to Williston, North Dakota (19-28 June 2016). An array of eight, one-person pontoon boats deployed Teledyne, RiverPro Acoustic Doppler Current Profilers (ADCP's) with fully integrated Hemisphere, Vector V102 GPS compass units deployed from catamaran rafts while floating on the river to measure water depth, velocities and current vectors throughout the water column from the surface down to the bottom boundary layer in 10 cm depth intervals. These instruments can collect depth and velocity data to within 1% of the actual flow and depths being sampled. The survey team measured river discharge at 20 transect locations along the river, once at the beginning of each day and once at the end. Discharge measurements were replicated 5 to 8 times at each location following standard USGS protocols for discharge measurements, resulting in a mean variance in discharge measurements less than 1% for most locations and less than 3% for all. River discharge during the survey was 247 cms at the confluence of the Milk River just below Fort Peck Dam, 287 cms above the confluence of the Yellowstone River and 612 cms at the take out in Williston, ND.

Teledyne collaborated with Freshwater Map, writing data acquisition software specific to this survey; they trained the survey crew in the operation of the equipment and software. The GPS Compass ensured optimum velocity estimates from the acoustic beams by 4 WILEY Applied (kthtystogy) DWX ()

### FIGURE 2 Study area map

removing potential moving bed condition errors that arise from bottom tracking methods of calculating flow velocity (Lorang & Tonolla, 2014). In addition, the GPS compasses removed velocity errors caused by magnetic drift that can impact standard magnetic compasses when rafts turn rapidly, and provided a 0.5 m position accuracy. Even so, compass calibration was conducted each day as a backup in case GPS signals were lost. Survey boats were equipped with 2.3 HP Honda outboards to maintain optimal bottom tracking and to allow maneuvering in the river without having to row. Boat speeds were kept at an optimum to maintain bottom tracking. If a given boat lost the bottom tracking, the surveyor returned upstream and resumed mapping, once the bottom track signal was reestablished. Additional mapping tracks were collected for higher data resolution in areas of visible complex channel and flow features. Each boat was custom-wired for power and data storage on an onboard computer. Hydraulic data from the ADPs and surface temperature were recorded simultaneously with each boat's GPS location on field laptop computers. Data ensembles were collected and recorded by each raft at a rate of 2 per second. Over 16 million velocity profiles were recorded, resulting in over 256 million spatially dispersed measures of flow velocity and current direction that were used to calculate particle drift speeds and pathways. The mean data ensemble density was 0.25 ensembles per square meter of river surface.

Freshwater Map's patent pending proprietary software, River Analyzer (RA) and associated software components, were developed in MATLAB and used to process the field data (bathymetry, 3D velocities and current vectors). RA interpolates linearly between adjacent data ensembles, and exponentially (log) from the deepest accurate velocity measurement to the river bottom and horizontally to the riverbank. This provides a 3D set of interpolated data points for every 2.5 m<sup>2</sup> of the river surface. River measurements were imported to ArcGIS to produce the bathymetry, mean flow and surface water temperature maps (20 maps in total). The channel bathymetry and flow data are then integrated with terrestrial elevations (LiDAR derived Digital Elevation Maps) and aerial photographs collected at approximately the same discharge by the USDA 2015 National Agriculture Imagery Program.

Depth-specific velocity data representing the mean water column and the bottom boundary layer were converted to a 2 m grid, using 2D ordinary kriging (Chiles & Delfiner, 1999). An RA software module called 'Drifter' used these velocity vectors from the bottom 0.5 m and those representing the complete water column for each 2 m gridded cell to calculate drift paths and drift speeds along those pathways. Although derived from a 3D hydraulic data, our drift simulations assume horizontal drift paths for both the bottom boundary and mean water column assessments. Our particle drift simulations (4000 in total) examine drift speed along each pathway from various userspecified spawning locations to downstream locations. Simulations of drift in the bottom boundary layer use data from three bins or 30 cm above the deepest valid cell above the river bottom. This eliminates using interpolated data from below the deepest accurate velocity measurement and ensures that our drift speed simulations represent the fastest flow speed and direction in the bottom 50 cm of the river. Drift is simulated using the fourth-order Runge-Kutta krigging approach for the 2 m gridded velocity data and using one-minute time-step intervals with a 3-day simulation limit on the time step duration (Chiles & Delfiner, 1999). Hence, a drift path ends if it reaches water so slow that it cannot reach the next cell, or recirculates in a small area of connected cells with slow moving water. This results in the ability to locate all stall positions along the riverbanks, along islands, no velocity zones along the bottom, and zones of flow recirculation (eddies).

We segregated the river into 100 river segments covering the 338km study reach. Two drift conditions were simulated: drift along the bottom boundary (~0.5 m above the river bottom) and a drift simulation using the average water column velocity and current direction. Drift simulation is a 3-step process beginning with kriging the RA flow information (speed and direction) that is interpolated from the raw data ensembles to put that data onto a cartesian plane coordinate system, so that the flow vectors can be linked cell by cell to create flow pathways with velocity information for each cell along the vector. Drift simulations begin in two transect locations: 1) at the top of each 3-km segment, and 2) the mid-point of each segment. When midsegment transects intersected islands, the start locations were repositioned immediately upstream. Ten starting points were spaced at regular intervals along each transect, starting and ending two meters in from each bank. Each of 4000 drift simulations ended when the particle reached the end of each segment, stalled in zero velocity, or



**FIGURE 3** The bathymetry (upper right panel), mean flow (lower left panel) and surface water temperature (lower right panel) are from empirical flow data measured by the Acoustic Doppler Current Profilers, compiled in River Analyzer and plotted in ArcGIS

made no downstream progress for 3 days of simulated duration. The fate of each drifter was categorized based on river geometry (river bank, island or eddies). All GPS locations where particles settled were recorded to identify habitats where embryos should concentrate along the river.

We provide examples of the maps and used box and whisker plots to summarize all drift simulation results. Drift start point 1 is always river left and 10 is river right for the beginning segment starting positions, and 11 for river right and 20 for river left for all mid-segment starting positions. The solid box is defined by the median value (solid line in the middle of the box), the upper quartile and lower quartile (top and bottom of box), plus the sign is the mean value, whiskers represent the 9<sup>th</sup> and 91<sup>st</sup> percentiles, and the solid dots represent data points lying outside these whisker parameters.

### 3 | RESULTS

No bathymetric map of the Missouri River existed prior to our surveys. In 2016, we used the data collected and River Analyzer to create bathymetric maps of the channel and overlaid mean column velocities and current vectors for comparison with channel complexity throughout the entire 338 km. Our results revealed complex bathymetry (to 15 m depth), braided flow channels, and mid-channel sand bars and islands, some of which can be seen on aerial photographs. Equally complex flow velocities and current vectors were measured, ranging from -0.3 to 3.5 m/s (negative flow indicates upstream direction) directing water from the thalweg into slow-velocity river margins, side-channels and backwaters, slowing the drift speed of larvae, and extending their river residence time. Bathymetric maps reveal the extensive complexity of the channel below the water surface not visible from the aerial photographs (Figure 3). Given that temperature controls the rate of embryo development, we used our ADP units to record surface temperature once per second and plotted those thermal data for comparison with the bathymetry and flow (Figure 3).

Drift simulations show drift paths relative to flow vectors in the bottom boundary (Figure 4, left photo) and the whole water column flow (Figure 4, right photo). Most drift paths in the bottom boundary and whole water column follow current vectors along flow paths that run into the bank or into islands. Note that only one flow path made it to the end point on this particular example (Figure 4). Numerous simulations revealed where drifters were forced from the thalweg into low velocity areas along the shore or an island, complex patterns that cannot be determined from aerial photographs, 1 or 2D modeling, or observed from a boat, which explains why drift simulations require measuring the 3D flow field to reveal these flow paths and the velocities along each flow path. Moreover, these results underscore the dispersive nature of the Missouri River.

The study reach was divided into 100 segments (Figure 3, upper left panel), and two drift simulations consisting of 20 release starting points per river segment were analyzed in the bottom boundary and for the whole water column. Drift simulations were summarized by recording the fate of all 4000 drift pathways (end points) in all river segments (Figure 5). Results were plotted as stacked histograms showing the number of drift paths that passed through each segment (Figure 5), the number that stalled in low velocity areas along the river bank or an island, the number that stalled due to low flow (<0.01 m/s), and the number that began the drift simulation in a stall condition. Drift simulations begin at positions 1–10 at the upstream edge of each river segment, and positions 11–20 begin at the mid-point of each segment. Locations (lat. & long. coordinates) were recorded and mapped where drifters stalled, so that environmental conditions in those habitats can be examined later for additional hypothesis testing on limiting factors preventing natural pallid sturgeon recruitment.

The average velocity of all drift paths was summarized in box and whisker plots (Figure 6). As expected, drift velocities along the bottom boundary and along the riverbanks were approx. twice as slow as drift throughout the water column (Figure 6, top and bottom panel comparison). Drift velocities in the thalweg were greater than along the banks, and the difference was greater for the mean water column as compared to the bottom boundary (Figure 6). Drift distances for all paths were tabulated and the difference between the bottom boundary drift distance and the mean water column drift distance for all comparable flow paths with similar start points (same start point for bottom boundary as mean water column) was tabulated in a box and whisker plot (Figure 7). The difference in drift distances in the bottom 0.5 m versus the whole water column were similar for most path comparisons, but when they did differ, they differed widely (up to ±3 km), indicating that sometimes the bottom boundary layer flow path is much different than the mean water column flow path (Figure 7). These results indicate that some segments of the river are widely dispersive.

# 4 | DISCUSSION

A naturalized spring pulse and natural water temperatures are apparently necessary to initiate pallid sturgeon spawning activity (DeLonay et al., 2014; USFWS, 2014). After eggs hatch and embryos begin to drift, drift distances and river residence time are dependent on the river stage, and larval development increases with water temperature (Braaten et al., 2011, 2012). Within a few days after hatching, drifting larvae develop the ability to make brief darting movements, as observed in tank experiments. However, due to low motility, it is uncertain whether developing free embryos can actively seek out specific habitat conditions or maintain their position in velocity gradients typical of turbulent flow. Motility increases gradually as larvae approach their exogenous feeding stage. Yet at velocities exceeding larval swimming ability, the rate and pattern of larval dispersion must be dominated by the flow. Drift simulations showed that most particles are flushed from the thalweg into low velocity water, which may be hundreds of meters from the fastest currents. We believe that broad dispersion due to turbulence is a reproductive strategy that is more likely than an alternative strategy based on volitional swimming to speed downstream migration. Volitional migration would require larvae to be able to sense the flow they occupy at any given time, and be able to sense faster currents to swim toward to maximize downstream drift.



FIGURE 4 A plot of the drift pathways in the bottom boundary simulation (left panel) and the simulated mean water column flow (right panel)





FIGURE 5 Stacked histograms summarizing fate of all 4000 drift simulations. The start points 1 and 11 represent river left and 10 and 20 representing river right. Start points 1-10 began at the top of each segment and 11-20 at the mid-reach locations

The energetics of volitional drift carries great metabolic risk, especially considering our measured flow velocities and current vectors. Our drift dispersion hypothesis assumes that larvae have little ability to control their drift, thus currents disperse them widely before they settle into low velocity habitats. Many other fish species use similar strategies to disperse at early juvenile life stages (Wolter & Sukhodolov, 2008). Therefore, it is logical that pallid sturgeon utilize the complexities of flow and channel bathymetry to broadly disseminate their developing larvae throughout the river, during a time when the larvae are not sufficiently developed to control their position in the water column.

Our results revealed complex bathymetry (to 15 m depth), braided flow channels, and velocity fields from -0.3 to 3.5 m/s. Equally complex flow velocities and current vectors direct water from the thalweg into slow-velocity river margins, side-channels and backwaters, slowing the drift speed of larvae and extending their river residence time. Our drift speed estimates corroborate previously published drift studies on this river reach and in the Upper Missouri and Yellowstone rivers (Braaten et al., 2008, 2010, 2011, 2012; Treanor et al., 2015), and offer insight into the wide dispersal and drift duration of the slowest moving drifters that represent most drifting larvae. Our results allow a detailed assessment of the physical drift patterns throughout the river and locations where drifting larvae enter low velocity habitat and then stall.



**FIGURE 6** Box and whisker plot summarizing drifter velocities for all 4000 drift simulations in the bottom boundary layer and mean water column flow

Our methods for river mapping and integration with terrestrial data layers allows for a detailed 3D assessment of channel bathymetry, flow patterns and drift path complexity over 338 km of the Missouri River. Four thousand drift simulations estimated that the fastest drifting larvae from the 2016 release point, located just downstream of the Milk River confluence, could drift downstream to the Williston Bridge, ND (338 km) in just 6.56 days, and the longest drift duration in the thalweg was 8.52 days. However, to drift that quickly, larvae must remain suspended above the bottom boundary layer in the upper water column, and remain within the thalweg of the river for the entire distance. Our drift simulations showed that drift paths diverged from the thalweg into low velocity water that may be as close as a few meters to as far as hundreds of meters from the fastest currents. We argue that it is more likely that larvae are dispersed by vertical and lateral velocity gradients.

Dispersion based on measured flow path pattern was broad, extending bank-to-bank over short (1 to 3 km distances) over the entire 338 km reach. Drift simulations showed that most of the drifters become dispersed throughout the river and that nearly half of the drift paths stalled in shallow shoreline along river banks, islands and in eddies, extending their river residence time (Figure 5). None of the 4000 drift simulations, along the bottom or in the whole water column, traveled the entire distance without stalling along the way. The



**FIGURE 7** Box and whisker plot summarizing the difference between continuous drift distances in the bottom boundary layer and mean water column flow

longest continuous drift distance was 22.3 km in the bottom boundary and 36.5 km in the whole water column drift. Hence, larvae must become re-suspended or swim back to the thalweg to continue drifting. Some do accomplish this as the past netting data reveal and our approach to drift simulation also confirms. However, both confirm that less than 10% of the larvae could drift 338 km in 6 days.

For all 4000 drift simulations, average drift speed along the bottom (0.5 m) of the river varied between 0.05 m/s to 0.13 m/s for 99% of all drift paths. Only 9% of the drift paths had drift velocities exceeding 0.3 m/s, and all of these stalled along banks or islands at least once. Variance was similar across the river, from river left to river right. Of all drift simulations in the entire water column, 91% varied between 0.05 m/s to 0.55 m/s. The remaining 9% had a drift speed greater than 0.6 m/s. There was more variation in drift speed across the river channel from river left to river right than in the bottom boundary layer.

Comparing drift speed in the bottom boundary layer with the whole water column shows that the drift speeds in the bottom boundary layer are approximately twice as slow (Figure 6). Eddies in the mean water column exist, with upstream flow velocity differences ranging from -0.01 m/s to -0.3 m/s but these represent less than 1% of the river flow.

Comparing drift distances that traveled near the bottom to those drift paths in the whole water column showed that the distance traveled ranged between 500 m (along banks) to 2.5 km in more central river positions, and that the total variance in drift distance was very large, ranging from a few meters to over 3.5 km (Figure 7). Most drift paths did not extend continuously for more than 3.1 km. Approximately 91% of the drift paths covered the same distance along the bottom as in the overlying water column, but variance ranged from a few meters to  $\pm$  3 km, demonstrating that most larvae would be highly dispersed throughout the river (Figure 7).

The shortest drift duration from the release point to SAK in the bottom boundary layer was 31.7 days and the longest was 37.4 days,

indicating that drift distance is likely not the limiting factor to pallid sturgeon recruitment from a spawning event near the embryo release site in the Missouri River; most larvae could residualize in the river, if environmental conditions were conducive to growth and survival.

Here we present examples of river maps that allow researchers to image the entire 338 km of river channel under investigation, and summarized results of larval drift simulations from the release site to the headwaters of Sakakawea Reservoir. We emphasize the long distances mapped with our field equipment and rapid analysis of that 3D data using River Analyzer as valuable tools for assessing Pallid Sturgeon larval drift. Field surveys were accomplished in 10 days and data processing and analysis of drift simulations can now be completed in a similar time frame. We conclude that our drift dispersion hypothesis is supported by direct measurements of the 3D flow field throughout the study reach. Moreover, results indicate recruitment failure must be the result of factors other than insufficient drift duration from the embryo release site. Probable limiting factors include predation, fragmentation of food web dynamics within juvenile rearing habitats, altered flow regulation, and hypolimnetic dam releases during the eight decades since Fort Peck Dam was completed.

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