Bedform distributions and dynamics in a large, channelized river: Implications for benthic ecological processes

Caroline M. Elliott , Geologist, U.S. Geological Survey, Columbia Environmental Research Center, Columbia, MO, USA (celliott@usgs.gov)
Robert B. Jacobson, Research Hydrologist, U.S. Geological Survey, Columbia Environmental Research Center, Columbia, MO, USA (rjacobson@usgs.gov)
Bruce Call , Physical Scientist, U.S. Geological Survey, Columbia Environmental Research Center, Columbia, MO, USA (bcall@usgs.gov)
Maura Roberts, Hydrologist, U.S. Geological Survey, Columbia Environmental Research Center Columbia, MO, USA (mroberts@usgs.gov)

Abstract

Sand bedforms are fundamental habitat elements for benthic fish in large, sand-bedded rivers and are hypothesized to provide flow refugia, food transport, and ecological disturbance. We explored bedform distributions and dynamics in the Lower Missouri River, Missouri, with the objective of understanding the implications of these features for benthic fish habitat, particularly for the endangered pallid sturgeon (*Scaphirhynchus albus*) and shovelnose sturgeon (*Scaphirhynchus platorynchus*) during their early life stages. We mapped bathymetry in a 3-kilometer-long reach of the highly engineered Lower Missouri River 22 times over a three-year period from 2019-2021 using a multibeam echosounder. Surveys included precise water surface and bed elevations over discharges ranging from 1,360-8,550 cubic meters per second. This included weekly surveys during a large flood event with a peak of 9,290 cubic meters per second in the spring and summer of 2019. Velocity was mapped with an acoustic Doppler current profiler during 11 of the 22 multibeam surveys. The dataset illustrates how bedforms are distributed in a typical Missouri River reach and how they evolve with changes in discharge. We measured a variety of bedform characteristics, including height, length, lee-slope angle, and crest orientation, and examined their relationship to larval sturgeon catch in the reach in 2020 and 2021. Bedform shapes are controlled by depositional environment and discharge and range in size from less than a meter in wavelength and amplitude to greater than 4 meters high and 75 meters long and generally have low angle lee-slopes. Small dunes were located in lower velocity regions on the inside of a bend and behind wing-dikes, as well as superimposed on larger dunes. Larger dunes were generally located in the channel thalweg and were associated with higher flow velocities. However, bedform size did not necessarily scale with discharge over the course of the 2019 flood, possibly due to sediment supply limitations and hysteresis effects. Changes in bedform size over the course of the flood event were most pronounced in the thalweg; less change in bedform size occurred behind wing dikes on the inside of channel bends, indicating some degree of habitat stability. Despite rarely getting caught in the thalweg, larval sturgeon drift in the thalweg until they are intercepted into off-channel habitats in wing dike fields, where they are caught in much higher numbers. Bedform orientations were affected by flow expansion around wing dikes, indicative of the role of wing dikes in influencing exchange of material between the thalweg and channel margins. Increased understanding of bedform distributions and dynamics will inform future sampling and habitat restoration designs for larval pallid sturgeon and contribute to increased understanding of their influence on benthic ecological processes.

Introduction

We explored bedform distributions and dynamics in the Lower Missouri River (LMOR), Missouri, with the objective of understanding the implications of these features for benthic fish habitat, particularly the endangered pallid sturgeon (*Scaphirhynchus albus*), including how bedforms might act as flow refugia, mediators of food transport, and instigators of ecological disturbance. Sand dunes in large rivers provide a continually changing habitat with well-defined grain sizes, low organic matter, and high oxygenation which has led to adaptations in invertebrates (Wantzen et al. 2014) and other benthic organisms that inhabit these environments.

The endangered pallid sturgeon is a native benthic fish that occupies the LMOR and its larger tributaries (Jordan et al. 2016). Nearly every stage of the pallid sturgeon's life cycle is associated with the bottom of the river, which is predominantly made up of sandy bedforms. Adults migrate hundreds of miles upstream in the LMOR to spawn (DeLonay et al. 2016; Elliott et al. 2020). There is some evidence that migrating adult sturgeon avoid the region of high velocity and sediment transport associated with the channel thalweg and use lower velocity areas in the channel during their upstream migrations. However, migrating sturgeon do at times occupy the navigation channel and cross the channel thalweg where it is hypothesized they use flow refugia in the lee-slopes of bedforms (McElroy, DeLonay, and Jacobson 2012). Spawning habitats on the LMOR are located on outside bends in deep areas with high velocity, hard substrates, and migrating sandy bedforms (Elliott et al. 2020). After spawning, pallid sturgeon embryos incubate in substrates for several days (Chojnacki, George, and DeLonay 2023), after which they hatch and larvae passively drift downstream until they reach a developmental stage that allows them to maintain position in river currents and begin to feed (Chojnacki et al. 2022). This behavioral transition occurs approximately 10-14 days after hatch, depending on water temperature when they are approximately 20 millimeters in length (Chojnacki et al. 2022) . At this point in their development they can be intercepted as they drift and end up in off-channel habitats in wing dike fields and over sand bars where it is hypothesized they find flow refugia, feed, and grow (Chojnacki et al. 2022). A flume study with 3-day old larvae found energy consumption rates were lower for sturgeon exposed to velocities of 0.2 and 0.5 meters per second (m/s) in an environment with static dunes compared to a flat bed, indicating that dune habitats may provide energetic relief for benthic fish (Porreca, Hintz, and Garvey 2017). The mechanism of interception into off-channel habitats, and the suitability of these habitats to support food production and foraging are not fully understood; nevertheless, construction of so-called "Interception-Rearing Complexes" has evolved as a key restoration strategy targeted at recovering the species (Jacobson et al. 2016). Furthermore, it has been hypothesized that the high-velocity habitats with actively migrating bedforms are likely not suitable habitats for larval pallid sturgeon to forage and feed. Testing this hypothesis is important to guide restoration and recovery efforts.

Flow separation on the downstream, or lee slopes, of dunes provides regions of lower velocity in the trough between dunes. Higher benthic macroinvertebrate densities have been measured in dune troughs compared to other parts of dunes, and particularly in the troughs of dunes outside of the channel thalweg with larger lee-slope angles (Amsler, Bletter, and Ezcurra de Drago 2009). Measurements in smaller rivers and flumes have shown that dunes with lee-slope angles less than 10 degrees lack permanent flow separation; dunes with lee-slope angles above 30 degrees tend to have permanent flow separation; and dunes with lee-slope angles less than 4 degrees may not have any flow separation (Kwoll et al. 2016; Lefebvre, Paarlberg, and Winter 2016). Dunes in large rivers are generally characterized by low-angle lee slopes with a mean slope of 10 degrees where the maximum slope occurs at the upper part of the lee slope (Cisneros et al. 2020).

The LMOR is defined as the river between the downstream-most mainstem dam at Gavins Point, South Dakota, to Saint Louis, Missouri; the lower 1000 km LMOR is channelized for navigation

(Figure 1). Channel engineering has resulted in heavily revetted banks on the outside of bends and dikes on the inside of bends. In general, larger bedforms are associated with higher velocities in the main channel, and smaller bedforms occur on channel margins; bedforms migrate at all discharges in the LMOR (Elliott and Jacobson 2016). Our study area is Sheepnose Bend on the LMOR 500 kilometers upstream from the confluence with the Mississippi River (Figure 1). Several off-channel habitats within this bend are sites where larval pallid sturgeon and more common surrogates, shovelnose sturgeon (*Scaphirhynchus platorynchus*), have been caught in high numbers compared to other heavily sampled bends on the LMOR. High catches in Sheepnose Bend have motivated research studies combining larval fish sampling and habitat surveys to understand interception processes and to develop engineering strategies for ongoing restoration projects in the LMOR . We describe the dune habitats within this bend and address the potential for larval interception from the navigation channel into the channel margin.

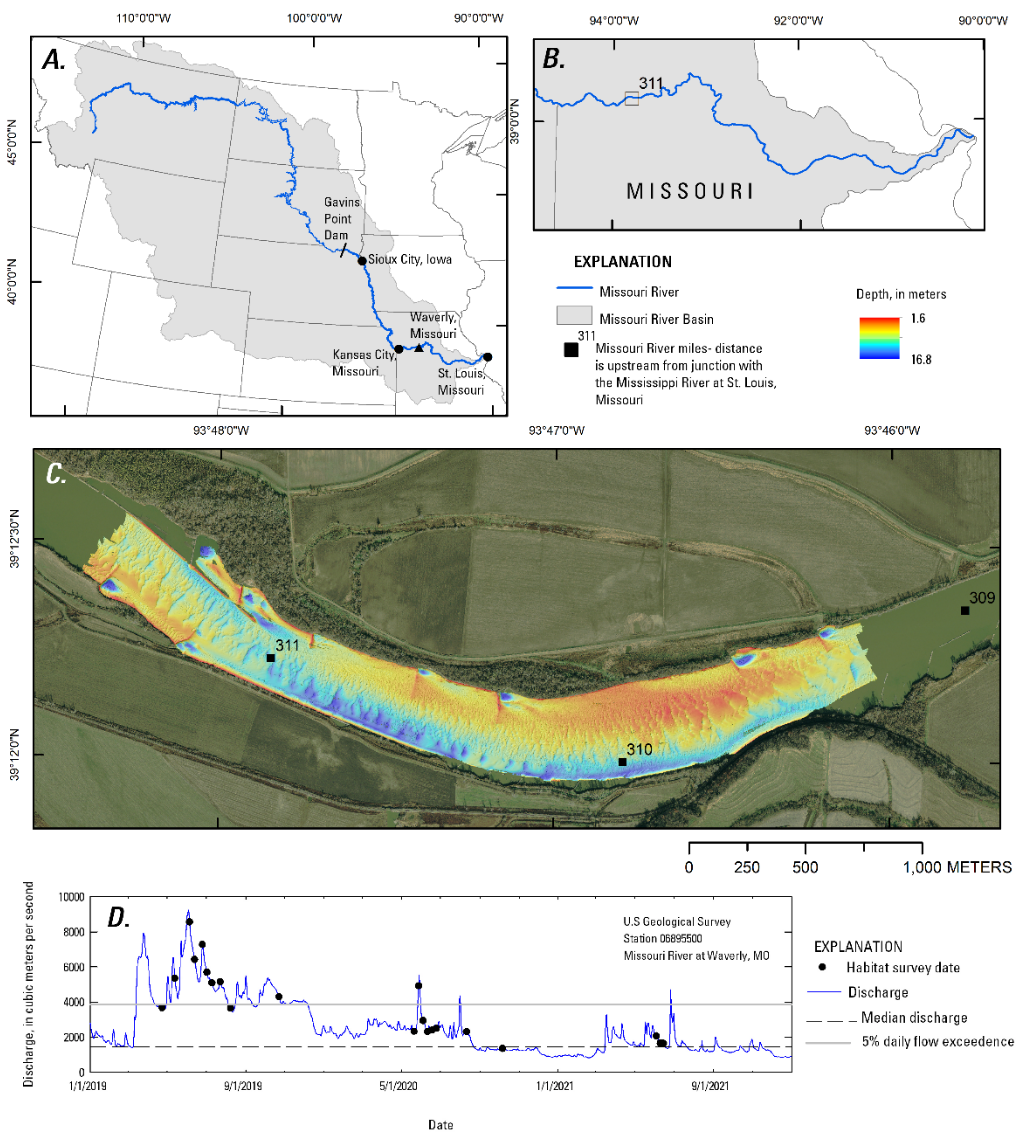

Figure 1. A.) The Missouri River basin, the Lower Missouri River, and B.) the Missouri River in Missouri, C.) Sheepnose Bend mapped on 5/13/2019 at a discharge of 5,350 cms, and D.) the hydrograph at Waverly, Missouri during the study. The channelized section of the Lower Missouri River extends from Sioux City, Iowa to the Mississippi River at St Louis, Missouri.

Methods

We surveyed 2-3.5-kilometer-long portions of Sheepnose Bend in the engineered LMOR 22 times over a three-year period from 2019-2021 over discharges ranging from 1,360-8,550 cubic meters per second (m^3/s), which constituted 50% to 1% daily flow exceedance probability at U.S. Geological Survey Station 06895500, Missouri River at Waverly, Missouri (Figure 1). Survey mostly occurred in late May and June when larval pallid sturgeon are drifting in the LMOR; opportunistic mapping occurred during the summer and fall, often targeting specific discharge targets. Bathymetry was mapped using a multibeam echosounder coupled with an inertial motion unit and global navigation satellite systems (GNSS) measurements of antenna height and corrected in real-time with a virtual reference station (VRS) over a cellular network to generate bathymetric maps of depth and elevation. This included weekly surveys during a large flood event with a peak of 9,290 m^3/s (1 % annual exceedance probability) in the summer of 2019 (Figure 1). The flood of 2019 also had a long duration, with 237 days above the 5% daily flow exceedance and at its peak was over bank, causing numerous levee breeches and floodplain inundation along the LMOR. Velocity was mapped with a 600 kHz acoustic Doppler current profiler on the same day or close in time to 11 of the 22 multibeam surveys over a representative range of discharges.

Multibeam data were edited and interpolated to raster grids with a 0.3 m cell size. Velocity data were processed and exported to georeferenced point summary files, and maps were interpolated and gridded to a cell size of 5 m. We measured a variety of bedform characteristics, including amplitude, wavelength, lee-slope angle, and crest orientation. To analyze bedform shape we used open-source Python code (Van Rossum and Drake 2009) to analyze longitudinal profiles and calculate statistics of dune amplitude, wavelength, and lee slope angle (Lokin et al. 2022; Lokin 2021). This code employs wavelet analysis (Torrence and Compo 1998) to identify dunes with different scales. We developed custom Python scripts to extract dune crests from raster data to determine dune crest angle in planform. Deviation between the dune crest angle and the direction of downstream flow was calculated to determine a metric for dune divergence from main channel flow. Geomorphic change detection (GCD) software was implemented with a threshold of 20 cm to determine the amount of geomorphic change between surveys (Wheaton et al. 2010).

Fisheries sampling was conducted by the U.S. Army Corps of Engineers using methods developed and standardized for Missouri River sampling (Welker and Drobish 2017; Ridenour, Doyle, and Hill 2011). Sheepnose bend was divided into a grid with sampling regions 50 m wide by 400 m long in an effort to sample all channel units. Expert judgement was used to select trawl locations within each grid cell, and trawl lines were recorded using VRS-corrected GNSS. OT16 benthic otter trawls were deployed from a boat and dragged moving downstream along the bottom of the river for approximately 100 m. Trawl contents were sorted to identify the number of undifferentiated sturgeon (shovelnose and pallid sturgeon, hereafter referred to as age-0 sturgeon) and samples were preserved for genetic analysis. Catch per unit effort (CPUE) was calculated by dividing the number of fish caught in a trawl by the area trawled and is reported as the number of fish per 100 m^2 (Ridenour, Doyle, and Hill 2011). Depths and velocities were associated with trawls by spatially joining the trawl location with multibeam depth and interpolated velocity habitat maps. Trawl transect lines were intersected with multibeam maps and analyzed using a modified Python script to generate summary bedform amplitude and wavelength values for each trawl (Ashley et al. 2020).

Results

All habitat data collected in this study are publicly available (Elliott 2022). The engineered LMOR fundamentally has two main habitats, the high-velocity environments of the main channel, and slower velocity off-channel dike-field habitats (Figure 1). Dike-field habitats include both wing dikes, which are perpendicular to flow, and L-head dikes and revetments, which are parallel to flow. Unless they are notched, L-head dikes have limited exchange of sediment and water with the main channel except when submerged during high flow events. Revetment and L-head dikes generally have scour holes and muddy substrates and were not analyzed in this study. Wing dikes obstruct flow and promote flow recirculation at most discharges and these processes which, in turn help to exchange flow, sediment, and biota between the main channel and off-channel habitats.

Dune shape

Bedform shapes generally scaled with discharge, and the largest bedforms occurred in the navigation channel (Figure 2). Small dunes were located in lower velocity regions on the inside bend and in dike fields, as well as superimposed on larger dunes (Figures 3 and 4). The largest bedforms in amplitude and wavelength were measured during or close to flood peaks (Figures 2-3). Peak flows during the 2019 flood occurred on 6/3/2019 and the survey from 6/5/2019 had the largest bedforms (Figures 2 and 3). Large bedforms were also observed during a secondary flow peak on the descending limb on 6/25/2019, and a survey during the peak in 2020 (Figure 4b and 4d). Thalweg bedforms during the highest flows (flow events with more than the 1% daily flow exceedance) had mean amplitudes 1.5 - 4.3 m, and mean wavelengths of 40 - 85 m (Figures 2-4). Bedform dimensions diminished on the descending limb of the 2019 flood, and during the 8/8/2019 survey mean dune amplitude in the thalweg was 0.35 m, the smallest recorded in the thalweg during any survey, and 1/3 the dune amplitude of surveys at similar discharges (Figure 4). Variation in the dune shape and discharge relationship is likely due to lags in dune response to rapid changes in flow and hysteresis effects in sediment transport, where sediment may be limited and transport rates are lower during the descending limb of the hydrograph compared to the rising limb of the hydrograph (Kleinhans et al. 2002; Venditti et al. 2019). Dune shapes in dike fields also scale with discharge similarly to the thalweg but are much smaller in magnitude at all discharges. The analyses in dike fields indicated that dune wavelength is relatively stable over a wide range of discharges.

Our results confirm that the thalweg of the LMOR has a high percentage of low lee-slope angle dunes with likely intermittent to low flow separation. Mean lee-slope angles are <10.5 degrees except at very high and rare (above bankfull) discharges (Figure 5) although some high angle dunes do exist in the thalweg at discharges with 30% daily flow exceedance or less. Similar to patterns in dune amplitude, dune lee-slope angles in the beginning of the flood event were higher compared to those measured in the survey on 8/8/2019 towards the end of the flood. Dunes in the dike field have uniformly low lee-slope angles, with means at or below 5 degrees during every survey except during the flood peak in 2019 (Figure 5).

Dune crest orientations indicate flow expansion in velocities near the streambed around wing dikes. Dune crest orientation is generally perpendicular to mean flow direction in the channel thalweg, but adjacent to wing dikes there is increasing deviation indicative of bottom-velocity vectors transporting sand toward the channel margin (Figure 6). We hypothesize that the dune crest orientations are a better surrogate for near-bed velocities responsible for transporting benthic larvae compared to vectors developed with ADCP or 2-dimensional hydraulic models and may help predict areas where benthic larvae are transported out of the thalweg into off-channel areas.

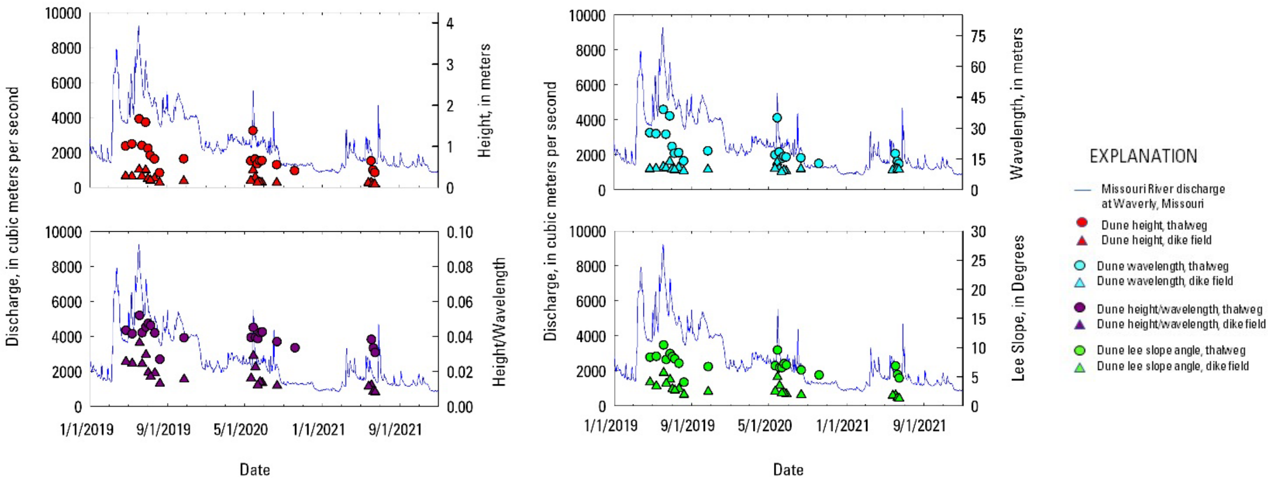

Figure 2. Discharge for the Missouri River at Waverly, Missouri for 2019-2021 with mean dune shape statistics from survey discharges for a thalweg transect and four averaged dike field transects over the course of 22 surveys.

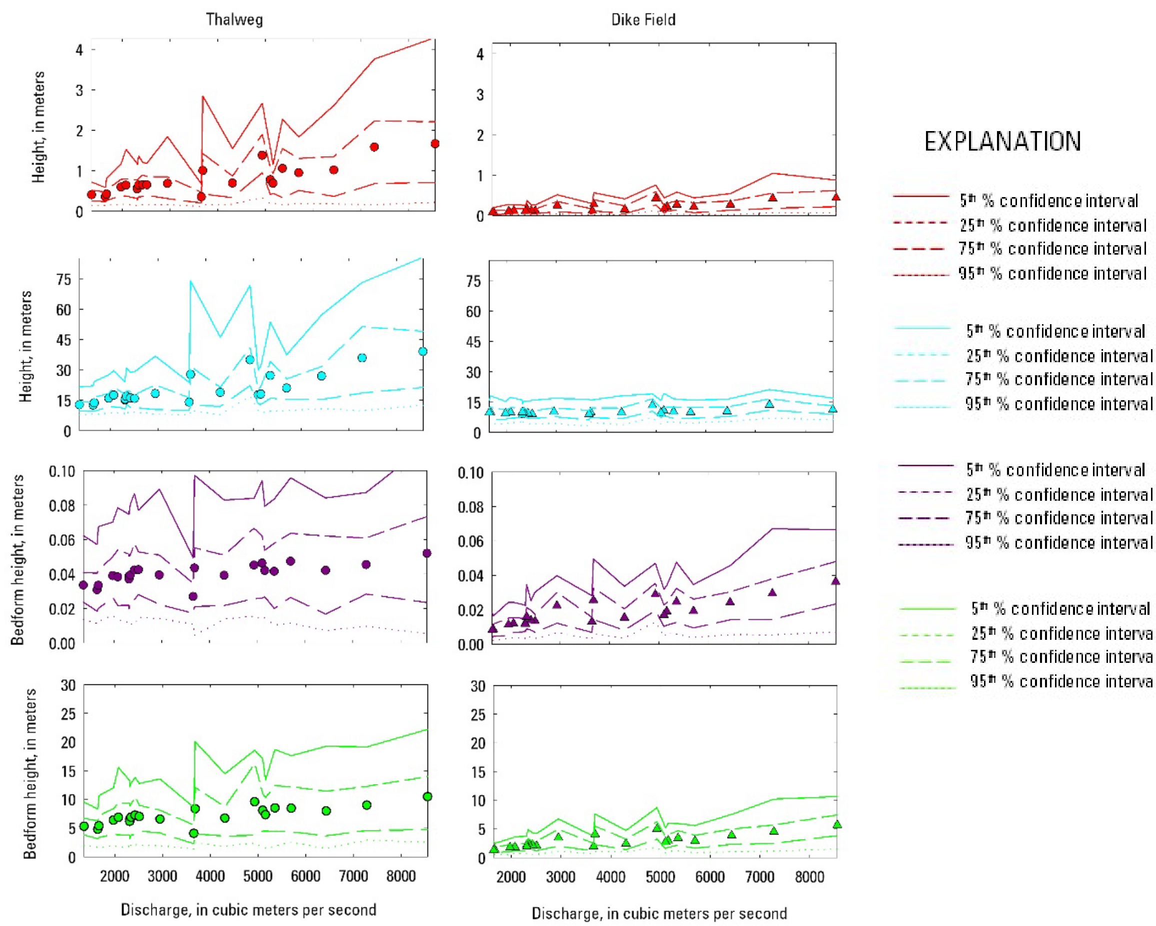

Figure 3. Dune shape statistics from survey discharges for a thalweg transect and four averaged dike field transects over the course of 22 surveys. Points represent the mean values, and lines in the discharge plots represent the 5, 25, 75, and 95 percent confidence intervals from the dune shape analysis.

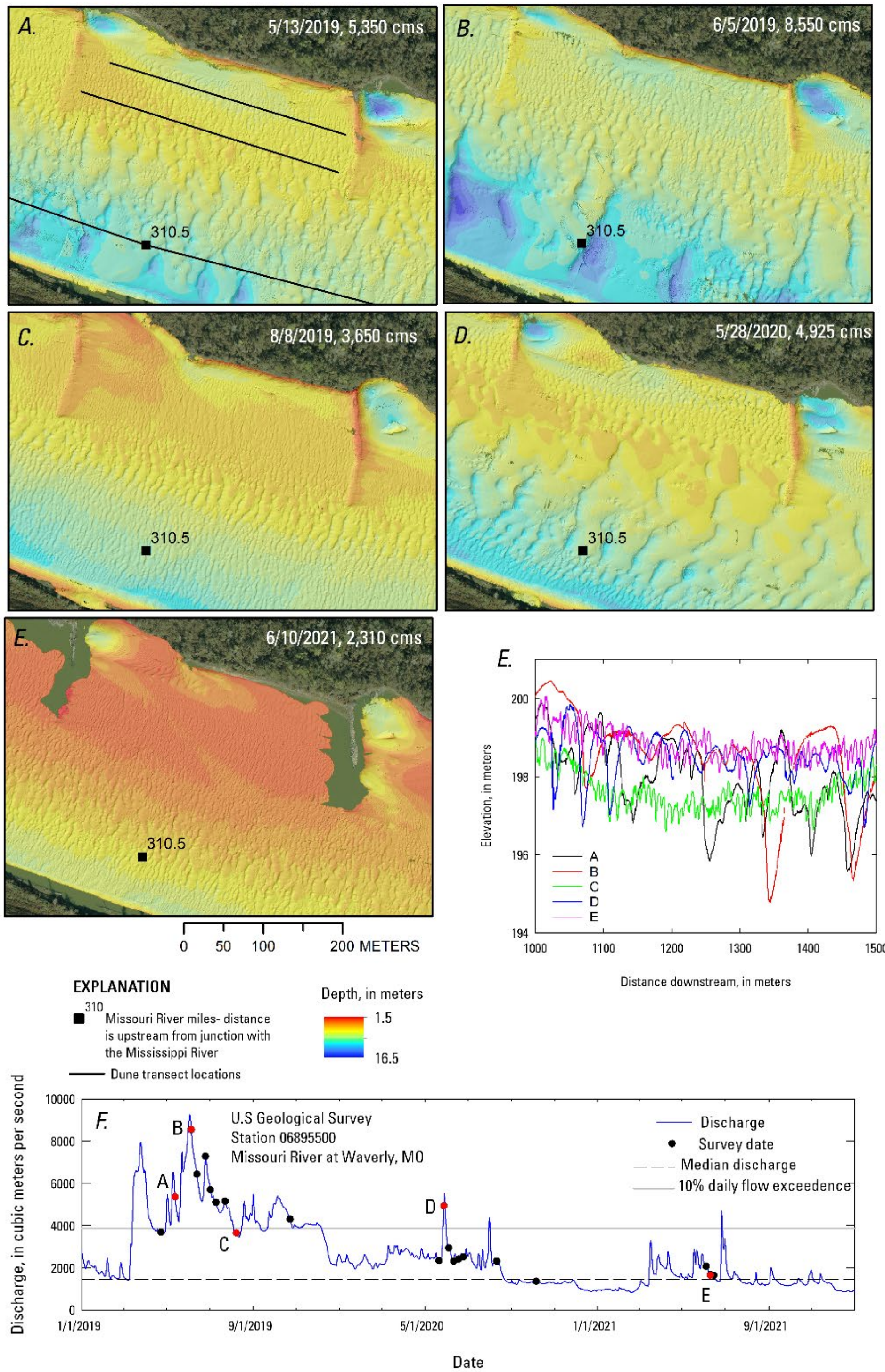

Figure 4. Examples of bathymetry and dune longitudinal profiles from the channel thalweg for five selected survey dates; A.) 5/13/2019, the rising limb of the hydrograph of the 2019 flood B.) 6/5/2019, near the peak of the 2019 flood, C.) 8/8/2019, small dunes indicative of sediment limitation on the falling limb of the hydrograph, D.) 5/28/2020, the peak of the highest flow event in 2020, and D.) 6/10/2021, a survey close to median discharge in 2021, a year with a lower peak flow than 2019 and 2020, E.) longitudinal profile in thalweg for location shown in A, and F.) hydrograph and survey dates during the survey period.

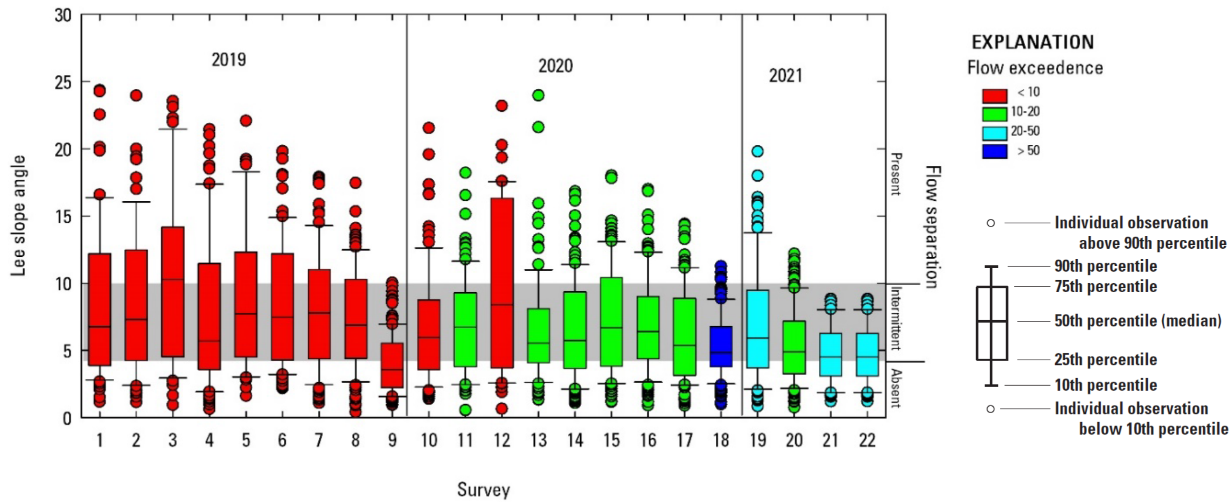

Figure 5. Lee-slope angle statistics for a transect in the channel thalweg for all surveys.

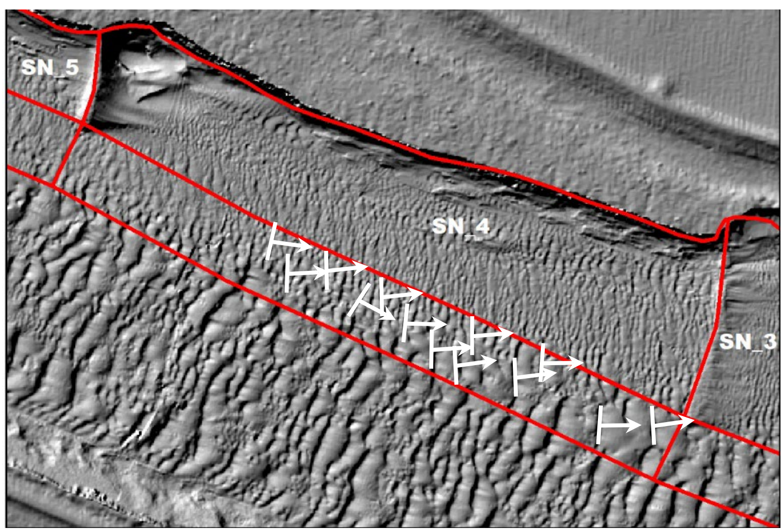

Figure 6. Dune crest orientation adjacent to wing dikes may be indicative of the lateral direction of sediment transport toward the channel margins. Smaller dunes are observed superimposing larger dunes. Dike fields are numbered and SN refers to Sheepnose Bend.

Larval fish presence and abundance

Trawling efforts during the 2019 flood did not capture many sturgeon and were limited to off-channel habitats; therefore, trawl data from Sheepnose Bend in 2020 and 2021 was used in this analysis. We selected trawls that occurred in the main channel and wing dike fields that coincided with dates and discharges when habitat was mapped. Age-0 sturgeon were caught in both main channel and dike field habitats (Figure 7A, B). Age-0 sturgeon in the main channel were caught in taller bedforms (mean 0.85 m, range 0.4-1.2 m) and at much higher depth-averaged velocities (mean 1.6 m/s, range 1.2-1.8 m/s) compared to dike fields. Dike fields, particularly where fish were caught, had bedforms with long wavelengths. These longer wavelengths may be associated with scour holes within the dike fields with superimposed smaller dunes (Figures 2, 4). In dike fields, age-0 sturgeon were caught in smaller dune sizes (mean 0.6 m, range 0.2-1.2 m) and lower velocities (mean 0.6 m/s, range 0.2-1 m/s) compared to dunes in the main channel. Abundance was much higher in dike fields. All trawls in the main channel that captured fish had very low CPUE, often only one fish in a trawl. Mean CPUE was 0.35 and the range was 1-2 fish per 100 m^2. Mean CPUE associated with dike-field environments was 4.85, with a range from 0.3-21.5 fish per 100 m^2 .

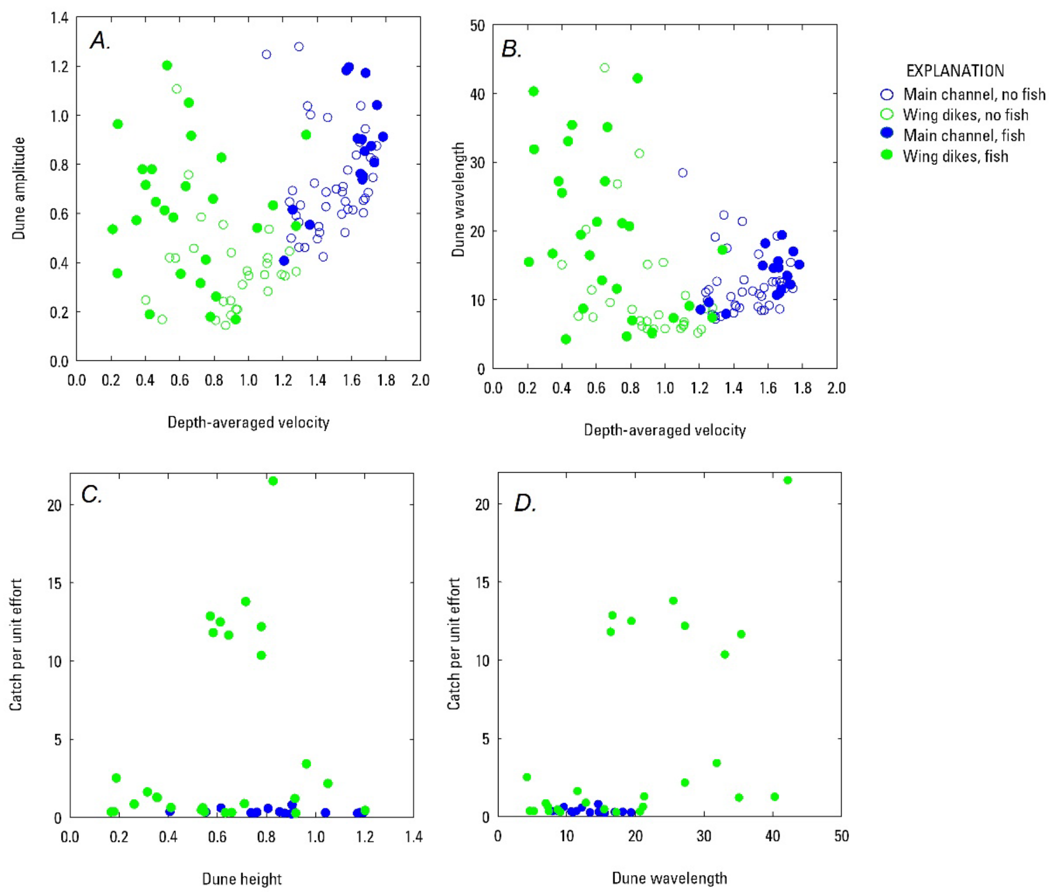

Figure 7. Trawl results from Sheepnose Bend at main channel and wing dike locations with habitat data in 2020 and 2021. A.) Dune amplitude and depth-averaged velocity, B.) Dune wavelength and depth-averaged velocity, C.) Catch per unit effort and dune amplitude, and D.) Catch per unit effort and dune wavelength.

Geomorphic change and ecological disturbance

GCD results show that 37-85% of the channel area had detectible change; some periods had more change than others (Figure 8). In all the surveys from 2019 through the first survey of 2020, over 75 percent of the survey area had measurable change; during 2020 and 2021 the areal extent of geomorphic change decreased to between 52 and 75 percent. During the 2019 flood, initial deposition associated with the first peak was followed by an extended period of erosion. After the 2019 flood, the reach experienced net deposition through the winter of 2019-2020, followed by net erosion during high flows in 2020. Deposition was dominant during the summer of 2020, but magnitude was low and error ranges were high. During the winter of 2020-2021 there was moderate net erosion. Surveys during the summer of 2021 documented very little overall change, indicative of equilibrium dune migration and low rates of deposition and erosion. These results document the pervasive mobility of the bed of the Missouri River and the apparent complexity resulting from sequences of flow events.

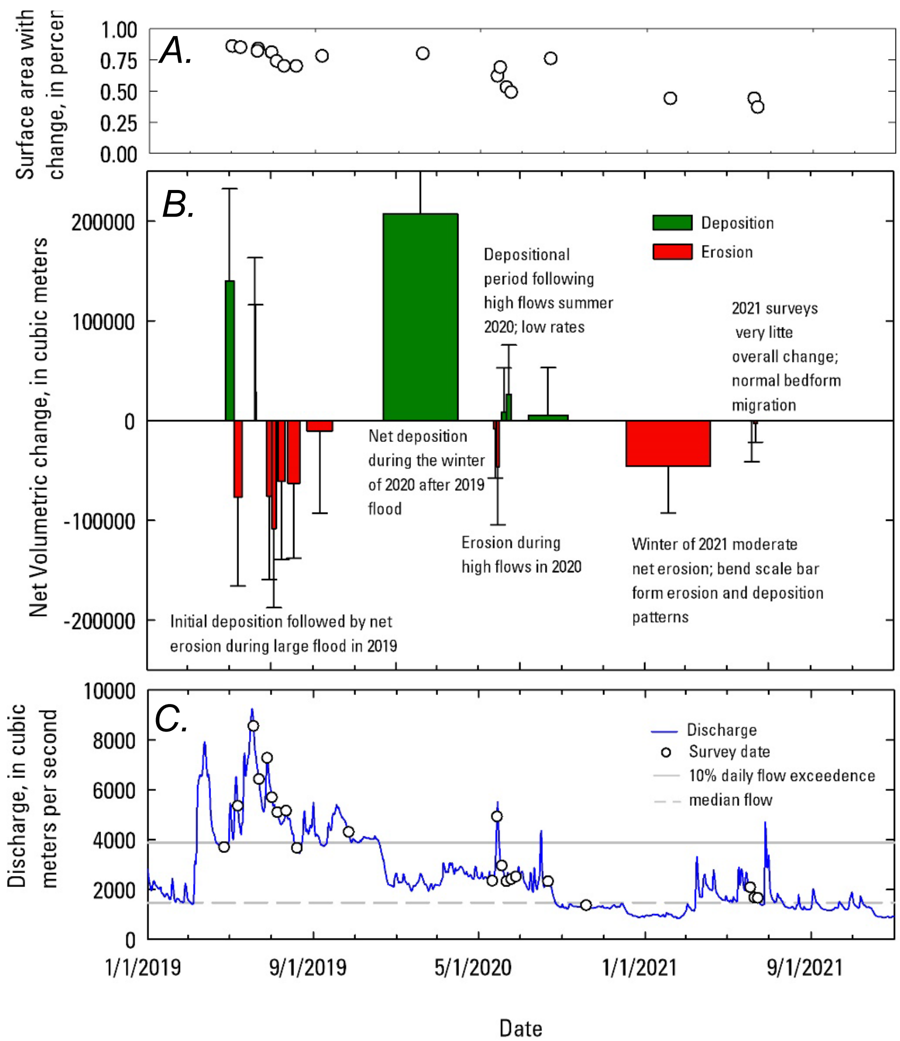

Figure 8. Geomorphic change between surveys. A.) Areal change over time, B.) Net volumetric change between flood events, and C.) Hydrograph showing survey dates, 10% daily flow exceedance, and median flow.

Discussion

Dunes in flumes and rivers have been observed to scale with depth when they are in equilibrium (van Rijn 1984; Simons and Richardson 1961); however more recent studies have shown predictive relationships to be more complex, and other factors, including shear stress and shear velocity influence dune size (Bradley and Venditti 2017). Dune size patterns on this bend of the LMOR show a complex response to flow events that may indicate of sediment lags and metastability. More predictable patterns seem to emerge during periods of stable, moderate flows. During the falling limb of the 2019 flood, dunes were substantially smaller than any other date measured and linear flow-parallel sand ribbon features were present (Figure 4C, in the middle of the channel), which may indicate sand supply limitation due to the extended period of high flow. GCD results show that the net effect of the 2019 flood was erosion, and that during the winter and spring after the flood the bed recovered. Net scour during the 2019 flood event, is consistent with Gibson and Shelley (2019) who documented rapid scour during large flood events (1993, 2011) on the LMOR, followed by a rebound period of several years.

In addition to the extreme flooding in 2019, discharges evaluated in this study were generally biased towards high flows that exist during the spring time period when larvae are drifting in the LMOR. Nevertheless, 2021 provided insight into dune dynamics when the river is not flooding or recovering from a recent flood event. In 2021, four surveys occurred during a 20-day period with the discharges fell in the 25-40th percent daily flow exceedance range and peak flows proceeded the surveys. These surveys are indicative of a relatively calm period where the areal extent of detectible change was limited to the main channel, and there were nearly equal amounts of erosion and deposition, which indicates equilibrium rates of dune migration. Although repeat measurements of topography at a scale to measure dune celerity rates were not a part of this project, Elliott and others (2016) measured dune celerity rates in the LMOR about 160 km downstream and documented that celerity increased with discharge, ranging from 0.15 to 3.75 meters per hour. The highest rates measured in that study were in the main channel, (3.75 meters per hour) at a 9% daily flow exceedance of 3,171 m^3/s. This rate translates to a bedform movement of about 90 m per day.

Although the LMOR is dominated by low-angle dunes, which are thought to cause little flow separation, higher angle (>10 degrees) dunes, which likely have persistent flow separation zones, do occur in the thalweg at higher flows. Surface "boils" from turbulence associated with separation zones are frequently observed in the main channel of the LMOR and understanding flow structures in these areas is a potential area for future research. Flow separation zones in the lee of sand dunes may constitute flow refugia and areas of food accumulation for larval sturgeon. The associated macroturbulence may be instrumental in transporting larval sturgeon from the near-bed transport region higher up in the water column where they may be intercepted into dike-field areas and end up in supportive habitats on the channel margins. Flow refugia created by dune geometry and flow separation may also provide foraging habitat for adults in the thalweg, as it is likely that drifting invertebrates may be retained in the dune environment (Amsler, Bletter, and Ezcurra de Drago 2009; Wantzen et al. 2014).

Age-0 sturgeon are rarely caught in the navigation channel of the LMOR or the Mississippi River (Phelps et al. 2010). However, as a whole, age-0 sturgeon in the LMOR and Mississippi River have been caught in a wide variety of depths and velocities, making biologically derived quantification of habitat criteria difficult (Gemeinhardt et al. 2019; Hintz et al. 2015). Gemeinhart and others (2019) hypothesized that if sand dunes and other local microhabitats provide flow complexity and refugia, there is a need to understand the interaction of bedforms, foraging, and ago-0 sturgeon behavior.

Our results show that low-angle lees slopes in dike field habitats may not produce flow separation, but the velocity fields within these off-channel habitats have not been measured in enough detail to fully understand their complexities. Finer scale measurements of velocity and turbulence, coupled with novel instrument deployment techniques, are needed to measure velocities in off-channel and navigation channel habitats at scales relevant to developing benthic fish.

Trawling results showed very low to no catch in the thalweg, despite sampling on the same dates that age-0 sturgeon were found in high numbers in dike-field habitats. This indicates that age-0 sturgeon may be transported in the thalweg but collecting and persisting longer in dike field habitats. However, there is also uncertainty about trawl efficiency as ability to capture age-0 sturgeon in bedforms of different scales. OT16 trawls are 2.5 meters wide and weighted to maintain contact with the bottom of the river. However, it is unknown how efficiently trawls capture fish in different dune shapes in the high-velocity, highly turbulent thalweg, and whether the trawl may also exert hydraulic effects on capture rates.

Summary

We explored bedform dynamics and implications for benthic habitats in a reach of the LMOR over 22 surveys in 2019-2021. Maps included a large and long duration over-bank flood event in 2019. Bedforms were larger and more dynamic in the navigation channel than in off-channel dike-field habitats. Smaller dunes were located in lower velocity regions on the inside bend and in dike fields, as well as superimposed on larger dunes. Bedform amplitude and wavelength generally increased as discharge increased; the largest bedforms in amplitude and wavelength were present during or close to flood peaks. Exceptions in dune scaling with discharge magnitude were likely due to lags in dune response to rapid changes in flow and in cases when sediment may be limited during the descending limb of the hydrograph. Dune sizes in the dike field also scaled with discharge similarly to the thalweg and were smaller later in the flood as well. The thalweg of the LMOR has a high percentage of low angle dunes with likely intermittent to low flow separation although more high-angle dunes were present at higher discharges. Dune crest orientation is generally perpendicular to flow in the channel thalweg, but adjacent to wing dikes there is increasing deviation from the downstream direction, indicating bottom velocity vectors are advecting material, and potentially sturgeon larvae, into channel-margin habitats. Trawl data from Sheepnose Bend in 2020 and 2021 show age-0 sturgeon were caught in both main channel and dike field habitats but abundance was much higher in dike fields. All trawls in the main channel that caught fish had very low CPUE. Age-0 sturgeon in the main channel were caught in taller bedforms and caught in much higher depth-averaged velocities compared to dike fields. Geomorphic change detection results show that net erosion dominated during the rare 2019 flood, followed by net deposition during the winter of 2019-2020. Erosion was again dominant during high flows in 2020 and change occurred at very low rates in 2021. Increased understanding of bedform distributions and dynamics in the LMOR will directly inform future benthic larval sampling and monitoring designs, such as planning optimal trawl locations for catching larval pallid sturgeon. This work also informs restoration engineering designs such as Interception Rearing Complexes that aim to restore sites in the LMOR to increase potential for larval pallid sturgeon transport out of the thalweg into off-channel habitats and contribute to a general understanding of the influence of bedforms on benthic ecological processes. (Gibson and Shelley 2020)

References

Amsler, M. L., M. C. Bletter, and I. Ezcurra de Drago. 2009. 'Influence of hydraulic conditions over dunes on the distribution of the benthic macroinvertebrates in a large sand bed river', *Water Resources Research*, 45: 1-15 https://doi.org/10.1029/2008WR007537.

Ashley, T. C., B. McElroy, D. Buscombe, P. E. Grams, and M. Kaplinski. 2020. 'Estimating Bedload From Suspended Load and Water Discharge in Sand Bed Rivers', *Water Resources Research*, 56: e2019WR025883, https://doi.org/10.1029/2019WR025883.

Bradley, Ryan W., and Jeremy G. Venditti. 2017. 'Reevaluating dune scaling relations', *Earth-Science Reviews*, 165: 356-76, https://doi.org/10.1016/j.earscirev.2016.11.004 .

Chojnacki, Kimberly A., Marlene J. Dodson, Amy E. George, James S. Candrl, and Aaron J. DeLonay. 2022. 'Ontogenetic development of pallid sturgeon (Scaphirhynchus albus) and shovelnose sturgeon (Scaphirhynchus platorynchus) from hatch through yolk absorption', *Ecology of Freshwater Fish*, n/a, https://doi.org/10.1111/eff.12680.

Chojnacki, Kimberly A., Amy E. George, and Aaron J. DeLonay. 2023. 'The effects of substrate and sediment burial on survival of developing pallid sturgeon (Scaphirhynchus albus) and shovelnose sturgeon (S. platorynchus) embryos', *Environmental Biology of Fishes*: 1-13, https://doi.org/10.1007/s10641-023-01387-0.

Cisneros, Julia, Jim Best, Thaiënne van Dijk, Renato Paes de Almeida, Mario Amsler, Justin Boldt, Bernardo Freitas, Cristiano Galeazzi, Richard Huizinga, Marco Ianniruberto, Hongbo Ma, Jeffrey A. Nittrouer, Kevin Oberg, Oscar Orfeo, Dan Parsons, Ricardo Szupiany, Ping Wang, and Yuanfeng Zhang. 2020. 'Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape', *Nature Geoscience*, 13: 156-62, https://doi.org/10.1038/s41561-019-0511-7.

DeLonay, A.J., K.A. Chojnacki, R.B. Jacobson, P.J. Braaten, K.J. Buhl, C.M. Elliott, S.O. Erwin, J.D.A. Faulkner, J.S. Candrl, D.B. Fuller, K.M. Backes, T.M. Haddix, M.L. Rugg, C.J. Wesolek, B.L. Eder, and G.E. Mestl. 2016. "Ecological requirements for pallid sturgeon reproduction and recruitment in the Missouri River: Annual report 2014." In, 131. U.S. Geological Survey, http://dx.doi.org/10.3133/ofr20161013.

Elliott, C. M., Call, B.C., Li, G., Wang., B. 2022. "Field Data and Models of the Missouri River at Sheepnose Bend, near Lexington, Missouri, 2019-2021: U.S. Geological Survey data release https://doi.org/10.5066/P9X5M3WH."

Elliott, C.M., and R.B. Jacobson. 2016. 'Measurement of bedform migration rates on the Lower Missouri River in Missouri, USA using repeat measurements with a multibeam echosounder.' in George Constantinescu, Marcelo Garcia and Daniel Hanes (eds.), *River Flow 2016* (Taylor and Francis Group: London) .

Elliott, Caroline M., Aaron J. DeLonay, Kimberly A. Chojnacki, and Robert B. Jacobson. 2020. 'Characterization of Pallid Sturgeon (Scaphirhynchus albus) Spawning Habitat in the Lower Missouri River', *Journal of Applied Ichthyology*, 36: 25-38, https://doi.org/10.1111/jai.13994.

Gemeinhardt, T.R., N.J.C. Gosch, A.P. Civiello, N.J. Chrisman, H.H. Shaughness, T.L. Brown, J.M. Long, and J.L. Bonneau. 2019. 'The influence of depth and velocity on age-0 sturgeon prey consumption: implications for aquatic habitat restoration.', *River Research and Applications*, 35: 205-15, https://doi.org/10.1002/rra.3395.

Gibson, S, and Shelley, J., 2020, Flood Disturbance, recovery, and inter-flood incision on a large sand-bed river, Geomorphology, 351, https://doi.org/10.1016/j.geomorph.2019.106973.

Hintz, W. D., A. P. Porreca, J. E. Garvey, Q. E. Phelps, S. J. Tripp, R. A. Hrabik, and D. P. Herzog. 2015. 'Abiotic Attributes Surrounding Alluvial Islands Generate Critical Fish Habitat', *River Research and Applications*, 31: 1218-26, https://doi.org/10.1002/rra.3395.

Jacobson, R.B., M.J. Parsley, M.L. Annis, M.E. Colvin, T.L. Welker, and D.A. James. 2016. "Development of working hypotheses linking management of the Missouri River to population

dynamics of Scaphirhynchus albus (pallid sturgeon)." In, 33. U.S. Geological Survey, http://dx.doi.org/10.3133/ofr20151236.
Jordan, G.R., E.J. Heist, P.J. Braaten, A.J. DeLonay, P. Hartfield, D.P. Herzog, K.M. Kappenman, and M.A.H. Webb. 2016. 'Status of knowledge of the pallid sturgeon (*Scaphirhynchus albus* Forbes and Richardson, 1905)', *Journal of Applied Ichthyology*, 32: 191-207, http://dx.doi.org/10.1111/jai.13239.
Kleinhans, M.G., A.W.E. Wilbers, A. de Swaaf, and van Den Berg. 2002. 'Sediment supply-limited bedforms in sand-gravel bed rivers', *Journal of Sedimentary Reseach*, 72: 629-40, https://doi.org/10.1306/030702720629.
Kwoll, E., J. G. Venditti, R. W. Bradley, and C. Winter. 2016. 'Flow structure and resistance over subaquaeous high- and low-angle dunes', *Journal of Geophysical Research: Earth Surface*, 121: 545-64, https://doi.org/10.1002/2015JF003637.
Lefebvre, Alice, Andries J. Paarlberg, and Christian Winter. 2016. 'Characterising natural bedform morphology and its influence on flow', *Geo-Marine Letters*, 36: 379-93, https://doi.org/10.1007/s00367-016-0455-5.
Lokin, L. R. 2021. "LiekeLokin/DuneDataAnalyisis: Dune Analysis Code." In *https://doi.org/10.5281/zenodo.5764363*.
Lokin, L. R., J. J. Warmink, A. Bomers, and S. J. M. H. Hulscher. 2022. 'River Dune Dynamics During Low Flows', *Geophysical Research Letters*, 49: e2021GL097127, https://doi.org/10.1029/2021GL097127.
McElroy, Brandon, Aaron J. DeLonay, and R. B. Jacobson. 2012. 'Optimum swimming pathways of fish spawning migrations in rivers', *Ecology*, 93: 29-3 4, https://doi.org/10.1890/11-1082.1.
Phelps, Q.E., S.J. Tripp, J.E. Garvey, D.P. Herzog, D. Ostendorf, J.W. Ridings, J.W. Crites, and R.A. Hrabik. 2010. 'Habitat use during early life history infers recovery needs for shovelnose sturgeon and pallid sturgeon in the middle Mississippi River', *Transactions of the American Fisheries Society*, 139: 106068, https://doi.org/10.1577/T09-199.1.
Porreca, A.P., W.D. Hintz, and J.E. Garvey. 2017. 'Do alluvial sand dunes create energetic refugia for benthic fishes? An experimental test with the endangered pallid sturgeon', *River Research and Applications,* https://doi.org/10.1002/rra.3132.
Ridenour, C.J., W.J. Doyle, and T.D. Hill. 2011. 'Habitats of age-0 sturgeon in the lower Missouri River', *Transactions of the American Fisheries Society*, 140: 1351-58, https://doi.org/10.1080/00028487.2011.620493.
Simons, D. B., and E. V. Richardson. 1961. 'Forms of bed roughness in alluvial channels', *Journal of the Hydraulics Division*, 87: 87-105, https://doi.org/10.1061/JYCEAJ.0000612.
Torrence, Christopher, and Gilbert P. Compo. 1998. 'A Practical Guide to Wavelet Analysis', *Bulletin of the American Meteorological Society*, 79: 61-78, https://doi.org/10.1175/1520-0477(1998)079%3C0061:APGTWA%3E2.0.CO;2.
van Rijn, L.C. 1984. 'Sediment transport, Part II: Suspended load transport', *Journal of Hydraulic Engineering*, 110: 29, https://doi.org/10.1061/(ASCE)0733-9429(1984)110:11(1613).
Van Rossum, G., and F. L. Drake. 2009. *Python 3 Reference Manual* (CreateSpace: Scotts Valley, California).
Venditti, Jeremy G., Jeffrey A. Nittrouer, Mead A. Allison, Robert P. Humphries, and Michael Church. 2019. 'Supply-limited bedform patterns and scaling downstream of a gravel–sand transition', *Sedimentology*, 66: 2538-56, https://doi.org/10.1111/sed.12604.
Wantzen, Karl M., Martin C. M. Blettler, Mercedes R. Marchese, Mario L. Amsler, Michel Bacchi, Inés D. Ezcurra de Drago, and Edmundo E. Drago. 2014. 'Sandy rivers: a review on general ecohydrological patterns of benthic invertebrate assemblages across continents', *International Journal of River Basin Management*, 12: 163-74., https://doi.org/10.1080/15715124.2014.885438.
Welker, T.L., and M.R. Drobish. 2017. "Missouri River standard operating procedures for fish sampling and data collection, v. 1.8." In, 195. U.S. Army Corps of Engineers.
Wheaton, J.M., J. Brasington, S.E. Darby, J.E Merz, G.B. Pasternack, D. Sear, and D. Vericat. 2010. 'Linking geomorphic changes to salmonid habitat at a scale relevant to fish', *River Research and Applications*, 26: 469-86, https://doi.org/10.1002/rra.1305.

Acknowledgements

This study was supported by the U.S. Geological Survey and the U.S. Army Corps of Engineers Missouri River Recovery Program. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Data availability statement: USGS data is available in a USGS data release on Science Base, https://doi.org/10.5066/P9X5M3WH. Fisheries data for Sheepnose Bend was collected and provided by the U.S. Army Corps of Engineers (USACE); these data are not currently available. Contact the USACE, Kansas City District for further information.