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Impact of Streambank Stabilization on Sediment Deposition and Erosion in Central Nebraska Streams

Matthew Russell
University of Nebraska - Lincoln, matthewrussell0314@gmail.com

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IMPACT OF STREAMBANK STABILIZATION ON SEDIMENT DEPOSITION AND EROSION IN CENTRAL NEBRASKA STREAMS

by

Matthew Vincent Russell

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IMPACT OF STREAMBANK STABILIZATION ON SEDIMENT DEPOSITION AND EROSION IN CENTRAL NEBRASKA STREAMS

Matthew Vincent Russell, M.S.

University of Nebraska, 2020

Advisor: Aaron R. Mittelstet

Stabilization projects are increasingly used to mitigate the effects of anthropogenic streambank erosion, yet the effectiveness of these practices has been insufficiently monitored and assessed to date. Sound monitoring practices promote engineered effectiveness, in addition to allowing adjustments in implementation and maintenance to improve practices over time. However, current methods to quickly and efficiently quantify deposition and erosion within a stream continue to be costly and inefficient. Therefore, the objectives of this project were to 1) Measure streambank migration of three reaches at Cedar River in Nebraska, from 1993 to 2006 (pre-stabilization) and from 2006 to 2018 (post-stabilization) using aerial imagery and 2) Quantify sediment deposition around jetties from 2006 to 2018 and in 2019 following a large flood using survey equipment. Results from objective 1 showed that erosion rates decreased significantly where stabilization practices were installed, and in some instances, increased deposition in the reach. Results from objective 2 reinforce findings from objective 1, showing increases of up to 406% in sediment deposition from 2018 to 2019. The surveys were completed seven months following the 2019 flood,

demonstrating that the significant increase in deposition was a long-term impact, influenced by the jetties in the reach.

To expand on our findings, we broadened our scope and assessed the impacts of stabilization structures on upstream and downstream sections of the river. To do this, we: 1) Measured the amount of riverbank loss/gain 1.5 wavelengths upstream and downstream of each stabilized reach and on the opposite bank from 1993 to 2006 (pre-bank stabilization), and 2006 to 2018 (post-bank stabilization) on Cedar River, in North-Central Nebraska using ArcGIS and historical aerial imagery. Unexpectedly, the differences in erosion from pre- to post-stabilization showed little to no statistical significance and deposition was significantly greater pre-stabilization in some reaches, supporting bank stabilization at Cedar River may be effective at the location of installation, but have little to no impact on decreasing erosion rates upstream or downstream.

The methodology proposed in this project to quantifying sediment deposition in the stream system, along with the stream migration information collected for adjacent segments of the stream, serve to reinforce the need for additional investigations to be completed to improve streambank stabilization projects, as well as the importance of subsequent stream monitoring programs.

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CHAPTER 1: QUANTIFICATION OF EROSION AND DEPOSITION NEAR STREAMBANK STABILIZATION STRUCTURES

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

[2]School of Natural Resources, East Campus, University of Nebraska-Lincoln, 101 Hardin Hall, Lincoln, NE 68583-0961, USA

Abstract

Stabilization projects are increasingly used to mitigate the effects of anthropogenic streambank erosion, yet the effectiveness of these practices has been insufficiently monitored and assessed to date. Sound monitoring practices promote not only engineered effectiveness, but further allow for adjustments in implementation and maintenance to improve the practices over time. Therefore, the objectives of this study were to: 1.) Measure streambank migration of three reaches at Cedar River in Nebraska, from 1993 to 2006 (pre-stabilization) and from 2006 to 2018 (post-stabilization) using aerial imagery and 2.) Quantify sediment deposition around jetties from 2006 to 2018 and in 2019 following a large flood using survey equipment. Based on the aerial imagery, erosion rates at Reaches 1, 2 and 3 were 0.41, 0.96 and 0.07 m^2 m^{-1} yr^{-1} from 1993 to 2006, respectively. After the streambanks were stabilized, Reach 1 had 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. In 2019, deposition was measured with a River Surveyor and Global Positioning System (GPS). Deposition was significantly greater following the 2019 flood with 1.61 and 0.81 m^2 m^{-1}. We propose a new methodology for quantifying sediment deposition in the stream system. Using this method for the Cedar River, we determined that jetties were effective at decreasing streambank migration and sediment deposition at the point of implementation. Understanding sediment dynamics near jetties provides crucial assistance for stream restoration designs, as well as informed decision making for future stabilization practices in similar streams and rivers.

Keywords: Erosion, sediment deposition, jetty, geomorphology, aquatic ecosystems

Introduction

Streambank erosion is a natural, dynamic process that plays a major role in the geomorphic evolution of streams and floodplains as well as the creation and maintenance of riparian habitat for organisms (Florsheim et al, 2008). Sediment erosion and deposition are undeniably essential attributes of healthy streams, but the acceleration of these processes, especially as sediment moves downstream, 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 worldwide (Mukundan et al. 2011, Lawler et al. 1999; Simon and Rinaldi 2006; Langendoen et al., 2012; Fox et al., 2007; Evans et al., 2006).

Streambank Erosion and Deposition

Three primary processes are key contributors to streambank erosion: 1) subaerial weathering, 2) fluvial erosion, and 3) mass wasting (Couper and Maddock, 2001; Hooke, 1979; Thorne 1972). Subaerial weathering is an in-situ process that is dependent upon the weather and climatic conditions in the area of interest (Thorne, 1982). One of the important processes regarding subaerial weathering is freeze-thaw, which occurs when soil temperatures fluctuate above and below freezing. This process slowly weakens the strength of the bank and acts as a preparatory process that increases the effectiveness of fluvial erosion and mass wasting (Couper and Maddock, 2011; Wolman, 1959). Fluvial erosion occurs when pushing and pulling forces repeatedly occur at the toe of the bank (Hooke, 1979, Knighton, 1973; Wolman, 1959). These forces increase with stream flow, thus increasing fluvial erosion. Mass wasting occurs when gravitational forces overcome the strength of bank material, which is conferred by cohesion, cementation, root systems and other variables (soil binding forces, vegetation/root systems, etc.) (Cancienne et al, 2008; Midgley et al., 2012). In addition to the three aforementioned processes, streambank erosion is impacted by adjacent land-use practices. Intensifying agricultural and urban land use have caused runoff rates and peak flow events within river systems to rise to historic rates (Biedenharn et al., 1997).

Several direct and indirect methods have been used to quantify streambank erosion. Although these methods are constantly being refined and improved, they are typically time-intensive and tend to be site-specific (Hamshaw et al. 2017). Lawler (1993) categorized methods for investigating streambank erosion into three categories: 1) *long term*: sedimentological evidence, botanical evidence, and historical sources; 2) *intermediate term*: planimetric resurvey and repeated cross profiling; and 3) *short term*: terrestrial photogrammetry, erosion pins, and the photo-electronic erosion pin (PEEP) system. The erosion pin method remains in widespread application because of its simplicity, low cost, and sensitivity (Laubel et al., 1999). Simultaneously, methods that quickly measure bank stability measurements using bank characteristics (height, angle, materials, vegetation surveying, and bank protection) have been employed to rapidly assess long stretches of streambanks (Rosgen 2001). These rapid geomorphic assessments (RGAs) continue to be adapted to fit individual studies (Heeren et al., 2012). Using information gathered from these assessments, or using assumed bank characteristics, allows for the creation of streambank erosion models. One of the most commonly used models is the bank stability and toe erosion model (BSTEM) (Simon et al., 2000). BSTEM, amongst its many applications, is primarily used to predict bank erosion due to fluvial erosion and mass wasting (Midgley et al. 2012). Although quantifying the characteristics and rates of streambank erosion has been studied extensively for decades, newly created methods now emphasize the quantification of sediment deposition (Wilson et al. 2008).

Aerial Imagery in Assessing Stream Migration

The usefulness of aerial imagery in quantifying and surveying streambank erosion and deposition is widely accepted (Green et al., 1999; Wolman, 1959; Brizga and Finlayson, 1990; Brooks and Brierly, 1997). Advancements of geographic information systems (GIS) have provided a better basis for assessing the lateral migration of streambanks (Johnston and Bonde, 1989; Fortin et al., 2000), but they are constrained by their accuracy, repeatability, and spatial and temporal scope (Pai et al., 2012). Heeren et al. (2012) concluded that the limitation for this type of analysis was due to the error related to geo-referencing, uncertainty in locating the bank edge, and precipitation events altering the river stage and the amount of visible bank on the image. Shading on aerial images can be caused by different factors (cloud cover, vegetation cover, reflections, etc.), but each impedes visibility and reduces accuracy. *In situ* tests (e.g., repeated cross section surveys, erosion pins, terrestrial photogrammetry, and photo-electronic erosion pins) were determined to be more accurate when measuring the actual bank retreat (Heeren et al., 2012). Aerial image analysis is commonly conducted over timescales of decades or more, but when assessing short time scales, certain stream characteristics must be closely monitored (Hooke and Redmond, 1989; Hooke, 2007). Additionally, many remote sensing instruments are not capable of penetrating the entire water column, leaving researchers with a gap in knowledge of the channel bathymetry (Mandlburger et al. 2013). Some instruments can penetrate water, but the depth of penetration changes with turbidity and other variables. Such variables are difficult to control or repeat in dynamic river systems (Mandlburger et al. 2013).

The assessment of stream migration can help identify areas where anthropogenic channel erosion is accelerating. Stream systems naturally change and alter themselves in response to their environments, but man-made manipulation of stream systems has increased since the 1990's (Bernhardt et al., 2005). This degradation has become an increasing concern in recent decades, with billions of dollars being allocated to streambank stabilization in the US alone (Lavendel, 2002; Bernhardt et al., 2005). The use of diverse streambank-stabilization structures–such as wooden jetties, tree revetments, root wads, rock vanes, and gravel banks–has steadily increased (Elmore and Bestcha, 1998).

Streambank Stabilization

The effectiveness of streambank stabilization practices in preventing erosion at the site of implementation has been well established. In one of the earliest papers to monitor streambank stabilization, Watson et al. (1997) examined over 9,000 willow posts installed in Harland Creek in east-central Mississippi. Despite the newness of this bioengineering technique and willow-post survivability rates as low as 29 to 34% in some reaches, the technique prevented further erosion better than traditional riprap stabilization methods. Dave and Mittelstet (2017) assessed the effectiveness of multiple erosion-control techniques used on the Cedar River, finding that the installation of wooden jetties had a success rate of ~70%, making it the most cost effective erosion control measures assessed. Yet, where any bank failure was unacceptable, a costlier approach such as the installation of reinforced concrete should be implemented to completely prevent erosion at the site (Dave and Mittelstet 2017). Streambank stabilization practices are typically designed to be resilient under "normal" weather conditions. However, as the definition of "normal" weather patterns shift towards more variable and unpredictable, historic storm events, unique opportunities have emerged to study the impacts and begin to shape methodologies for future studies for evolving weather patterns.

In 2004, the Cedar River Corridor project was created with the Loup Basin Resource Conservation and Development--in cooperation with the Nebraska Environmental Trust--in an attempt to reduce bank degradation in North Central Nebraska on the Cedar River. The project provided matching funds to citizens living or farming the area in order to install a variety of bank stabilization practices (i.e., rock vanes, wooden jetties, root wads, sloped gravel banks, etc.). In June, 2010, heavy rains led to a breach in the Ericson dam, located along the Cedar River in North-Central Nebraska, and days later the dam's spillway failed, resulting in major flooding downstream (Dave et al., 2020). Historic flooding throughout Nebraska and much of the Midwest, U.S. in March 2019 altered the Cedar River's geomorphology. Therefore, the presented study followed the aftermath of both floods to 1) measure streambank migration in three reaches stabilized with wooden jetties in 2005 using NAIP aerial imagery from 1993 to 2005 and from 2005 to 2018, and 2) quantify the deposition that occurred around the jetties between 2005 to 2018 (using remote sensing) and between

2018 and 2019 (using a survey-grade Global Positioning System (GPS) and a RiverSurveyor S5).

Materials and Methods

Reach Description

Cedar River is located in Central Nebraska on the eastern edge of the Nebraska Sandhills. The river originates as the groundwater fed Cedar Creek and feeds into the Loup River south of Fullerton, Nebraska. Cedar River is a meandering river with sparse woody vegetation on the riverbanks. At the northwest section of the Cedar River near Ericson, Nebraska, the dominant soil series (nearly 50%) in the surrounding landscape are the Valentine fine sand and Ipage fine sand. The remaining soil textures are primarily fine sandy loams and sandy loams. Near the middle section of the river, the primary soil series is the Hord silt loam. Soils around the southeastern section of the river transition

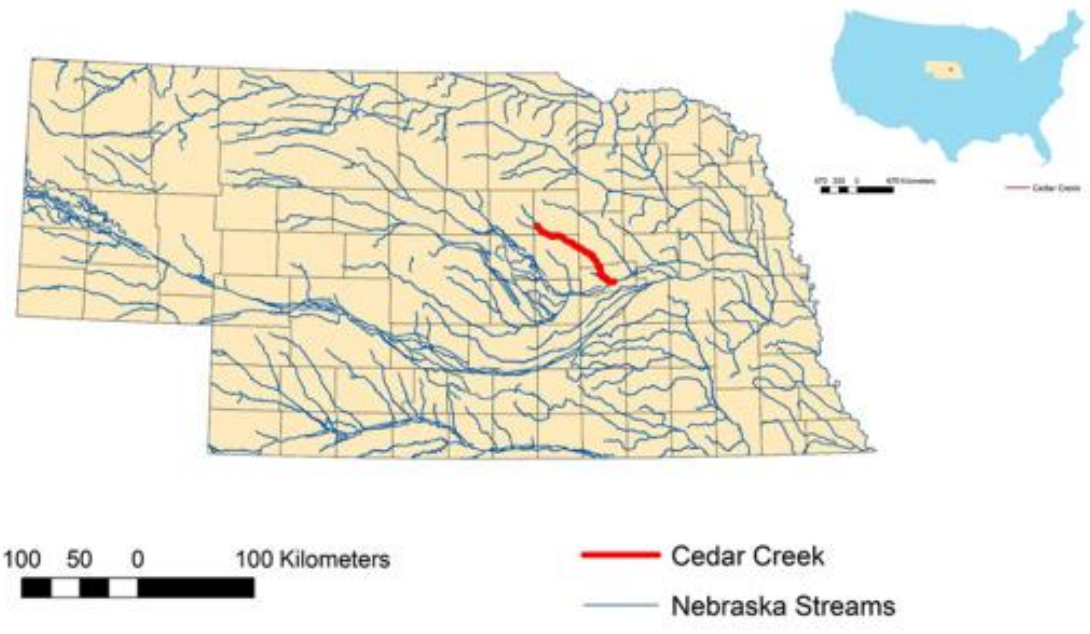


Figure 1. An overview of Nebraska and its major streams/rivers. Highlighted in red is Cedar River

toward predominantly silt and clay with dominant soils being Cass and Gibbon silt loams. Changes in land use from pasture and riparian areas to increased row-crop agricultural parallels the transition from the sandy soils of the Sandhills towards siltier soil textures. In many sections of the stream, riparian areas are extremely narrow with grazing areas and row crops being directly adjacent the streambanks.

Installed Jetty Structures at Reaches 1, 2, and 3

Three reaches of Cedar River were stabilized with wooden jetties (Figure 2) in 2005 in an attempt to prevent further degradation and encroachment into landowner's property. Each of the jetties were installed using the same materials, methods, and contractor. However, because of the disparities between the three reaches, each reach varied in the jetty length, angle, spacing, and number of jetties installed (Table 1). Unlike the first two study reaches, reach 3 had a large section of exposed bank between jetties 4

Figure 2. An image of the wooden jetty structures used on Cedar River as part of the Cedar River Stabilization Project

and 5, which was omitted from our calculation of jetty spacing, with the average spacing of the first four jetties and following five jetties being calculated separately. Jetties 1 - 4 had an average spacing of 30.6 meters, while jetties 5 - 9 had an average spacing of 38.5 meters. 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 river flow deflected off of the bank and continued downstream. The remaining jetties were installed where the flow next contacted the riverbank downstream of the previous jetty.

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

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. Disparities 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 on the bank.

Aerial imagery clearly depicted stream migration over time; however, the water level prevented 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 deposition below the water level.

Data Collection

Two survey instruments were used to conduct depositional surveys in 2018 and 2019. A survey-grade GPS with real time kinematics (RTK) were used to conduct

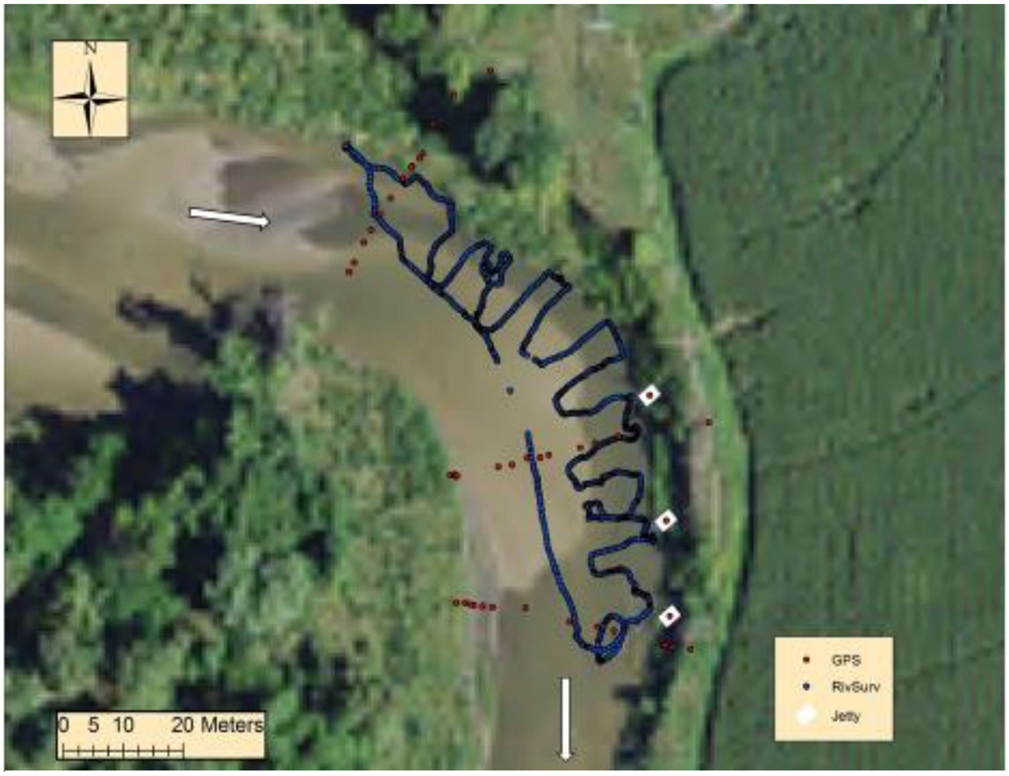


Figure 3. Two different surveying methods were used in this study: GPS cross sections (Red) and RiverSurveyor S5 (Blue). White arrows depict flow direction.

multiple cross-sectional surveys including on the upstream, downstream, and middle section of each stabilized reach and at each identified (Figure 3). Water depth was measured around the jetties using the RiverSurveyor S5. A grid pattern was carried out along the critical bank, extending into the middle of the river. This pattern allowed for representative, high coverage surveys to be conducted in a timely manner. While beneficial due to its high rate of sampling (~0.75 data points per second), the RiverSurveyor S5 allows measurements to be taken in areas that were too deep or out of reach of the GPS. The horizontal resolution 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.

Data Analysis

Each of the collected data points were added to ArcMap and interpolated using the Kriging method (Figure 4 – A). Contours using the interpolation maps were then created to further interpret the variability of deposition within the river. 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 (Figure 4 - 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.

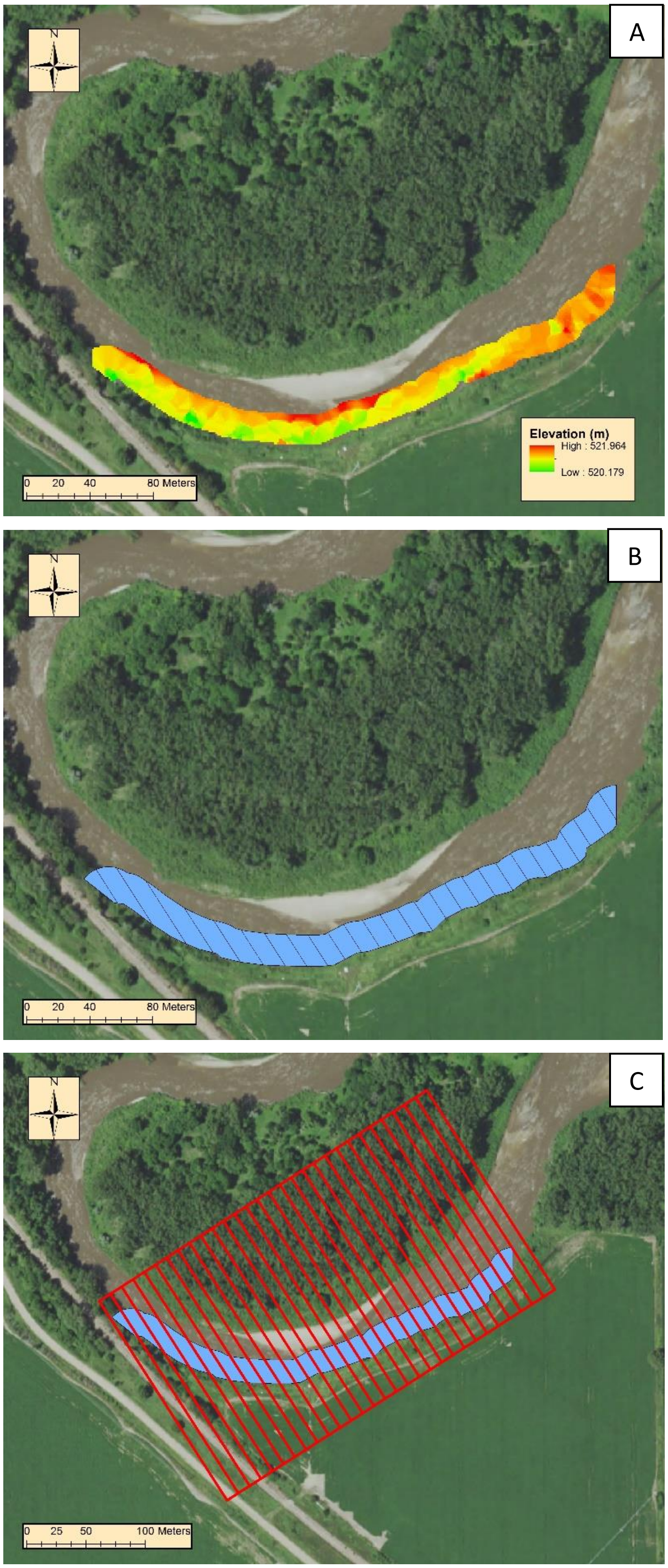


Figure 4. ArcMap 10.5.1 was used to analyze the collected data. An interpolation using the Kriging method (A), a buffer (B), and equidistant gridlines (C) were some of the tools used during analysis.

A grid (Figure 4 – C) was placed over the surveyed area to establish reach zones and equidistant lines were drawn in the grid to partition the buffer zone. The gridline breakdown into zones allowed for deposition within the reach to be assessed using the zonal statistics tool. Each zone was assigned an average elevation based on each elevation found in the buffered, interpolated zone.

Finally, sediment thickness in each zone was calculated 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 thickness and make comparisons between zones at the reach. The equation to calculate the sediment thickness in each zone is as follows:

$$ASD = AZE - BAE \qquad \text{Equation 1}$$

where ASD is the average thickness 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 (Figure 5) using Equation 2:

$$SVZ = ASD * ZA \qquad \text{Equation 2}$$

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

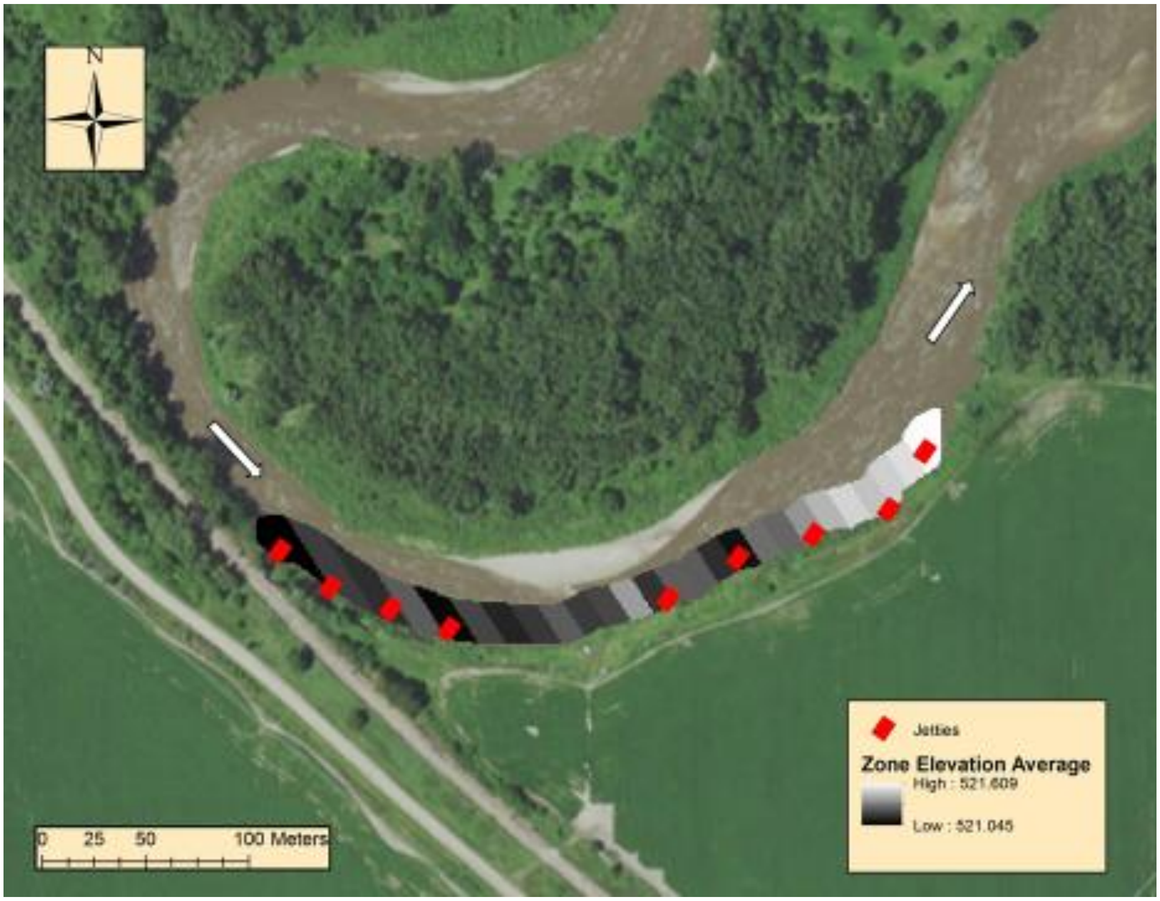


Figure 5. Reach 3 – Zonal analysis of each reach was completed in ArcMap 10.3.1. Each reach was divided into equidistant zones and the average elevation in each zone was used to quantify deposition at the reach.

The Ericson dam breach in June 2010 peaked at 148.6 m^3 s^{-1}. From 2006 to 2016, the average annual flow recorded at the Spalding gage station was between 5.6 m^3 s^{-1} and 8.4 m^3 s^{-1} (Dave and Mittelstet 2020). In March 2019, Cedar River experienced another historic flood, providing an opportunity to conduct GPS and RiverSurveyor surveys immediately following the event. Flow peaked for the 2019 flood at 207.8 m^3 s^{-1} on March 15th. The next highest flow recorded on the river dating back to 1944 was 63.4 m^3 s^{-1}. GPS points were taken from the top of the bank to the edge of the water. Surveys using the RiverSurveyor were then conducted in a manner as similar as possible to the surveys taken in the summer of 2018.

Results and Discussion

Streambank Migration and Deposition

Analysis of the NAIP imagery for erosion and deposition at the three study reaches was separated into two parts: 1) Image analysis of 1993 to 2006 (pre-stabilization), and 2) Image analysis of 2006 to 2018 (post-stabilization). From 1993 to 2006, we observed 278, 520 and 362 m^2 of erosion at Reaches 1, 2 and 3, respectively. After jetty installation in each of these reaches, the result for total change in the streambank area was noticeably different. Reach 1 had 68 m^2 of erosion while Reaches 2 and 3 had 67 and 44 m^2 of deposition area over the 12-year time period. However, the two time periods and reach lengths studied were not equal. To adjust for this, each value was divided by the number of years in their respective time frames, and again by the reach length. Once corrected, Reach 1 had a loss of 0.41 m^2 m^{-1} yr^{-1} from 1993 to 2006, and 0.1 m^2 m^{-1} yr^{-1} from 2006 to 2018. Reach 2 had a loss of 0.96 m^2 m^{-1} yr^{-1} from 1993 to 2006 and a gain of 0.13 m^2 m^{-1} yr^{-1} from 2006 to 2018. Reach 3 had an overall loss of 0.07 m^2 m^{-1} yr^{-1} from 1993 to 2006 and gained 0.01 m^2 m^{-1} yr^{-1} from 2006 to 2018. An average bank height was calculated using measurements from the GPS survey. Bank height was multiplied by the area of erosion and/or deposition for both pre- and post-stabilization at each reach. From 1993 to 2006, we observed 649 m^3, 2306 m^3 and 1194 m^3 of erosion at Reaches 1, 2 and 3, respectively. After stabilization, Reach 1 had 649 m^3 of erosion while Reaches 2 and 3 had 297 m^3 and 145 m^3 of deposition area over the 12-year time period. These values, like the area values, were then broken down into per meter of the reach, per year. From 1993 to 2006, there was 0.9 m^3 m^{-1} yr^{-1}, 4.3 m^3 m^{-1} yr^{-1} and 0.2 m^3 m^{-1} yr^{-1} of erosion at Reaches 1, 2 and 3, respectively. After jetty stabilization, Reach 1 had 0.25 m^3 m^{-1} yr^{-1} of erosion while Reaches 2 and 3 had 0.6 m^3 m^{-1} yr^{-1} and 0.03 m^3 m^{-1} yr^{-1} of deposition.

At each studied reach, significantly more erosion was observed in the aerial images during pre-stabilization compared to post-stabilization years. This was best observed when comparing disparities at the downstream end of the 1993 bank line to the 2006 and 2018 lines at Reaches 1 and 2 (Figure 6). At Reach 3, a considerable amount of

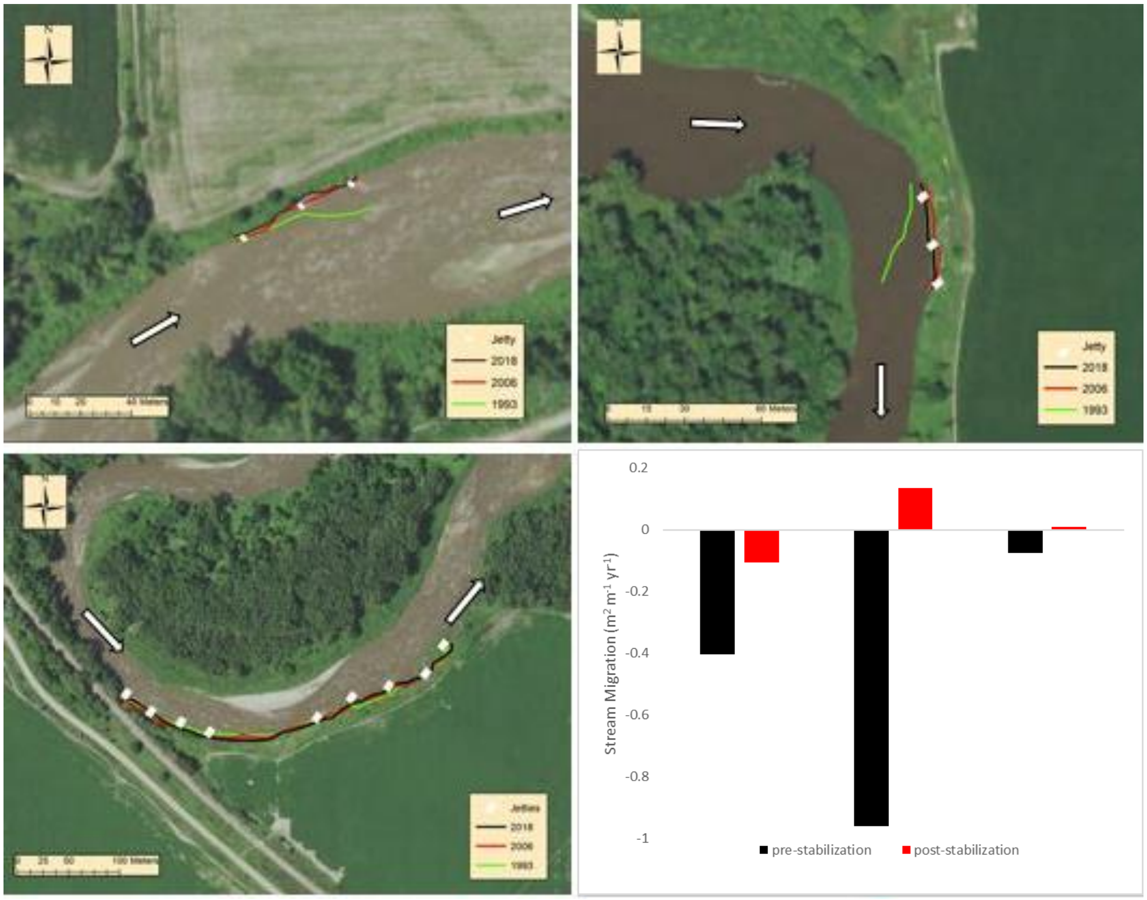


Figure 6. Bank lines were drawn for all three study reaches. 1993, 2006, and 2018 lines were drawn using different colored lines. Flow direction is denoted by white arrows. Also pictured (bottom right), average migration values for pre- and post-stabilization time periods at Reaches 1-3 (left to right).

deposition was observed in the 2018 NAIP image 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 previous 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.

Additional factors known to influence stream migration are woody vegetative cover and the stream's radius of curvature. Using the values presented in Figure 3, none of the study reaches had substantial woody vegetative cover on the stabilized bank. This was likely one of the primary reasons stabilization was needed along these river sections. 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 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.

1950s Jetties

Much of the stabilization implemented throughout Cedar River was funded by and installed during the Cedar River Corridor Project that began in 2002. Each landowner dealt with erosion through different methods. However, in some instances, the river was eroding locations that could not be ignored due to human safety and infrastructure concerns. Specifically, this was the case in 1950 when the erosion of the bank was threatening to encroach into a county road. The solution at the time, was to drive wooden pilings into the riverbed and connect them with sheets of wood to deflect the flow. However, these structures were not built or installed the same way as the jetties installed for the Cedar River project, but did serve the same purpose: to deflect and dissipate flow and prevent further riverbank erosion. Today, these two jetties are still functional having survived numerous high flow events, and continue to protect the riverbank. After seeing the success of these two jetties, we analyzed historical aerial images from 1951, 1957, 1963, and 1969, as well as the current images used in the previous section. A significant amount of deposition has occurred at the upstream section of the two jetties since their installation (Figure 7). This observation helps to reinforce the trends observed at Reaches 1-3, and supports that in the event the jetties at these reaches survive the peak flows and winter conditions in the area, they will continue to be effective at reducing bank erosion and aiding in depositon.

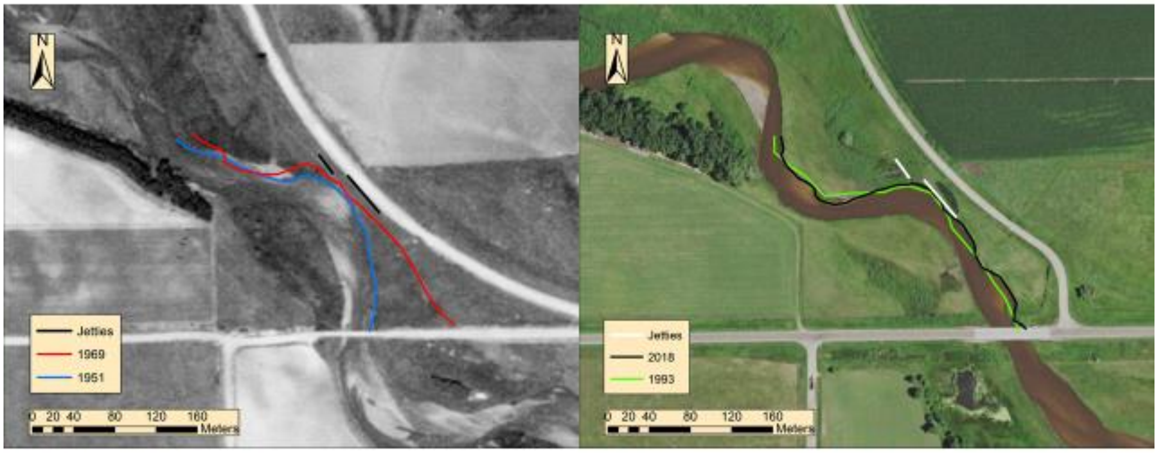


Figure 7. Two jetties were installed in 1950 to protect a county road and bridge from being encroached on by the river. The structures remain today and have protected the bank from erosion, and helped add significant deposition at and upstream of the stabilized area.

Quantification of Deposition

The deposition measured with the aerial images was limited to observations above the water level. Surveying each reach permitted us to not only calculate the streambed below the water table, but also to quantify a volume of deposition. On the basis of our RiverSurveyor S5 and GPS survey data, estimated volume of 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 adjusted 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. Figure 8 shows the variation from zone to zone at each reach. The maximum value seen in 2018 at any of the three reaches was 1.4 m^3 m^{-1} and the minimum value was 0.0 m^3 m^{-1}. Because the pre-stabilization bed elevation was unknown for each reach, the lowest average elevation was used as a baseline (zero value) to quantify sediment thickness in the 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 jetty structures 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 where the deflected water re-enters the current. This causes swirling and bed scouring at the tip of the jetty and in areas behind the jetty, which could result in 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 depositional characteristics to Reach 1, and zones 14-28 displayed similar depositional characteristics to Reach 2. These similarities in depositional trends highlight the need for further study on the impact stream ecosystems and their morphology following the introduction of stabilized structures.

Function of jetties during historic 2019 floods

Using repeated surveys in 2018 and 2019, we quantified sediment deposion and erosion during this period (Figure 8). Historic flooding across the Midwest during the spring of 2019 preseneted a unique opportunity to conduct a year to year comparison of the deposition at Cedar River using our newly created survey and deposition quantification method. 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.

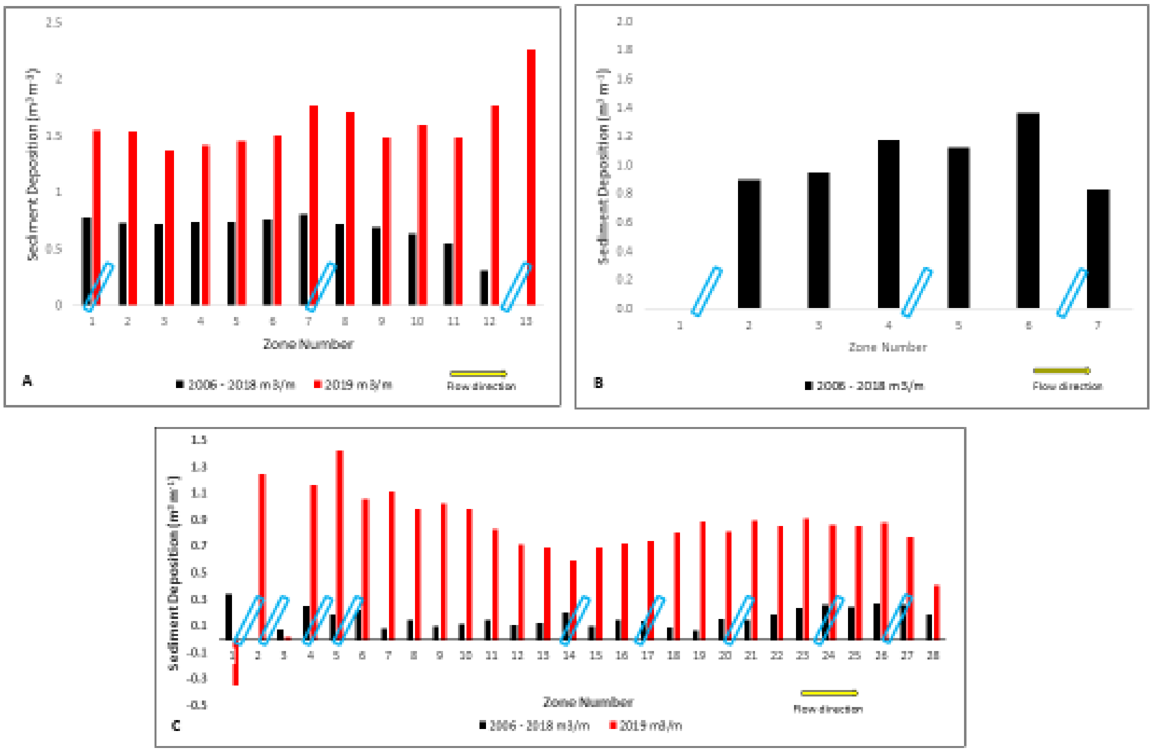


Figure 8. Quantification of deposition for each reach: 1 (A), 2 (B), and 3 (C). Black bars are deposition totals from 2006-2018, red bars are deposition from 2018-2019, and blue bars are jetty locations at each reach.

Flooding in early 2019 was found to carry a large amount of sediment that was deposited throughout the stream. In 2018, Reach 1 had an average of 0.03 m^3 m^{-1} yr^{-1} within the study area. In 2019, that number increased to 1.61 m^3 m^{-1}, a 335% increase from the total deposition seen from 2006-2018. At Reach 3, the overall amount of deposition in the studied area was lower, but the increase in deposition from year to year was similar to Reach 1. In 2018, Reach 3 had an average 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}, a 406% increase. This dataset is just a small snapshot of the dynamic process occuring each day within this specific river system. The survey was completed seven months following the 2019 flood, which exhibits the significant 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 significantly, but in some cases had significant deposition in the reach.

CHAPTER 2: ASSESSING THE INFLUENCE OF INSTALLED STABILIZATION STRUCTURES ON THE UPSTREAM AND DOWNSTREAM REACHES ON CEDAR RIVER, NEBRASKA

Matthew Russell[1], Aaron R. Mittelstet[1] Tiffany L. Messer[1], Jesse T. Korus[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, USA

[2]School of Natural Resources, East Campus, University of Nebraska-Lincoln, 101 Hardin Hall, Lincoln, NE 68583-0961, USA

Abstract

The need to stabilize streambanks continues to increase as human-induced erosion accelerates, yet the effectiveness of these practices has been insufficiently monitored and assessed to date. Previous studies have shown that stabilization structures are effective at reducing, and in some cases, eliminating streambank erosion locally. However, little is known about how the stabilized reach influences the river's upstream and downstream reaches. The objective of this study was to measure the amount of riverbank loss/gain 1.5 wavelengths upstream and downstream of each stabilized reach and on the opposite bank from 1993 to 2005 (pre-bank stabilization), and 2005 to 2018 (post-bank stabilization) on Cedar River, in North-Central Nebraska using ArcGIS and historical aerial imagery. We hypothesized that streambank erosion would be less post-stabilization. However, after data collection and analysis was complete, we found the opposite to be true. The differences in erosion from pre- to post-stabilization showed little to no statistical significance and deposition was actually greater during the pre-stabilization period, informing us that bank stabilization at Cedar River may be effective at the location of installation, but shows little to no impact on decreasing erosion rates up or downstream. The insight gained from this project reinforces the need for improved streambank monitoring practices and understanding how streambank stabilization impacts the entire river system. Improving these practices will allow for enhancements in stream restoration design as well as informed decision making for future stabilization practices in similar streams and rivers.

Introduction

As erosion rates increase across a growing number of landscapes, so too does the need for streambank stabilization. Despite their increasing implementation, the overall effectiveness and potential impacts of these practices has been insufficiently monitored and assessed to date. Previous studies have shown stabilization structures are effective at reducing, and in some cases, eliminating streambank erosion locally. However, there is little known on how a stabilized reach influences the river’s upstream and downstream reaches. To better understand these impacts at Cedar River, we measured the amount of riverbank loss/gain 1.5 wavelengths upstream and downstream of each stabilized reach and on the opposite bank from 1993 to 2006 (pre-bank stabilization), and 2006 to 2018 (post-bank stabilization) using ArcGIS and historical aerial imagery. Based on findings from Dave and Mittelstet (2017), we hypothesized that streambank erosion rates would be significantly less post-stabilization, and deposition rates would be greater in stabilized reaches and their adjacent stream segments.

Materials and Methods

Characterization of Study Reaches

Twenty-four study reaches, installed in or around 2005 in response to the Cedar River Corridor Project, were evaluated (Figure 9). The sites were stabilized with various stabilization practices: 13 wooden jetties, 4 tree jetties, 3 rock vanes, 1 root wad, and 4 sloped gravel banks (one reach has both tree jetties and a sloped gravel bank). Wooden jetties (Figure 10 – A) are structures that have two to three vertical posts and one horizontal tree trunk tied in with woody vegetation. The jetties are angled downstream and used to slow down and deflect flow. Tree revetments (Figure 10 – B) are similar in structure to wooden jetties. The tree trunk was keyed into the bank and angled

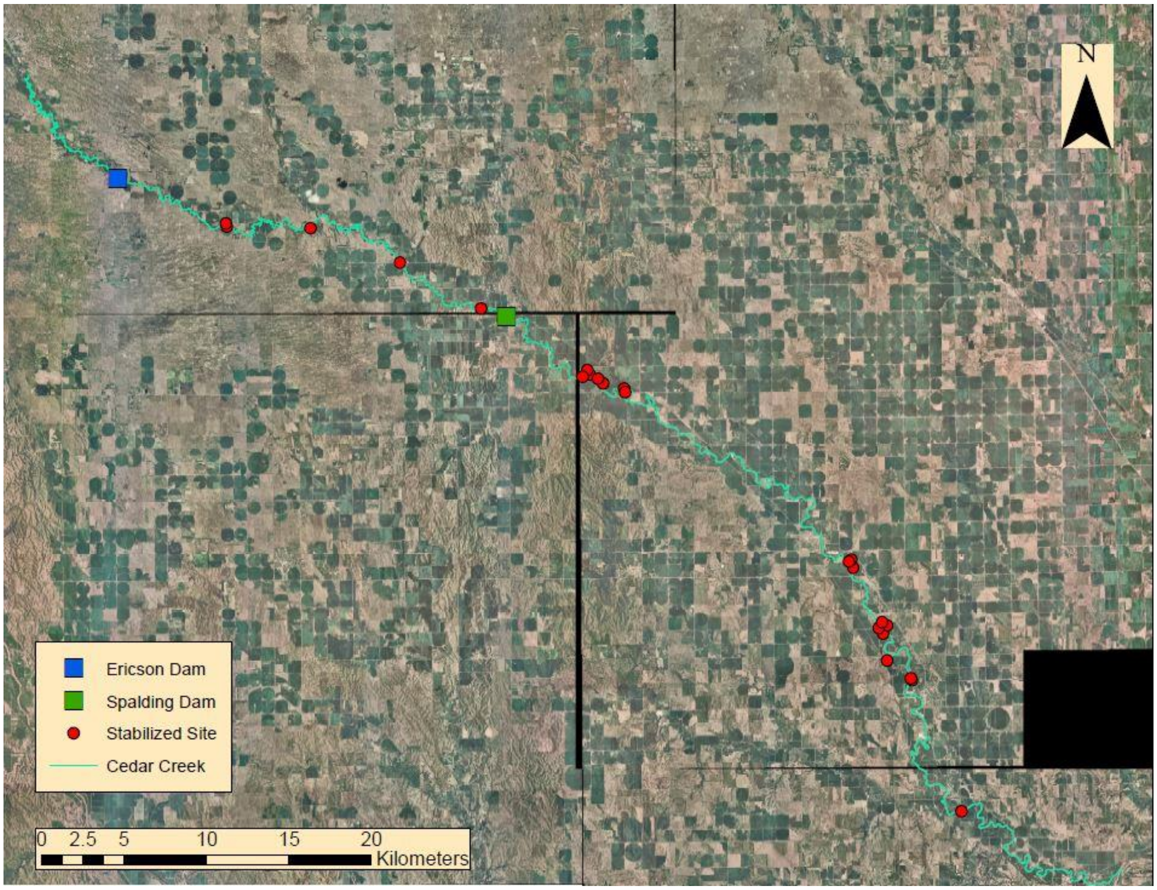


Figure 9. 24 reaches were assessed throughout this project. All studied reaches are found downstream of Ericson dam.

downstream to slow down and deflect flow. There were no vertical supports used in tree revetments. The reinforced concrete wall (Figure 10 – C) was located at the Spalding golf course directly downstream of the Spalding dam. The wall was installed to ensure protection of the golf course that is directly adjacent to the river. Rock vane (Figure 10 – D) structures were comprised of rip rap, beginning at the toe of the bank, and extending into the river to slow down water and protect the bank. Root wads (Figure 10 – E), similar to tree revetments, were tree trunks keyed into the bank. Unlike tree revetments, root wads had the bottom of the trunk and its roots exposed to reduce flow. Sloped gravel banks (Figure 10 – F) were graded sections of the river with gravel added for bank protection. Each reach with a sloped gravel bank was completely vegetated during the site visit.

Five of the reaches were located between the Ericson and Spalding Dams (Figure 9). The closest reaches to Ericson Dam were Reaches 10 and 11 at approximately 8 kilometers downstream. The remaining 19 study reaches were located downstream of Spalding Dam. The furthest downstream site was Reach 8, approximately 72 km

downstream of Ericson Dam. At each reach, erosion and deposition were quantified and the radius of curvature (ROC), sinuosity, and slope were calculated to further characterize each reach.

Erosion and Deposition Measurements

Since the distance streambank stabilization practices influenced the upstream and downstream reaches were unknown, the streambanks were evaluated 1.5 wavelengths upstream and downstream of the stabilized reach using ArcMap 10.7.1 (ESRI) and historical National Agricultural Imagery Program (NAIP) images. To create a comparable dataset, each studied reach was divided into six segments, individually determined by the inflection points of the stream curvature in 2006 (Figure 11). Inflection points are the locations on the stream where the stream curvature changes direction. The middle of the upstream and downstream sections were the areas of stabilization, and each new segment began at each inflection point of the following meander and continued until the next inflection point. These segments were labeled as Upstream 1 (US1,) Upstream 2 (US2), Upstream 3 (US3), and Downstream 1 (DS1), Downstream 2 (DS2), Downstream 3 (DS3). In some circumstances, not all segments for each reach were assessed due to large migrations from oxbow lake formation. In these cases, the segments that could be assessed were completed, and the unobservable segments were not assessed. Stream migration was assessed for two time periods: 1993 – 2006 (pre-stabilization) and 2006 – 2018 (post-stabilization). At each reach, an edge of bank line was drawn to distinguish the disparities in the location of the bank. For consistency and since inflection points changed during the time periods, the 2006 images were used to identify the inflection points.

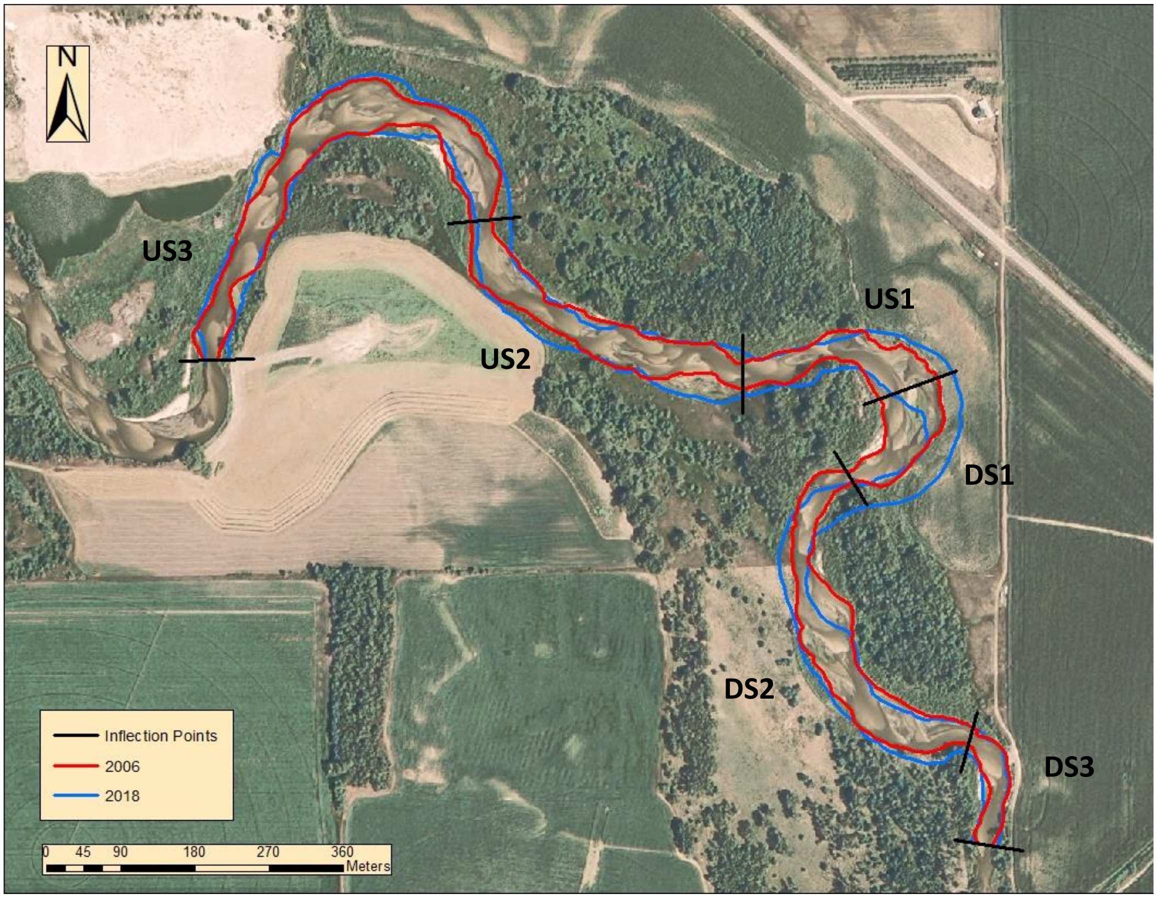


Figure 11. Site 20 - Each reach was divided into six stream segments: DS1, DS2, DS3, US1, US2, US3. Stream inflection points were used to determine the length of the stream segment.

The area between the polylines created over the NAIP images for both the left and right bank of the reach was measured with the ArcMap measuring tool (Figure 12). Each polygon was measured and recorded in an Excel sheet where the cumulative erosion and depositional data were summed. Due to the varying lengths from segment to segment, as well as the changing lengths of the streambank from year to year, a value for each segment was measured and recorded alongside the corresponding erosion and deposition data. Each bank segment's total erosion and deposition was divided by its reach length, resulting in a m^2 m^{-1} value, creating a more comparable dataset.

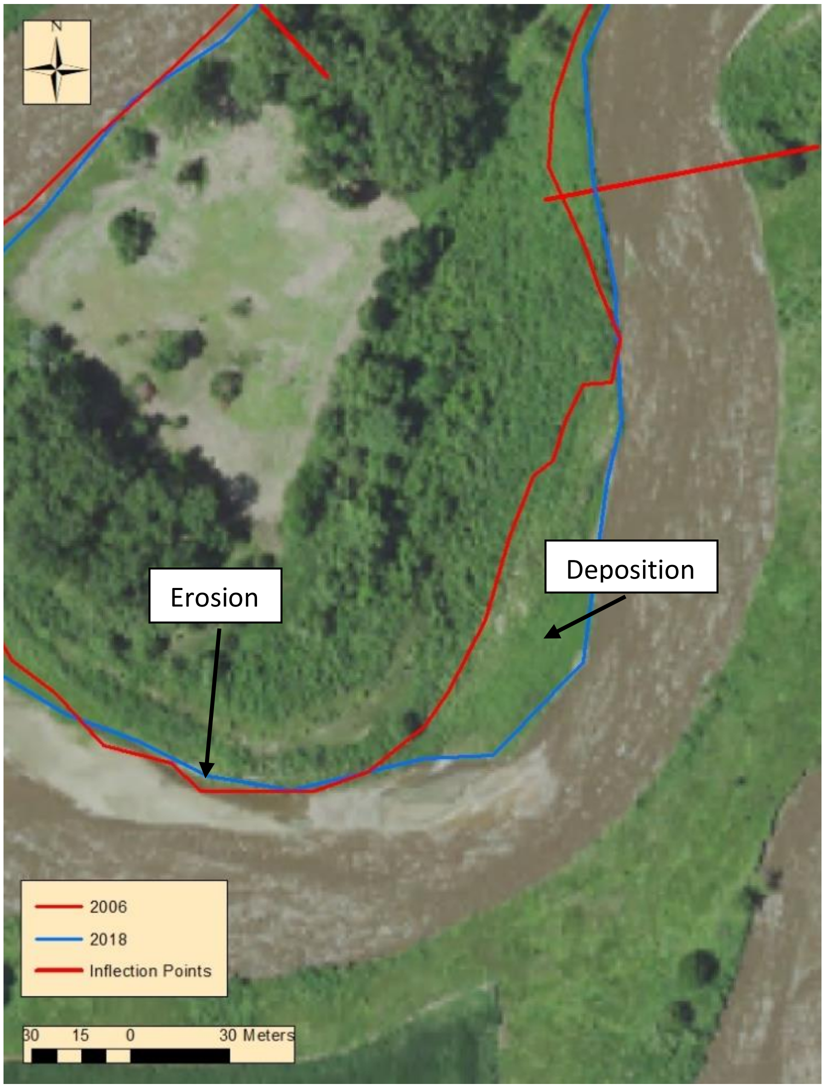


Figure 12. Deposition and erosion were carefully measured at each reach using the ArcMap polygon measuring tool.

Reach Characterization

To characterize each study reach, the ROC, sinuosity and slope were calculated. The ROC was calculated by creating circle polygons for each meander using the 2006 aerial image and measuring the radius. Slope was measured using USGS topographic maps (USGS 1985) and the channel length. Additionally, sinuosity of each reach was calculated by dividing the length of stream from US3 to DS3 by the straight-line distance.

During reach visits, the current functionality of each stabilized structure was noted. It was documented if a stabilized structure was fully functional (Y), partially functional (P) or not functional at all (N). Partially functional sites were categorized by those that had only part of the stabilized structure remaining at the time of visit, but continued to maintain some of the whole structure's function. The current functionality of most reaches is attributed to the historic 2010 flood.

Data Analysis

Descriptive statistics, mean, median, minimum, maximum, and standard deviation, were calculated for the measured erosion and deposition for each stream section. An ANOVA (alpha=0.05) was completed to determine significant differences in erosion and deposition for the six segments for the pre and post stabilization periods. The analysis was conducted for all 24 reaches and for the fully functional reaches.

Results and Discussion

Stream Characteristics

Each studied reach posed a unique set of features that inherently make meandering streams difficult to characterize and their components difficult to quantify. Table 3 shows the reach numbers and the corresponding stabilization structures that were installed. Each of the stabilization structures served a different function, but all serve the same singular purpose: to reduce the amount of erosion occurring at the point of stabilization. At almost half of the reaches, the practices installed were not functioning, or only partially functioning during our site visit in 2018. Each of the reaches that were no longer fully functional were jetties. All of the other stabilization structures were still fully functional. As noted by Dave and Mittelstet (2017), jetties are the most cost-efficient but also the most likely to fail. The exact reason for the loss of total or partial functionality at each reach is not known. However, based on the slowing of erosion at these reaches until 2010, and the following acceleration of erosion following 2010, we infer that the extreme peak flow event due to the breach in Ericson Dam was likely associated with the loss of functionality at many of the reaches. Another parameter of interest was the proximity of each reach to Ericson dam. Dave and Mittelstet (2020) assessed the impacts specifically from the 2010 flood on erosion rates for pre- and post-stabilization at 18 stabilized reaches and their controls. The erosion rates during the flood were 0.74 m^2 m^{-1} and 3.1 m^2 m^{-1} for the stabilized streambanks and controls. They found erosion control structures as far away as downstream of Spalding dam (>27 km) lost functionality due to the flood. From this information, we inferred that the closer the reach was to the dam, the more prominent the impact would be from the flood. Impacts from the 2010 and 2019 flooding may be seen in many ways, namely, the increase in erosion upstream or downstream of the stabilized reach, assuming the reach did not lose its function in the flood event. Conversely, if the reach partially or fully lost its functionality, a significant increase of erosion rates would be seen at and around the previously stabilized reach. In our study, five reaches were located between Spalding and Ericson Dams, and 19 reaches were located downstream of Spalding Dam, which is approximately 27 kilometers downstream of the Ericson Dam.

Table 3 also provides information on the sinuosity of each reach. A sinuosity of >1.5 is considered to be a meandering stream. The average of the 24 study reaches was

1.7, which would qualify the river as a whole to be a meandering stream. However, not all of the reaches had high sinuosity. Two reaches (8, 18) were nearly straight.

Table 3. Each site was categorized into functioning (Y), non-functioning (N), or partially functioning (P), and a sinuosity value was calculated for each. Distance is relative to the Ericson Dam. Spalding Dam is located at km 27.

Site Number	Stabilization Practice	Functioning?	Sinuosity	Distance (km)
1	Wooden Jetties	P	1.4	13
2	Rock Vanes	Y	1.3	26
3	Wooden Jetties	P	1.7	34
4	Sloped Gravel Bank	Y	1.7	34
5	Sloped Gravel Bank	Y	1.7	34
6	Wooden Jetties / Rip Rap	P	3.3	61
7	Reinforced Concrete Wall	Y	1.8	27
8	Wooden Jetties	P	1.1	72
9	Wooden Jetties	P	1.4	55
10	Sloped Gravel Bank	Y	1.5	8
11	Wooden Jetties	Y	1.8	8
12	Root Wads	Y	1.6	34
13	Rock Vanes	Y	1.4	20
14	Wooden Jetties	Y	2.0	63
15	Wooden Jetties	N	2.3	62
16	Tree Jetties	N	2.5	37
17	Tree Jetties	N	2.3	40
18	Wooden Jetties	N	1.1	35
19	Tree Jetties	Y	2.0	62
20	Wooden Jetties	N	1.8	57
21	Wooden Jetties	P	1.4	60
22	Tree Jetties	Y	1.3	63
23	Tree Jetties	Y	1.3	62
24	Tree Jetties	Unknown*	1.8	59

*Water level too high to determine

Erosion and Deposition Data

Though it was hypothesized that streambank erosion would be less post-stabilization, the opposite was found (Figures 13 and 14). Each segment, with exception of DS2 and DS3, were found to have an increase in average erosion rates for the post stabilization period. We postulated this was attributed to the 2010 flood and the current state of functionality of each practice. To illustrate this, we considered Reach 15 (Figure 15), which had a stabilization structure that was not functional during our site visit in 2018. From 1993 to 2006 the average annual erosion rate was 0.43 m^2 m^{-1}, the post-stabilization (2006-2010) with the 2010 flood increased to 0.61 m^2 m^{-1}, and post flood from 2010-2018 remained high at around 0.56 m^2 m^{-1}.

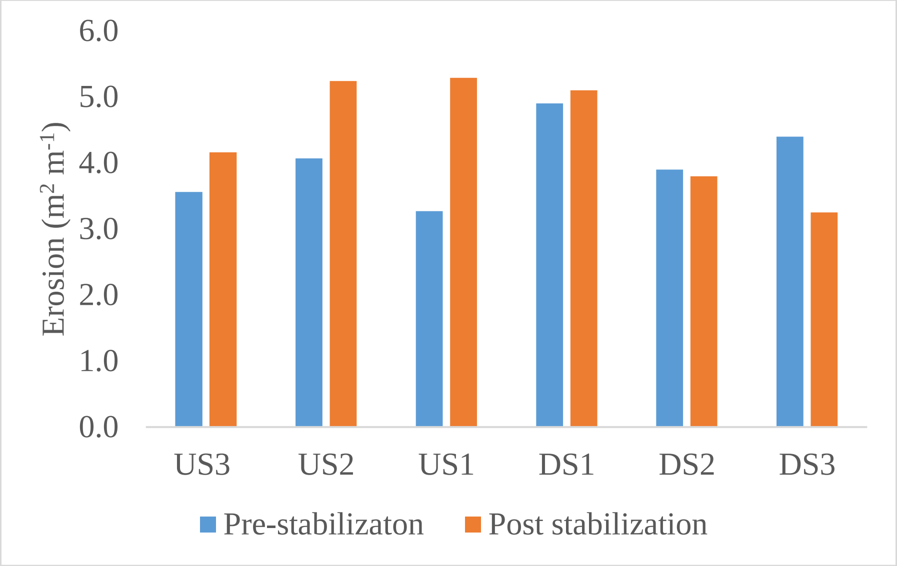


Figure 13. Erosion remained largely the same throughout the studied area from pre to post stabilization.

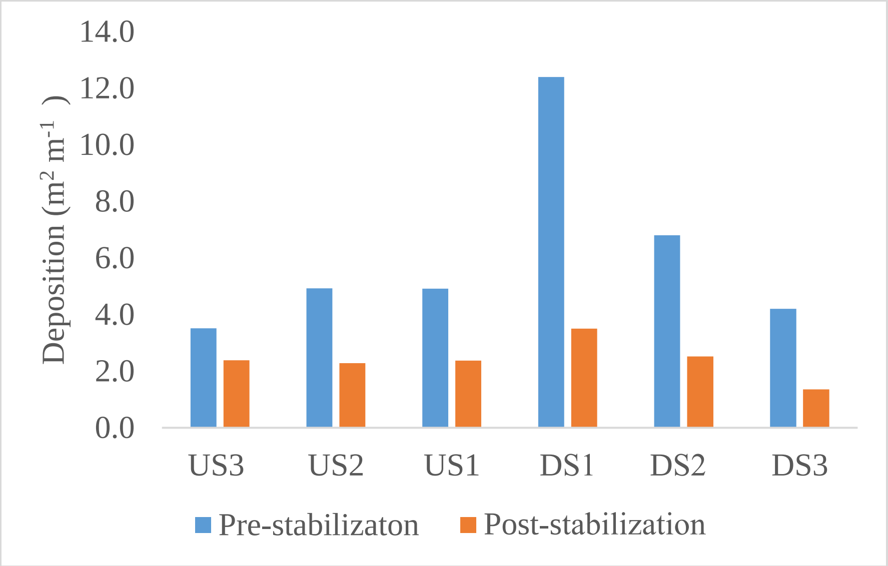


Figure 14. Deposition decreased in each reach, with the largest reduction in the downstream segments of the river.

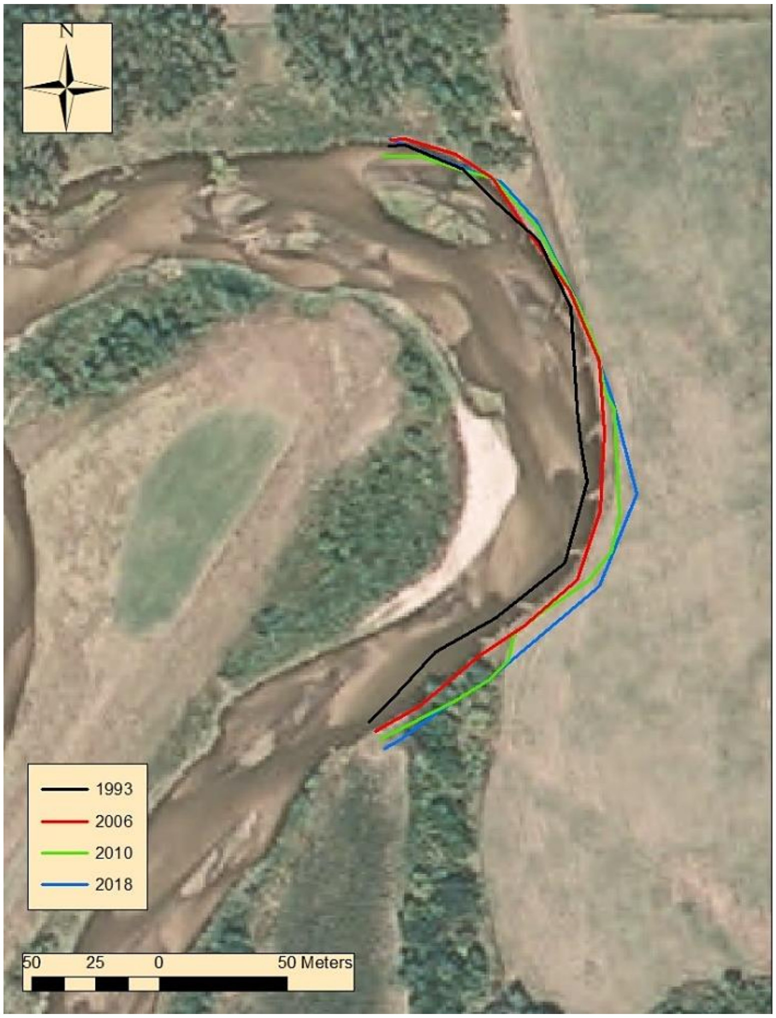


Figure 15. Reach 15 – Streambank retreat continued after jetties were installed on the reach (2006). This indicates that the stabilization practices are not properly functioning.

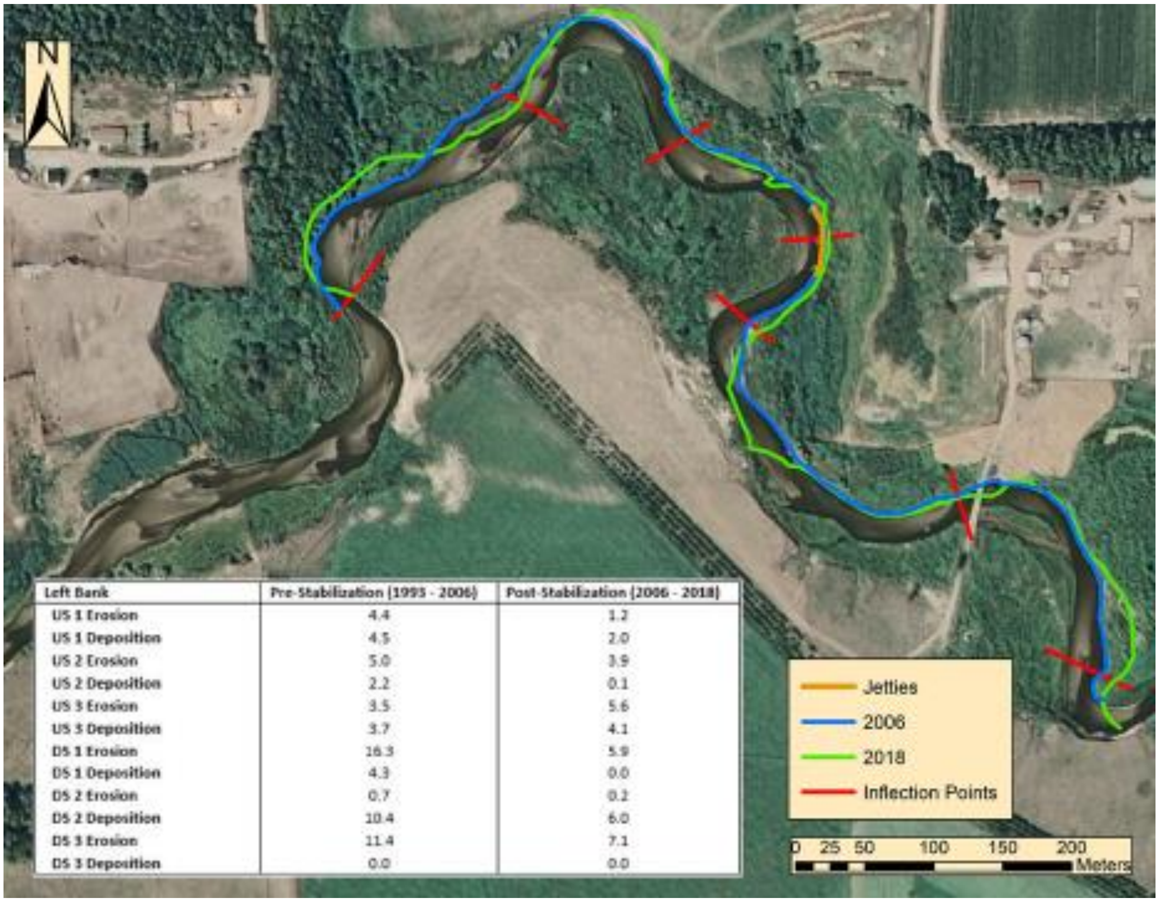
A variety of statistics were collected for each reach from the stream migration calculations (Table 4). These statistics were the first step in assessing the changes of each reach over time, and how the reach changed segment by segment. Standard deviation values throughout the river were highly variable and, in many cases, very large. These deviations from the mean inform us that there were outliers in many of the stream segments, namely, Pre-Deposition DS1 at Reach 14 (20.4 m^2 m^{-1}).

Table 4. Statistics for each stream segment before and after stabistabilization.

Reach	Min ($m^2\ m^{-1}$)	Max ($m^2\ m^{-1}$)	Median ($m^2\ m^{-1}$)	Mean ($m^2\ m^{-1}$)	Std. Dev.
Pre-stabilization					
DS1 Erosion	0.0	23.0	1.4	4.2	6.1
DS2 Erosion	0.0	98.9	5.2	9.8	16.6
DS3 Erosion	0.0	93.0	6.3	9.1	14.7
DS1 Deposition	0.0	124.5	4.0	9.7	20.4
DS2 Deposition	0.1	98.2	8.2	11.6	16.6
DS3 Deposition	0.0	81.0	5.4	9.2	13.2
US1 Erosion	0.0	22.5	1.9	3.0	4.6
US2 Erosion	0.0	50.8	2.3	4.4	8.3
US3 Erosion	0.0	30.7	1.9	3.3	4.8
US1 Deposition	0.0	19.5	2.8	3.4	3.5
US2 Deposition	0.1	37.7	3.4	4.8	6.5
US3 Deposition	0.2	34.8	3.0	4.7	5.7
Post Stabilization					
DS1 Erosion	0.0	22.3	2.0	3.9	4.7
DS2 Erosion	0.1	13.9	2.8	3.6	3.1
DS3 Erosion	0.1	8.4	2.6	3.1	2.1
DS1 Deposition	0.0	27.2	0.7	2.7	5.1
DS2 Deposition	0.0	8.3	1.2	2.3	2.5
DS3 Deposition	0.0	9.3	0.8	1.8	2.2
US1 Erosion	0.0	27.5	2.6	4.3	5.1
US2 Erosion	0.1	17.8	3.1	4.2	4.0
US3 Erosion	0.2	14.3	3.2	3.8	2.9
US1 Deposition	0.0	10.3	1.3	2.4	2.6
US2 Deposition	0.0	16.9	1.4	2.5	3.0
US3 Deposition	0.1	14.8	1.6	2.7	3.2

To account for the reaches that failed during the 2010 flood, only the fully functional reaches were evaluated. Based on a Fisher post-hoc test, segments US1 and US2, both post-stabilization, were significantly greater than the other segments with 4.83 and 4.81 $m^2 m^{-1}$ of erosion, respectively. US1 pre-stabilization was significantly less than the other segments with 2.2 $m^2 m^{-1}$.

Based on these findings, our modified hypothesis states that while the section of the streambank stabilized has a reduction in erosion rates, the practices have little to no influence in reducing erosion rates upstream and downstream. Dave and Mittelstet (2017) discussed that introducing stabilization structures into Cedar River was an effective method for reducing erosion at the site of implementation. Effectiveness varied depending on the type of structure installed and on what reach it was installed, but they documented that in any case, erosion was reduced due to the introduction of bank protection. During our stream migration analysis, the effectiveness of these structures was supported. The stabilized section at Reach 11 (Figure 16) lines up closely to the 2006 and 2018 edge of bank lines that were drawn over the corresponding aerial images. This shows that since installation, the edge of bank has largely remained in the same place where there is bank stabilization. Conversely, nearly every other segment of the reach saw considerable bank migration before, and after, jetties were installed.



Left Bank	Pre-Stabilization (1993 - 2006)	Post-Stabilization (2006 - 2018)
US 1 Erosion	4.4	1.2
US 1 Deposition	4.5	2.0
US 2 Erosion	5.0	3.9
US 2 Deposition	2.2	0.1
US 3 Erosion	3.5	5.6
US 3 Deposition	3.7	4.1
DS 1 Erosion	16.3	5.9
DS 1 Deposition	4.3	0.0
DS 2 Erosion	0.7	0.2
DS 2 Deposition	10.4	6.0
DS 3 Erosion	11.4	7.1
DS 3 Deposition	0.0	0.0

Figure 16. Erosion and deposition occurred in all segments of the study reach prior to stabilization. After installation, erosion no longer occurred in the stabilized area. Only the right bank lines illustrated to reduce number of lines.

We originally hypothesized that the deposition would be greater post-stabilization than pre-stabilization. This was not the case as the deposition pre-stabilization was significantly greater than the post-stabilization for the 24 reaches (Table 5). Based on a Fischer post-hoc test, the mean deposition rate for segment DS1 – pre-stabilization was significantly greater than the other five segments with 9.93 m^2 m^{-1}. The next two tests were run across the same dataset using only the reaches that were fully functional at the time of our site visit. When assessing only the functional segments, no one mean was significantly different than the rest, but there were three groupings found in the deposition test, and two groupings in the erosion test. This tells us that, similar to the analysis of all reaches, deposition has some significant difference in rates from pre- to post-stabilization. Erosion shows little to no significant differences whether it be pre- to post-stabilization, evaluating all reaches, or just those that are fully functioning. The absence of significant change in erosion rates over the 25-yr time period shows us that bank stabilization may be effective at the point of installation, but that it has little to no impact on decreasing erosion rates directly up or downstream.

Table 5. ANOVA with Fisher post-hoc tests were conducted for erosion and deposition at each reach, and once for erosion and deposition at the fully functioning stabilized reaches.

All Sites - Deposition

Reach	N	Mean	Grouping			
DS1-Pre	44	9.9	A			
DS2-Pre	42	6.5		B		
DS3-Pre	40	5.5		B	C	
US2-Pre	46	5.1		B	C	
US1-Pre	46	4.9		B	C	D
US3-Pre	46	4.5		B	C	D
DS1-Pos	44	2.9			C	D
US3-Pos	46	2.7			C	D
US2-Pos	46	2.6			C	D
DS2-Pos	42	2.6			C	D
US1-Pos	46	2.5			C	D
DS3-Pos	40	1.8				D

Fully Functional Deposition

Reach	N	Mean	Grouping		
DS2-Pre	20	7.9	A		
US2-Pre	24	5.9	A	B	
DS3-Pre	20	4.8	A	B	C
US1-Pre	24	4.6		B	C
US3-Pre	24	4.1		B	C
DS1-Pos	22	3.9		B	C
DS1-Pre	22	3.7		B	C
US3-Pos	24	2.7			C
US2-Pos	24	2.7			C
US1-Pos	24	2.3			C
DS2-Pos	20	2.2			C
DS3-Pos	22	2.1			C

Fully Functional Erosion

Reach	N	Mean	Grouping	
US1-Pos	22	4.8	A	
US2-Pos	22	4.8	A	
DS1-Pre	22	4.1	A	B
DS2-Pre	20	3.9	A	B
DS1-Pos	22	3.9	A	B
DS3-Pre	18	3.7	A	B
DS2-Pos	20	3.6	A	B
US2-Pre	22	3.5	A	B
US3-Pos	22	3.5	A	B
DS3-Pos	18	3.4	A	B
US3-Pre	22	2.8	A	B
US1-Pre	22	2.2		B

CHAPTER 3: OVERALL CONCLUSIONS OF FINDINGS, RECCOMENDATIONS, FUTURE WORK, AND ACKNOWLEDGMENTS

Conclusion

Cedar River, like many other streams and rivers in the state of Nebraska and the central/upper Midwest, is facing 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 the high flows away from property. This short-term solution not only impacted the river where it was altered, but could potentially impact the geomorphology of upstream and downstream river sections.

The introduction of jetties in 2005 resulted in substantially less erosion during post-stabilization than in any of the years prior to stabilization. In some instances, erosion stopped completely, and deposition began to occur in the area. However, erosion only stopped where stabilization structures were installed. Erosion and deposition rates for sections of the river upstream and downstream of the stabilized reaches continued to increase and the streambanks remain degraded. These findings lead us to question the large-scale effectiveness and use of stabilization practices in large streams and rivers. It is well documented, and we have found that, when installed correctly, streambank stabilization practices reduce erosion rates at the area of installation. However, additional research is needed in this field, and the field methods for this project will act as the foundation for a new method of calculating and quantifying sediment deposition. Further work needs to be completed to assess the upstream and downstream impacts that stream restoration and stabilization structures have on the river systems. Further studies for

Cedar River may include: 1) Surveys conducted in five years at the three study reaches found in Chapter 1 to further assess changes in deposition location and quantities, 2) Continued analysis of stream migration at Cedar River and comparable streams and rivers across the U.S.

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