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Matthew Russell

Aaron R. Mittelstet

Tiffany Messer

Jesse T. Korus

R.M. Joeckel

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Matthew Russell,[1] Aaron R. Mittelstet,[1] Tiffany L. Messer,[1] Jesse T. Korus,[2] and R. M. Joeckel [2]

1 Biological Systems Engineering Department, East Campus, University of Nebraska-Lincoln, 5223 L.W. Chase Hall, P.O. Box 830726, Lincoln, NE 68583-0726,

2 Conservation and Survey Division, School of Natural Resources, East Campus, University of Nebraska-Lincoln, 101 Hardin Hall, Lincoln, NE 68583-0961

Corresponding author — M. Russell, *email* matthew.russell03@uky.edu

Abstract

Stabilization projects are increasingly used to mitigate the effects of anthropogenic streambank erosion, yet the effectiveness of stabilization has been insufficiently measured. Sound monitoring practices inform adjustments in implementation and maintenance, which improve engineered effectiveness. Thus, the objectives of this study were to: 1) measure streambank migration from in three reaches stabilized with wooden jetties following a major flooding event, and 2) quantify deposition around the jetties between pre-flood and post-flood. Streambank deposition was measured in 2019 with a River Surveyor and Global Positioning System (GPS). Bank erosion rates in Reaches 1, 2 and 3 were 0.41, 0.96 and 0.07 $m^2\,m^{-1}\,yr^{-1}$, respectively, from pre-installation of wooden jetties. After streambanks in these reaches were stabilized, Reach 1 experienced 0.11 $m^2\,m^{-1}\,yr^{-1}$ of erosion while Reaches 2 and 3 had 0.13 and 0.01 $m^2\,m^{-1}\,yr^{-1}$ of deposition. Deposition increased in 2019 (1.61 and 0.81 $m^2\,m^{-1}$) following a high magnitude flood. We utilized a new method for quantifying accumulated sediment in stream beds and banks. Our application of this new method

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demonstrates that jetties in the Cedar River have decreased streambank migration and increased sediment deposition at the point of implementation. The quantification of stream-sediment dynamics near jetties provides crucial information for stream-restoration design and decision-making, specifically for bioengineering design implementation.

Keywords: Erosion, Sediment deposition, Jetty, Geomorphology, Aquatic ecosystems

1. Introduction

Streambank erosion is a natural, dynamic process, which plays a major role in the geomorphic evolution of streams and floodplains as well as the creation and maintenance of riparian habitat for a diversity of organisms (Florsheim et al., 2008). Sediment erosion and deposition are undeniably essential attributes of healthy streams, but the acceleration of these processes, especially if there is net downstream transport of sediment, is not ideal for the health of many stream systems (Trimble, 1997).

Streambank erosion is a well-documented contributor to stream sediment loading, accounting for 30–80% of fluvial suspended sediment (Lawler et al., 1999; Simon and Rinaldi, 2006; Fox et al., 2007; Evans et al., 2006; Mukundan et al., 2013; Langendoen et al., 2012; Stryker et al., 2017). Bank erosion is directly related to stream power, which increases with discharge, and is inversely related to bank resistance, a product of the nature of bank vegetation, material strength, and other variables (Micheli et al., 2004; Larsen et al., 2007; Günderalp and Rhoads, 2009). Further, streambank erosion is strongly impacted by the presence or absence of riparian areas, where, as riparian zones decrease, streambank erosion increases (Brierly and Murn, 1997; McKergow et al., 2003; Micheli et al., 2004; Purvis and Fox, 2016; Zaimes, 2006; Zaimes and Schultz, 2015). Moreover, intensifying rural/agricultural and urban land use have caused historic increases in runoff rates and peak flow events (Biedenharn et al., 1997).

While stream systems naturally change and alter themselves in response to environmental pressures, manmade manipulation of stream systems has increased since the 1990’s due to concerns for human safety and species threat and extinction (Gleick, 2003). However, these manmade manipulations have been observed to increase streambank degradation resulting in billions of dollars spent on streambank stabilization in the USA alone (Lavendel, 2002; Bernhardt et al., 2005).

Streambank stabilization practices are effective in preventing erosion at the site of implementation (Elhakeem et al., 2017; Dave and Mittelstet, 2017; Dave et al., 2020; Rosgen, 2001; Watson et al., 1997). Thus, streambank-stabilizing jetties, tree revetments, root wads, rock vanes, and gravel banks have proliferated in an effort to reduce the impact of streambank erosion (Elmore and Beschta, 1987). Recently, an evaluation of wooden jetty installation was reported as the most cost-effective erosion control measure applied in a Midwestern stream, reducing streambank erosion by 70% (Dave and Mittelstet, 2017). However, identifying which of these stabilization practices are most effective and cost efficient remain limited and are important for enhancing the benefits of ecological design in highly-altered river systems, specifically for stream bank erosion (Palmer et al., 2014). Specifically, bioengineering practices have been found to enhance nutrient removal and retention along with erosion control (Symmank et al., 2020).

The use of aerial imagery has long been accepted as a basis for assessing streambank erosion and deposition (Brizga and Finlayson, 1990; Brooks and Brierly, 1997; Green et al., 1999; Wolman, 1959). Geographic information systems (GIS) provide a mechanism for comparing imagery over time (Johnston and Bonde, 1989; Fortin et al., 2000), but their efficacy is ultimately determined by issues of accuracy, precision, and spatial and temporal scope (Pai and Saraswat, 2013). Heeren et al. (2012) concluded limitations of GIS analysis stemmed from the errors incurred in georeferencing photographic images, uncertainty in locating the bank edge in such images, and the differences in river stage and the amount of visible bank at the time any given image was acquired. Shading of the banks on aerial images, which occurs because of sun angle, cloud cover, reflection, and the height of riparian vegetation, impedes visibility and also reduces accuracy. In-situ tests (i.e., repeated cross section surveys, erosion pins, terrestrial photogrammetry, terrestrial laser scanning, and photo-electronic erosion pins) provide more accurate measurements of bank retreat (Heeren et al., 2012; Plenner et al., 2016; Myers et al., 2019). While aerial image analysis is commonly conducted over timescales of decades or more, assessment of short time scales for stream characteristics (i.e., channel slope, channel width, depth, etc.) must be closely monitored (Hooke and Redmond, 1989; Hooke, 2007). Additionally, many remote sensing instruments cannot penetrate the entire water column, leaving researchers with a gap in knowledge of the channel bathymetry (Dietrich, 2017; Mandlburger et al., 2013). Even though recently developed monitoring instruments penetrate water, the depth of penetration changes with turbidity and other variables, which are difficult to control or repeat in dynamic river systems (Dietrich, 2017; Mandlburger et al., 2013).

Recently, modeling techniques have developed numerical modeling to quantify hydrodynamic changes following implementation of bioengineering measures (Hurson and Biron, 2019). However, streambank stabilization structures are typically designed to be resilient under “normal” weather conditions. As weather becomes more variable and less predictable, however, major storm events present opportunities to shape strategies for change weather patterns (Groisman et al., 2005; Li and Fang, 2016).Therefore, the specific objectives of this study were to: 1) measure streambank migration from in three reaches stabilized with wooden jetties following a major flooding event, and 2) quantify deposition around the jetties between pre-flood and post-flood. We hypothesized the jetties would promote increased deposition downstream of their installation locations due to water velocity reduction and changes in flow direction.

2. Materials and methods

2.1. Reach description

The Cedar River is located in central Nebraska on the eastern edge of the Nebraska Sand Hills (**Fig. 1**). The river originates as the groundwater fed Cedar Creek and joins the Loup River south of Fullerton, Nebraska. Cedar River is a meandering river with localized woody vegetation on the riverbanks. In the upper basin of the Cedar River, nearly 50% of the land surface is underlain by soils with fine sand textures. Other soils in the upper basin are mostly fine sandy loams and sandy loams. Soils in the middle and lower basin are primarily silt loams. An overall downstream shift in land use from pasture and riparian areas to row crops parallels the transition from the sandy soils of the upper basin towards siltier soil textures. In many stretches of the river, riparian areas are extremely narrow and grazing lands and row crops are directly adjacent the streambanks.

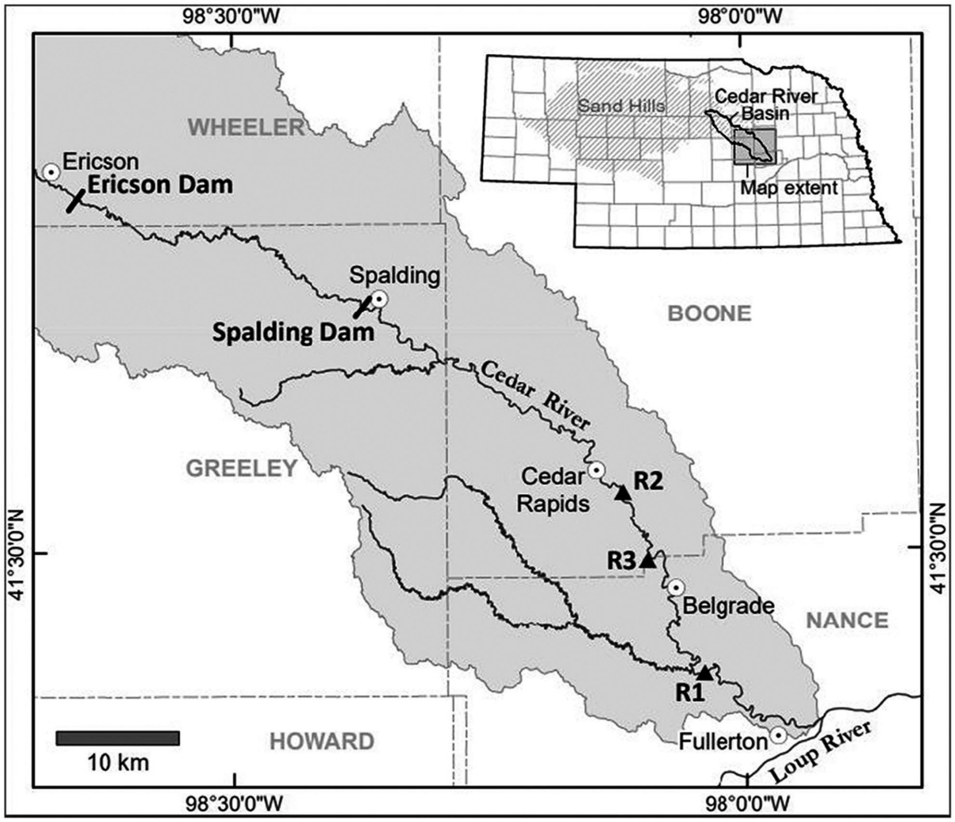

Fig. 1. Located in parts of Greeley, Wheeler, Nance, and Boone County, Cedar River runs throughout the Cedar River Basin. Two dams are located on the first half of the river (Ericson and Spalding). We evaluated stream migration and sediment quantification at three reaches (R1, 2, and 3) downstream of those dams.

The Cedar River Corridor project began in 2004 with the Loup Basin Resource Conservation and Development, in cooperation with the Nebraska Environmental Trust, in order to reduce bank degradation in on the Cedar River (Fig. 1). The project provided matching funds for the installation of rock vanes, wooden jetties, root wads, sloped gravel banks, and other bank-stabilization techniques. In June 2010, heavy rains led to a breach and spillway failure at the Ericson Dam (Fig. 1), resulting in major flooding downstream (Dave et al., 2020). Nine years later (March 2019), historic flooding in Nebraska altered the Cedar River's channel width, depth, and planform. The present study evaluates the evolution of three streambanks before and after historic flooding and pre and post stabilization.

Table 1 Each of the three reaches present unique stream characteristics including jetty length, jetty placement and location, stream width, reach length, etc.

Reach name	*Number of jetties*	*Average jetty angle*	*Average jetty length (m)*	*Average jetty (J) spacing*	*Reach length (m)*	*Radius of curvature*	*Woody vegetative cover on bank*
Reach 1	3	45.8	6.4	24.2	52.7	227.9	No
Reach 2	3	46.7	5.3	18.1	41.6	68.2	No
Reach 3	9	36.2	7.4	30.6 (J1–4) 38.4 (J5–9)	375.2	182.8	No

2.2. Installed jetty structures at reaches 1, 2, and 3

Three reaches of Cedar River were stabilized with wooden jetties (Fig. S1) in 2005 in an attempt to prevent further degradation and encroachment into landowner's property. Each of the jetties was installed using the same materials, methods, and contractor, but due to differences in each reach, jetty length, angle, spacing, and number installed varied from site to site (**Table 1**). Unlike the first two study reaches, reach 3 had a large section of exposed bank between jetties 4 and 5, which was not used in our calculation of jetty spacing. The average spacing of the first four jetties had an average spacing of 30.6 m and jetties 5–9 had an average spacing of 38.5 m. These values are more comparable to the spacing measurements calculated for reach 1 and 2. According to the contractor, the methodology for installing the jetties was not a set spacing distance. Jetty placement was determined by visual inspection with the upstream jetty being placed at the location of first bank failure and the downstream end being positioned where maximum flow velocity coincided with the cut bank. The following jetties were then installed where the deflected flow next contacted the riverbank downstream of the previous jetty.

2.3. Streambank migration

ArcMap 10.5.1 (ESRI) was used to analyze historical National Agricultural Imagery Program (NAIP) images to measure the streambank migration of three stabilized reaches on Cedar River. The streambank retreat was measured using NAIP images from 1993 to 2005 (pre-stabilization) and 2005 to 2018 (post-stabilization). An edge of bank line was drawn for each year, for each reach, to distinguish the bank edge in comparison to other years. Differences in the location of the bank edges provide information on whether the bank had eroded or experienced deposition over the observed time period. Further, elevation data were collected along with the average bank height along each reach to determine a volume of erosion.

Aerial stereophotographs clearly depict stream migration over time; however, the water level prevents the assessment of the streambed below the water surface. Therefore, to bridge this gap, the collection of high-density, in-situ data was essential in creating a methodology capable of quantifying accumulated sediment below the water level.

2.4. Data collection

Two survey instruments were used to conduct sediment accumulation surveys in 2018 and deposition surveys 2019. Using a survey-grade GPS with real time kinematics (RTK), we conducted multiple cross-sectional surveys including the upstream, downstream, and middle section of each stabilized reach (Fig. S2). We then measured water depth around the jetties using the RiverSurveyor S5 and surveyed in a grid pattern along the critical bank, extending into the middle of the river. This pattern permitted rapid, high coverage surveys. RiverSurveyor S5 allows measurements to be taken in areas that were too deep or out of reach of the GPS and it has the additional benefit of a high rate of sampling (~0.75 data points per second). The horizontal resolution of the data collected using both the GPS and RiverSurveyor S5 ranged from 1.5 to 3.0 m for the three reaches for 2018 and 2019. No data was collected for reach 2 in 2019 due to equipment malfunction. Lower resolution (3.0 m) was seen where the water was too shallow for the River Surveyor (20 cm). For those areas, GPS was used to complete the remaining profile.

2.5. Data analysis

We measured the error associated with both the Kriging method and Inverse Distance Weighting (IDW) to determine what method would provide the most accurate representation of the streambed. The Root Mean Square Errors (RMSE) for Kriging and IDW were comparable, ranging from 0.10 to 0.13, and the Kriging method was chosen for further analysis.

The collected data points were then added to ArcMap aerial images (U.S. Geological Survey a–h, 1983), and interpolated using the Kriging interpolation method (Fig. S3 – A). To isolate the critical bank in the analysis, a buffer stemming from the critical bank was created in order to isolate the critical bank in the analysis (Fig. S3-B). The width of the buffer was approximately half of the width of the river for each reach. This width was selected to encompass any depositional effects of the stabilized structures, and to exclude any deposition effects from sandbars/point bars or effects due to the opposite bank. The interpolated map was then masked to fit the buffer area.

To establish comparable reach zones, we placed a perimeter (Fig. S3- C) over the surveyed area and equidistant lines were drawn in the area to partition the buffer zone. The separation of the area into zones allowed for sediment accumulation within the reach to be assessed using the zonal statistics tool. Each of these zones was assigned an average elevation based on each elevation found in the buffered, interpolated zone.

Finally, we calculated sediment accumulation in each zone using a baseline elevation. The baseline elevation is defined here as the lowest average zonal value at each reach. This value is used as a reference value to compute sediment accumulation and make comparisons between zones at the reach. The equation to calculate the sediment accumulation in each zone is as follows:

$$ASA = AZE - BAE \tag{1}$$

where *ASA* is the average sediment accumulation in m of sediment in the zone, *AZE* is the average zonal elevation in m and *BAE* is the baseline average elevation in m. This value was then used to calculate a total volume of sediment in each zone (Fig. S4) using Eq. (2):

$$SVZ = ASA * ZA \tag{2}$$

where *SVZ* is the volume of sediment in each zone in m^3 and *ZA* is the zone area in m^2.

Prior to the Ericson Dam breach in June 2010, the greatest peak flow recorded at Cedar River was 63.4 $m^3 s^{-1}$ in 1944 (U.S. Geological Survey, 2010). The June 2010 breach, in comparison, generated a peak discharge of 148.6 $m^3 s^{-1}$, with an average annual discharge at the Spalding gage ranging from 5.6 $m^3 s^{-1}$ to 8.4 $m^3 s^{-1}$ (Dave and Mittelstet 2020; U.S. Geological Survey, 2010). The focus of this study was initially to evaluate the impact of the 2010 peak flow event. However, in 2019 another historic peak flow event in the area registered at 209.8 $m^3 s^{-1}$ on March 15th (Nebraska Department of Natural Resources, 2020). Both events provided an opportunity to conduct GPS and RiverSurveyor surveys following historic peak flows recorded on the river. Following the 2018 survey analysis, we completed GPS cross sectional surveys in 2019, capturing bank changes from the top of the bank to the edge of the water. Surveys using the RiverSurveyor were again completed, with an effort to recreate a survey grid similar to the surveys taken in the summer of 2018.

3. Results and discussion

3.1. Streambank migration and deposition

Analysis of NAIP imagery for erosion and deposition at the three study reaches comprises: 1) Image analysis of 1993 to 2006 (pre-stabilization), and 2) Image analysis of 2006 to 2018 (post-stabilization). From these two time periods, we observed more erosion in each study reach during pre-stabilization years relative to post-stabilization years, shown clearly by the downstream end of the 1993 bank line to the 2006 and 2018 lines in reaches 1 and 2 (**Fig. 2**A, B) (**Table 2**). In reach 3, considerable deposition accumulated by 2018 in front of the last jetty in the reach. This deposition was disconnected from the bank due to a channel that had formed, creating an island in the stream that was substantial enough to sustain vegetation, which was a clear indicator that sediment had been deposited consistently in this area since the introduction of the jetties in the reach, and the formation of this island may be the reason that reach 3 did not exhibit the same erosional trend that the other two reaches showed. The precise reason for the island's formation in this area is not known. Reaches 2 and 3 even had an increase in total bank area, while reach 1 had nearly zero change in bank area over the entire post-stabilization time period.

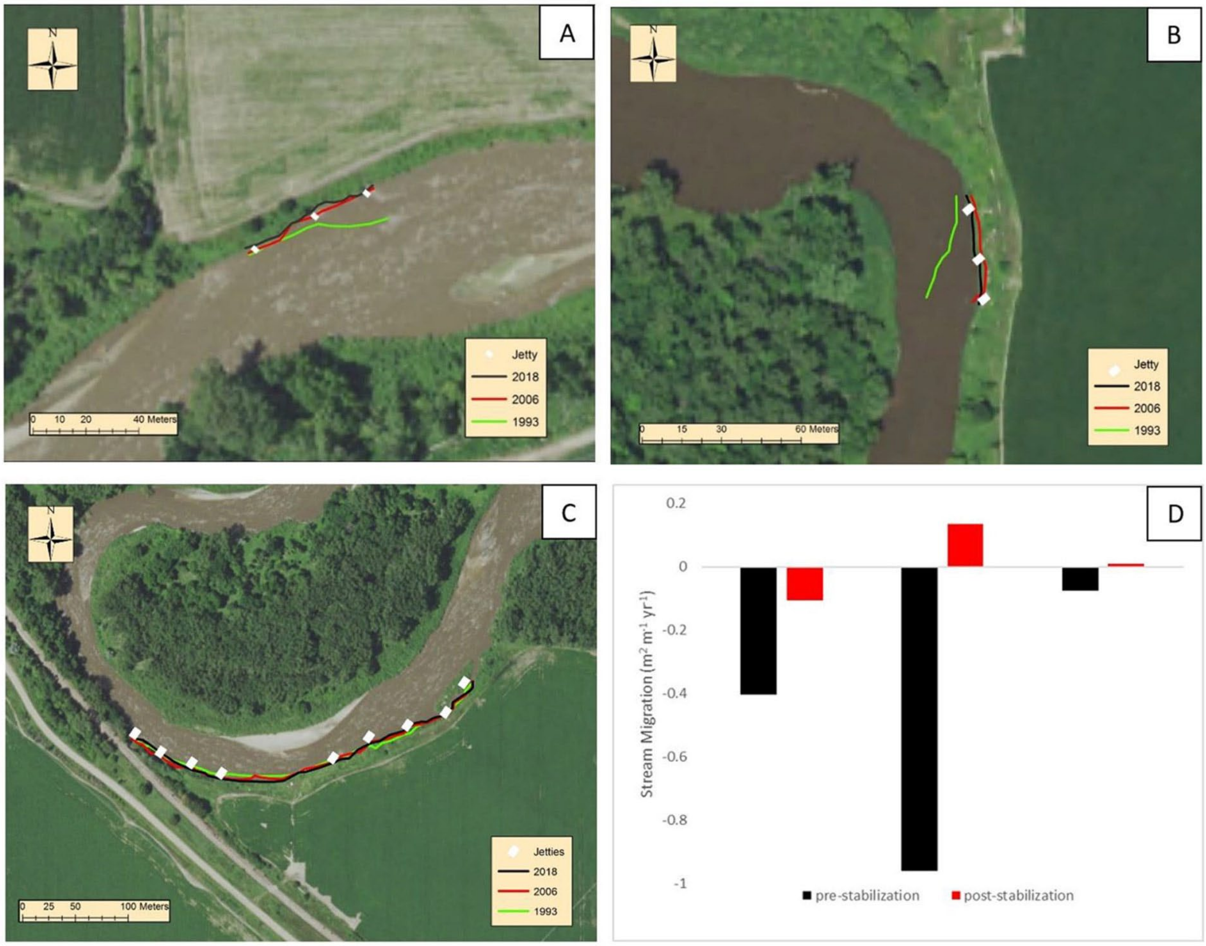

Fig. 2. Bank lines were drawn for Reaches 1–3 (A-C) study reaches. 1993, 2006, and 2018 lines were drawn using different colored lines. Flow direction is denoted by white arrows. Also pictured (D), average migration values for pre- and post-stabilization time periods. Photographs from 2018 were used for each reach.

Woody vegetative cover and the stream's radius of curvature have a large influence on stream migration (Beeson and Doyle, 1996; Micheli and Kirchner, 2002; Rutherfurd and Grove, 2004; Simon and Collison, 2002). Using the values presented in 2, none of the study reaches had substantial woody vegetative cover on the stabilized bank. Though reach 1 had the highest radius of curvature out of the studied reaches, it also had more erosion than reaches 2 and 3. Dave et al. (2020) reported similar observations, where no correlation was seen between radius of curvature and streambank erosion for 38 meanders on Cedar River. This analysis of streambank loss/gain using NAIP not only exhibited the

Table 2 Erosion and deposition values were calculated for pre- and post-stabilization periods. Total area and volumetric calculations were calculated and then normalized into yearly values.

Pre-stabilization			*Post-stabilization*		
Reach	*Erosion (m^2)*	*Deposition (m^2)*	*Reach*	*Erosion (m^2)*	*Deposition (m^2)*
1	278	0	1	68	0
2	520	0	2	67	0
3	362	0	3	44	0
Reach	*Erosion ($m^2\ y^{-1}$)*	*Deposition ($m^2\ y^{-1}$)*	*Reach*	*Erosion ($m^2\ y^{-1}$)*	*Deposition ($m^2\ y^{-1}$)*
1	0.41	0	1	0.1	0
2	0.96	0	2	0	0.13
3	0.07	0	3	0	0.01
Reach	*Erosion (m^3)*	*Deposition (m^3)*	*Reach*	*Erosion (m^3)*	*Deposition (m^3)*
1	637	0	1	155	0
2	2309	0	2	0	297
3	1107	0	3	0	135
Reach	*Erosion ($m^3\ y^{-1}$)*	*Deposition ($m^3\ y^{-1}$)*	*Reach*	*Erosion ($m^3\ y^{-1}$)*	*Deposition ($m^3\ y^{-1}$)*
1	0.9	0	1	0.25	0
2	4.3	0	2	0	0.6
3	0.2	0	3	0	0.03

effectiveness of the jetties over a longer time period but reinforces the need for further research in stabilization structure placement, stabilization structure angle, and sizing of installed structures.

3.2. 1950s jetties

Jetties were installed locally along the Cedar River as early as 1950. Although these jetties were not built or installed the same way as the jetties installed for the Cedar River project, they did serve the same purpose: to deflect and dissipate flow and prevent further riverbank erosion. Today, these two jetties are still functioning, having survived numerous high flow events, and continue to protect the riverbank. To further assess these success of these two jetties, we evaluated aerial stereophotographs from 1951, 1969, 1993, and 2018. A substantial amount of deposition accumulated at the upstream section of the two jetties since their installation (**Fig. 3**), helping to reinforce the trends observed at reaches 1–3. This observation supports that, in the event the jetties at Cedar River survive the peak flows and winter conditions, they will continue to be effective at reducing bank erosion and aiding in deposition.

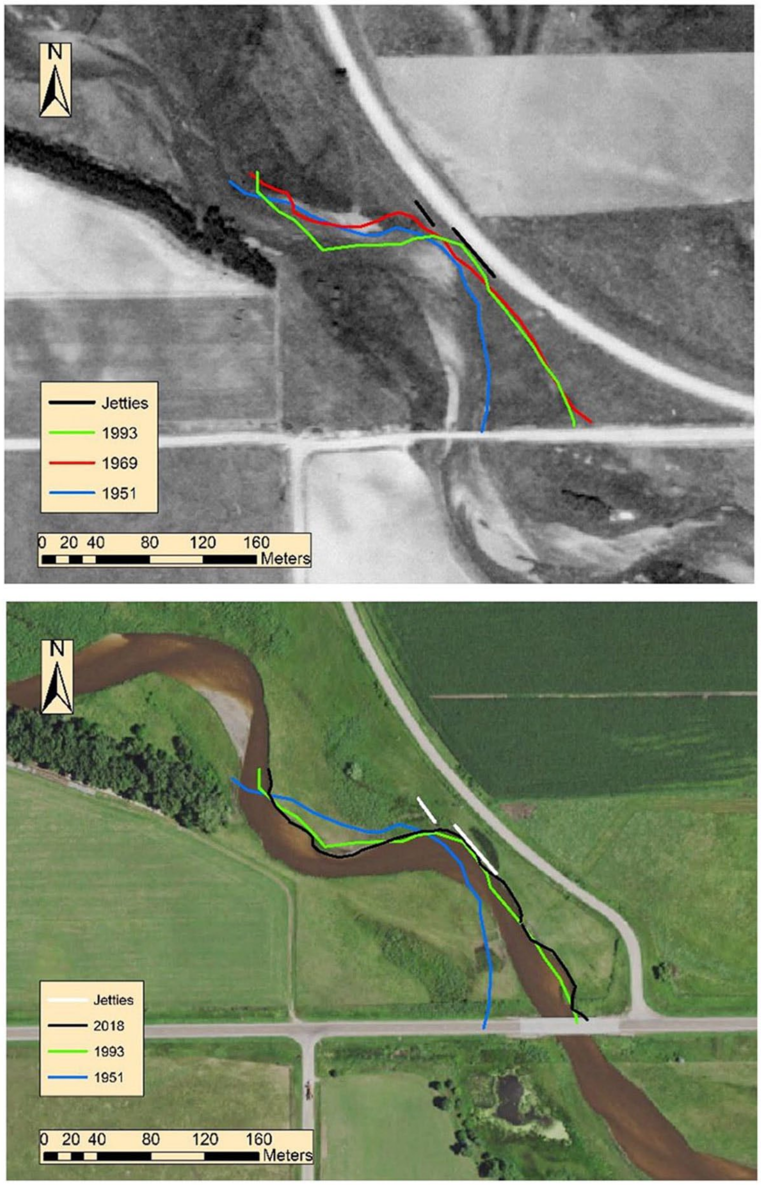

Fig. 3. Two jetties were installed in 1950 to protect a county road and bridge from being encroached on by the river. The structures remain today and have protected the bank from erosion and helped add substantial deposition at and upstream of the stabilized area. Photographs from 1951 (left) and 2018 (right) were used for the reach.

3.3. Quantification of accumulated sediment

Measurements of sediment deposition from aerial stereophotographs are limited to that which is visible above the flow stage on the dates of image capture. Surveying, in contrast, permits us to calculate the streambed below the water, but also to quantify a volume of accumulated sediment. Based on our RiverSurveyor S5 and GPS survey data, estimated volume of accumulated sediment at each of our three study reaches was determined. Sediment volume at reach 1 totaled 434.5 m^3, reach 2 was 264.7 m^3, and reach 3 was 1755.2 m^3. Each reach was normalized for the variability in reach length and an average value of sediment volume per meter of the reach was calculated. The 2018 zonal average for reach 1 was 0.37 $m^3\,m^{-1}$, 0.46 $m^3\,m^{-1}$ at reach 2, and 0.16 $m^3\,m^{-1}$ at reach 3. **Fig. 4** shows the variation from zone to zone at each reach. The maximum value at any of the three reaches in 2018 was 1.4 $m^3\,m^{-1}$ and the minimum value was 0.0 $m^3\,m^{-1}$. Because the prestabilization bed elevation was unknown for each reach, the lowest average elevation was used as a baseline (zero value) to quantify sediment accumulation in the

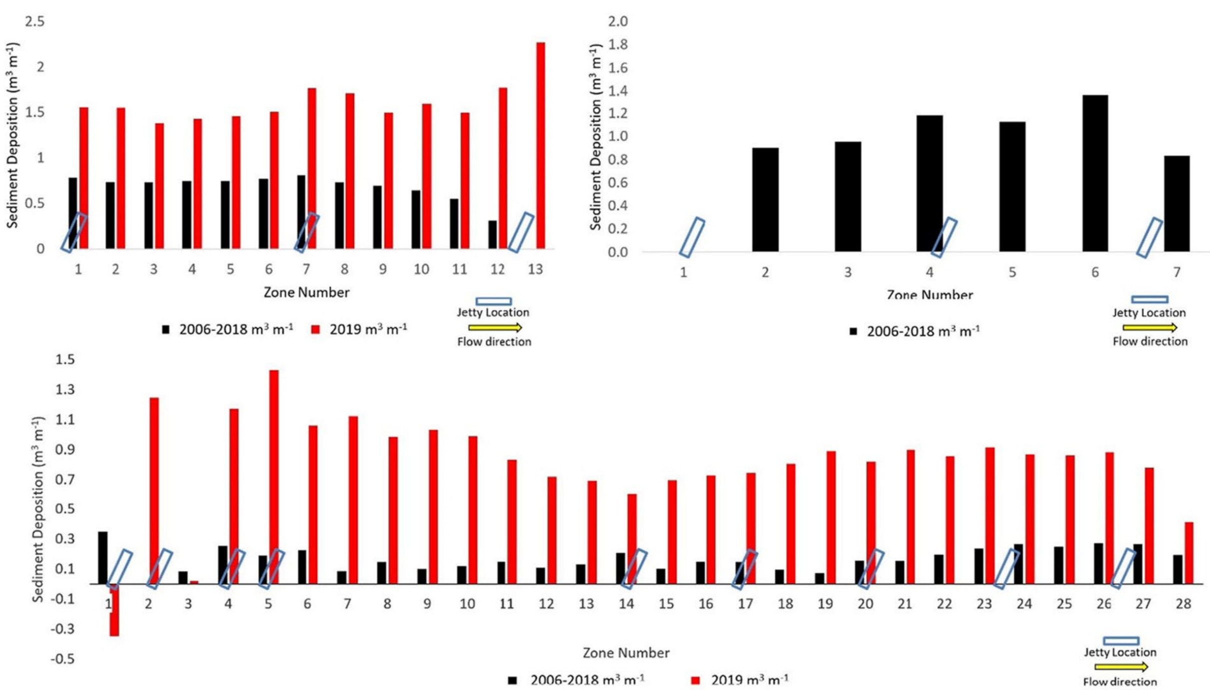

Fig. 4. Quantification of sediment accumulation /deposition for each reach: 1 (A), 2 (B), and 3 (C). Black bars are sediment accumulation totals from 2006 to 2018, red bars are deposition from 2018 to 2019, and blue bars are jetty locations at each reach.

remainder of the reach. When we set this value, it was observed that the lowest point in two of the reaches (2 and 3) was at or near the first zone in the study area. Although jetties are installed to dissipate flow and allow for residence times long enough for sediment to deposit, they also create an eddy effect that occurs at the endpoint of the jetty where the deflected water re-enters the current, causing swirling and bed scouring at the tip of the jetty and in areas behind the jetty. This effect may have resulted in the observed low average elevations seen in these two reaches. Reach 3 exhibited substantial differences compared to reaches 1 and 2. Reach 3 was larger compared to the first two reaches and had a large stretch of reach not protected by jetties (the stretch of bank in between jetties 4 and 5). Due to this difference, we decided to split the reach into two sections: zones 1–13 and zones 14–28. When split, zones 1–13 showed similarities in sediment accumulation characteristics to reach 1, and zones 14–28 displayed similar sediment accumulation characteristics to reach 2. These similarities highlight the need for further study on the impact to stream ecosystems and their morphology following the introduction of stabilized structures.

3.4. Function of jetties during historic 2019 floods

Historic flooding across the Midwest during the spring of 2019 presented a unique opportunity to conduct a year to year comparison of the sediment accumulation at Cedar River using our newly created survey and quantification method. Using surveys in 2018 and 2019, we quantified sediment accumulation per year from 2006 to 2018, and sediment deposition and erosion from 2018 to 2019 (Fig. 4). During the summer of 2019, surveys of the same three study reaches were conducted, and the data was evaluated using the same method as the previous year. However, due to equipment malfunction, 2019 data was not available for reach 2.

A substantial volume of sediment was eroded, transported, and deposited by the March 2019 flood on the Cedar River. In 2018, reach 1 had an average accumulation of 0.03 $m^3\,m^{-1}\,yr^{-1}$. In 2019, that number increased to 1.61 $m^3\,m^{-1}\,yr^{-1}$, a 335% increase from the total accumulation seen from 2006 to 2018. At reach 3, the overall amount of sediment accumulation in the studied area was lower, but the increase in accumulation from year to year was similar to reach 1. In 2018, reach

3 had an average accumulation of or 0.01 $m^3 m^{-1} yr^{-1}$ within the study area. In 2019, that number increased to 0.81 $m^3 m^{-1} yr^{-1}$, a 406% increase. This dataset is just a small snapshot of the dynamic process occurring each day within this specific river system. The survey was completed seven months following the 2019 flood, exhibiting a substantial increase in deposition had a lasting impact by the jetties in the reach. In Dave and Mittelstet (2017), the effectiveness of stabilization techniques were measured against the cost for their installation, where wooden jetty structures proved to be the most cost-effective option when compared to the rest of the methods. The findings in our study continue to reinforce those findings by showing the introduction of jetties not only reduced erosion, but in some cases had substantial deposition in the reach.

4. Conclusion

Methods developed in this project act as a foundation for ecological engineering practitioners as a novel method for assessing and quantifying sediment accumulation and loss in stream channels. Cedar River, like many other streams and rivers in the Midwest, is experiencing increasing rates of flooding and erosion, leading to losses of property and arable land. Historically, the solution for increased flooding in the region was to channelize the river, directing high flows away from the banks. This short-term solution not only impacts the river locally, but also has the potential to impact the geomorphology of upstream and downstream river sections. However, we determined the introduction of jetties into Cedar River resulted in substantially less erosion during poststabilization than in any of the years prior to stabilization. Additionally, streambank migration slowed, and in some regions even ceased, resulting in sediment accumulation in the stabilized areas. Further, we presented a novel method to utilized survey data and aerial stereophotographs to assess streambank stabilization following implementation of jetties, which were observed to have the potential for both short and long-term impact on reducing erosion. Observed increases of 335% and 406% sediment volumes reiterate peak flows result in substantial mobility of bank and bed material, and during periods of dissipated flows due to installed bioengineering structures (wooden jetties), substantial sediment deposition was measured in the stabilized reach. While our findings provide a unique and cost-effective method to monitoring and assessing the implementation of bioengineered practices for reducing streambank erosion, additional research is still needed. Future work should include: 1) surveys conducted in 3–5+ years at each of the three study reaches to further assess changes in deposition location and quantities and 2) Continued assessment of implementation and resiliency of bioengineering designs for stream migration of bioengineered streams and rivers across the U.S..

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Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data Supplementary data for this article — Figures S1 to S4 — follows the **References**.

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Figure S1. An example of a wooden jetty used on Cedar River as part of the 2005 Cedar River Stabilization Project.

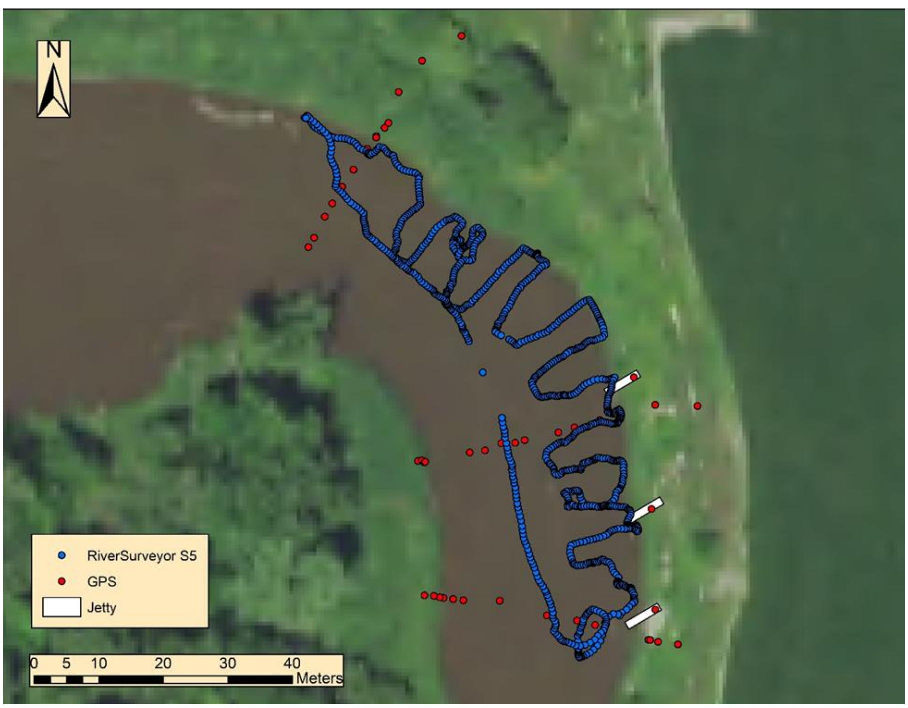

Figure S2. Two different surveying methods were used in this study: GPS cross sections (Red) and RiverSurveyor S5 (Blue). White arrows depict flow direction.

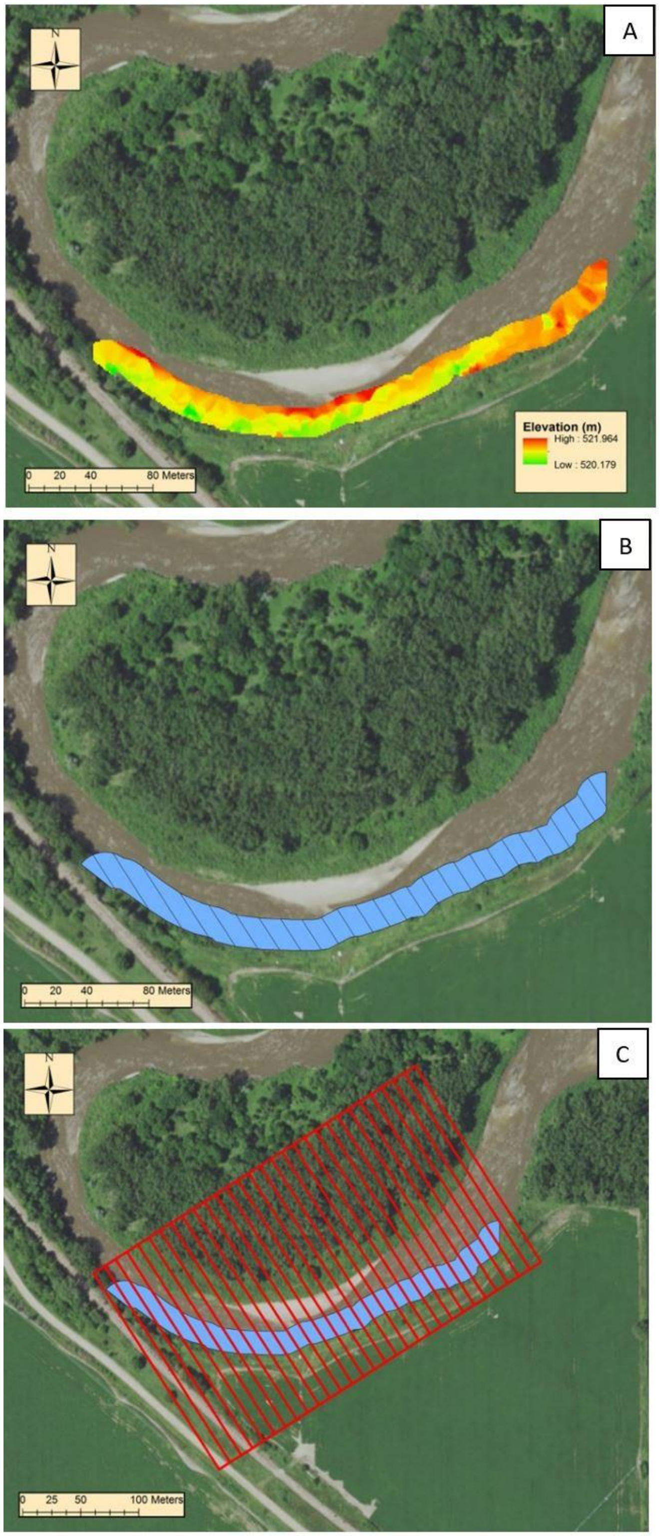

Figure S3. An interpolation using the Kriging method (A), a buffer (B), and equidistant gridlines (C) were some of the tools used during analysis.

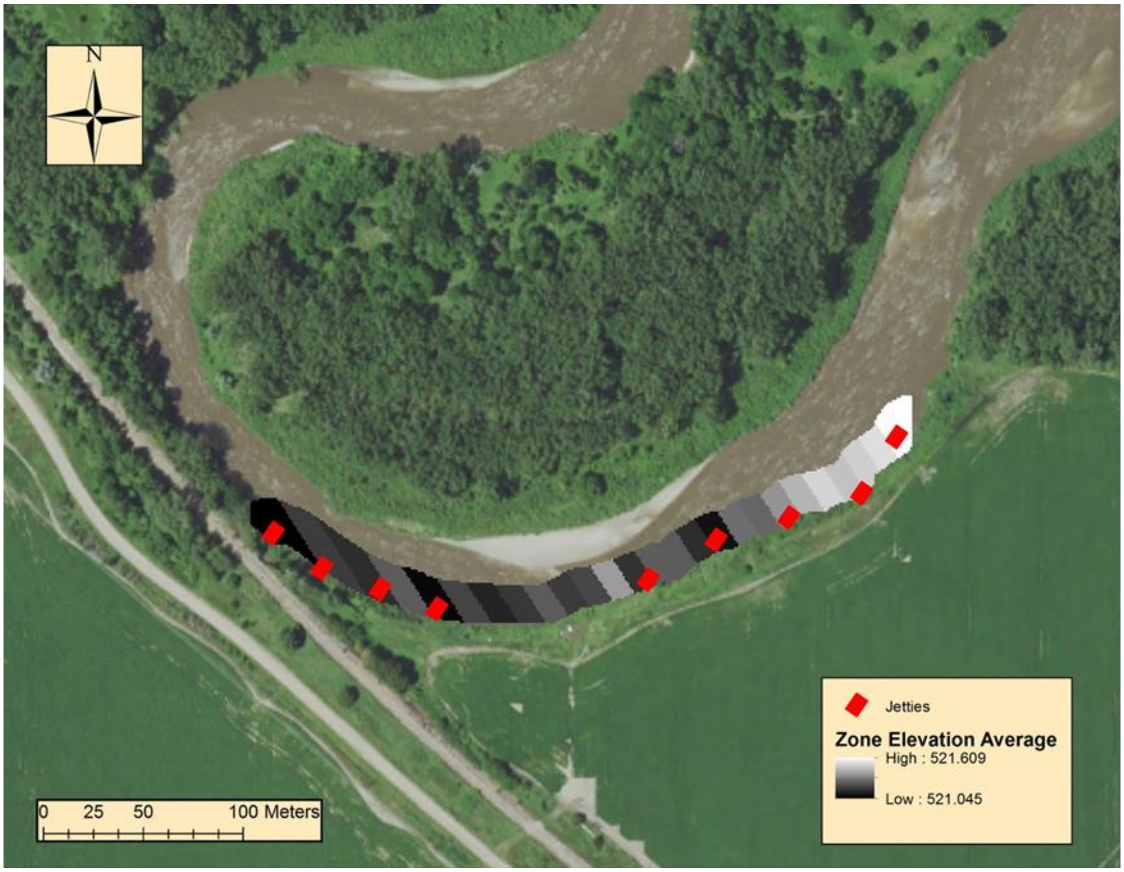

Figure S4. Reach 3 – Zonal analysis of each reach was completed in ArcMap 10.5.1. Each reach was divided into equidistant zones and the average elevation in each zone was used to quantify sediment accumulation at the reach.