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RESEARCH ARTICLE

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Can deciduous tree revetments reduce streambank erosion rates on a sand-bed stream?

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Abstract

Accelerated streambank erosion can threaten infrastructure and land, as well as water quality and aquatic habitats. Streambank stabilization techniques have been developed with the intent to reduce or halt streambank erosion. One such technique is the use of woody revetments. This case study evaluates the effectiveness of deciduous tree revetments on stabilizing streambanks on the Smoky Hill River, a low-gradient, sand-bed stream located in central Kansas in the United States. It was hypothesized that deciduous tree revetments would mimic bank protection processes of permeable-type spurs, capturing sediment and reducing velocities and shear stresses near the toe of the streambank. To test this hypothesis, cross-sectional dimensions of four streambanks were obtained before and after installation of tree revetments and compared to four natural, control streambanks (i.e., not stabilized) over a 5-year period. Rates of bank erosion were calculated and compared. This study found that, in its current design form, deciduous tree revetments were not effective at reducing bank erosion, as all sites had experienced revetment failures by the end of the study period. Furthermore, the installation of tree revetments accelerated bank erosion rates following revetment failure. Increased bank erosion was attributed to both the construction disturbance, as well as improper anchoring of the revetment. The results of this case study show the importance of collecting bank stratigraphic data and incorporating it, as well as expected flow scenarios, in numerical modelling tools to assess designs and adjust accordingly. While conducting these analyses upfront may result in higher design costs, long-term maintenance or replacement costs would be decreased.

KEYWORDS
streambank erosion, streambank stabilization, tree revetment, woody revetment

1 | INTRODUCTION

Streambank erosion is a natural and necessary geomorphic process. Streambank erosion dissipates flow energy and introduces both sediment and organic debris that are essential for the creation, maintenance and diversification of aquatic habitat (Florsheim et al., 2008). Rates of streambank erosion depend on both localized shear strength of bank materials and the gravitational and hydraulic forces that act on the streambank (Simon et al., 2000). Depending on the balance of these forces, streambanks erode in three general ways: via subaerial weakening and weathering, fluvial erosion and/or mass wasting. Dominant streambank erosion processes and rates often vary through space and time, as boundary conditions change and forces shift or change (Couper, 2004; Palmer et al., 2014).

Streambank erosion rates can also be affected by disturbances that occur within the watershed or along the channel (Simon &

Hupp, 1987). Disturbances can cause channel instability and, as a result, accelerate streambank erosion due to bed degradation (e.g., due to increased bank height/angle) and/or aggradation (e.g., due to shifts in hydraulic forces). Channel instability and accelerated streambank erosion lead to biological impairment locally and downstream due to an increase in sediment and nutrient loading (Feio et al., 2021; Inamdar et al., 2018; Noe et al., 2020; Purvis et al., 2016). Furthermore, accelerated streambank erosion threatens infrastructure and land (Fox et al., 2016; Morris et al., 1996; Renetzky, 2014). Both natural and anthropogenic influences can cause channel instability. Natural influences generally occur over a geological timescale and include changes in climate, vegetation, topography and sediment sources. Alternatively, anthropogenic influences can have almost immediate effects on channel stability. Examples of anthropogenic influences include channelization, construction of dams and levees, dredging, human-induced climate change, urbanization and conversion of land for agricultural purposes (Goudie, 2006; Kondolf, 1997; Simon & Rinaldi, 2000; Trimble, 1997). Furthermore, in streams impaired by excess sediment, several case studies have identified streambank erosion as a leading source of sediment (Belmont et al., 2011; Gellis et al., 2019; Gellis & Sanisaca, 2018; Hassan et al., 2017; Juracek & Ziegler, 2009).

To reduce the impacts of accelerated streambank erosion, streambank stabilization techniques can be implemented to maximize localized streambank shear strength and/or minimize the forces acting on a streambank with the intent of halting or minimizing lateral retreat. Bigham et al. (2020) provides a thorough review of 11 types of streambank stabilization techniques, from in-stream structures that divert flow away from streambanks (e.g., impermeable/permeable spurs, rock vanes, bendway weirs) to streambank management techniques that protect against direct hydraulic forces (e.g., retaining wall, bank shaping/grading, bioengineering techniques, toe protection). The use of wood in streambank stabilization projects was also reviewed by Bigham et al. (2020). Woody revetments have been used as flow deflectors, streambank toe protection or both. In general, Bigham et al. (2020) calls for more studies showing the effectiveness of streambank stabilization structures, as it remains unclear if implemented streambank stabilization techniques successfully reduce site-scale bank erosion and if so, over what timescales. Addressing this gap requires long-term, field-scale monitoring of streambank stabilization projects and is essential to inform future physical model experiments and to improve numerical simulation of the site- to reach-scale effects of stabilization techniques to overall channel morphology.

This study examines four eroding streambanks along the Lower Smoky Hill River in central Kansas in the United States that were stabilized in 2016 and 2017 using a novel form of woody revetments. The need to stabilize streambanks along the Lower Smoky Hill River came soon after a report identified 69 streambanks that were eroding at rates of 0.3 to 2 m/yr (TWI, 2009). Government cost-share funds were not available to assist landowners in installing streambank stabilization systems, so a low-cost technique was developed using locally harvested deciduous trees strategically placed near the toe of an eroding streambank, referred to here as deciduous tree revetments. The deciduous tree revetment design called for placing a series of trees, with lengths of roughly one-third of the bankfull width and a diameter at breast height of about 30 cm, with their root wads buried 3 m into the streambank toe and each angled downstream at 30 degrees from the bank tangent line. In addition to keying each tree into the streambank, a 30-cm diameter by 3-m long footer log was placed on top of the root wad, and perpendicular to the tree revetment. The footer log was secured by placing a 1.5-m cable around the tree and driving it into the streambank with an 8-cm duckbill anchor. Each root wad and footer log were then buried in a series of compacted soil lifts. Exposed lengths of tree revetments were designed to be 0.2 times the bankfull width with spacing between the revetments three times of the exposed length (or 0.6 times the bankfull width). Figure 1 provides a schematic of this design, as well as photographs of the implementation process.

To the authors' and designers' knowledge, the described deciduous tree revetment is a novel approach of using wood in streambank stabilization projects; however, similarities with other types of streambank stabilization techniques do exist. Tree revetments or jetties, described by Russell et al. (2021), are most like deciduous tree revetments; however, no form of anchoring (e.g. footer log and duckbill anchor) were used. Coniferous tree revetments are another technique that is similar to the described deciduous tree revetment approach (e.g., Dave & Mittelstet, 2017; Shelley et al., 2022); however, they differ in that (1) they are anchored with only a cable and duckbill anchor and (2) they are laid parallel with the streambank toe. Permeable spurs are also similar to the described deciduous tree revetment technique. A permeable spur allows flow through the structure, which, in turn, reduces near-bank stream velocities and may induce sediment deposition in the vicinity of the structures (Bigham, 2020). Fence-type structures are the most popular form of permeable spurs. Permeable spurs differ from the deciduous tree revetment approach in that the permeability and the spurs' structural dimensions can be controlled (Bigham, 2020).

Given the novelty of the described deciduous tree revetment design, the research question addressed here is: Can deciduous tree revetments reduce streambank erosion rates on a sand-bed stream? We hypothesized that deciduous tree revetments would reduce overall bank erosion rates. To test this hypothesis, streambank erosion rates pre- and post-installation, as well as at nearby control (i.e., not stabilized) streambanks were measured and compared.

2 | STUDY AREA DESCRIPTION

The Smoky Hill River watershed drains 51,300 km^2 of northwestern Kansas and a portion of eastern Colorado and combines with the Republican River to form the Kansas River. Deciduous tree revetments were installed along reaches of the Smoky Hill River located within the Lower Smoky Hill River watershed (HUC 10260008). Figure 2 provides a location map of the sites of interest, relative to the overall Smoky Hill River watershed.

The Lower Smoky Hill watershed is located in the Central Great Plains ecoregion with the majority of the area in the Smoky Hills (Chapman et al., 2010). Geology of this region consists of sandstones, limestones and chalks (Brosius, 2005). Silt loam is the dominant soil type in the A and B soil horizons (USDA-NRCS, 2019). Land cover

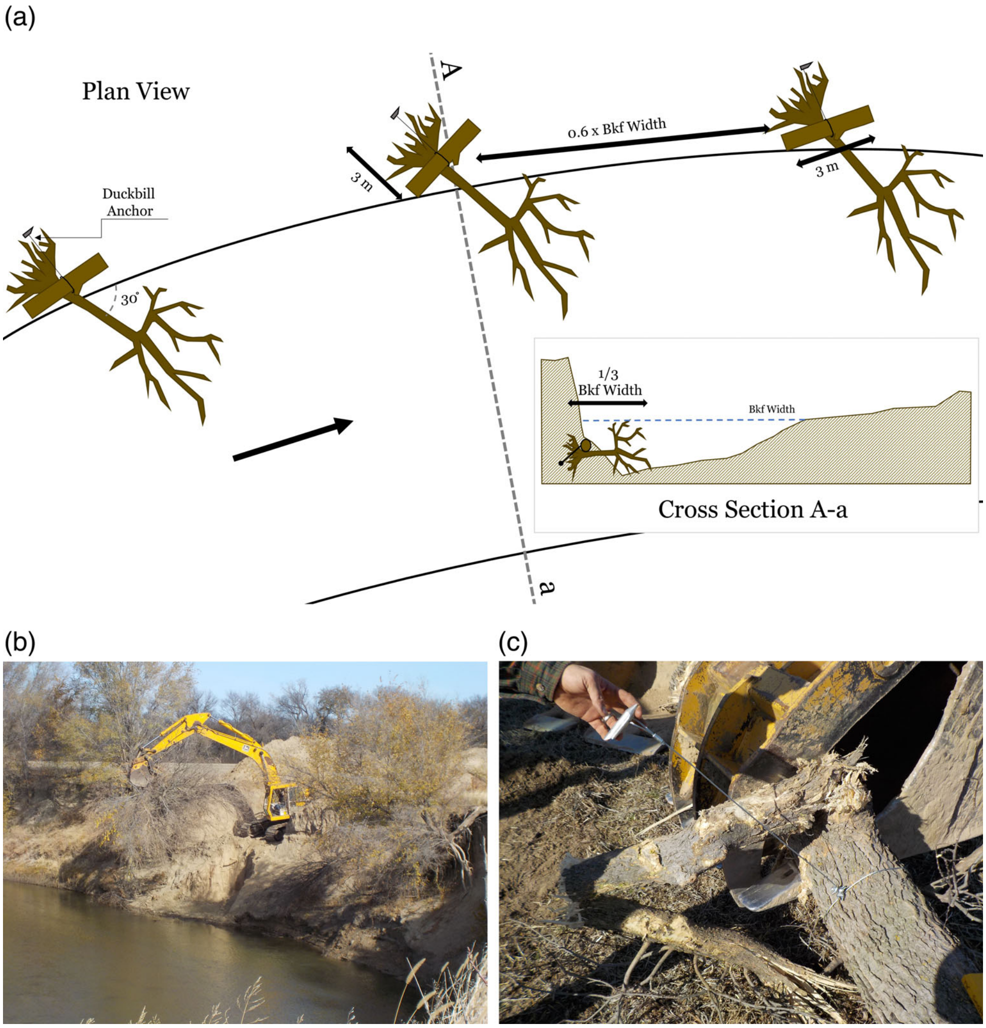


FIGURE 1 (a) Typical plan view and cross section of deciduous tree revetments. Bkf: bankfull; Arrow represents flow direction; Image is not to scale. (b) Excavator placing deciduous tree revetment in the Lower Smoky Hill River. (c) Example of footer log with duckbill anchor. [Color figure can be viewed at wileyonlinelibrary.com]

throughout the Lower Smoky Hill watershed includes a mixture of grassland (49%), cropland (39%), developed land (6%) and forest (5%; USGS, 2016). The climate in this region is near a transitional zone between semi-arid, hot continental and humid subtropical and is characterized by hot, humid summers and cold winters (Peel et al., 2007). Mean annual precipitation for this region ranges from 640 to 890 mm (PRISM Climate Group, 2011).

Field measurements by Bigham et al. (2020) indicate that the bed of the control and treatment study reaches on the Lower Smoky Hill River are composed of medium to coarse sand, based on the Wentworth (1922) scale. Bank heights range from three to eight meters with the majority nearing the latter. Similar to the soil composition of the watershed, the banks are composed mainly of silt loam soils with occasional deposits of sandy loam material, representative of channel fill (Bigham et al., 2020). Upper bank materials roughly 3 m in depth represent post-settlement alluvium (A. Layzell, KGS, personal communication, January 20, 2021). The Lower Smoky Hill River is a meandering river, with a high measured sinuosity (ratio of channel length to valley length) that ranges from 1.7 to 2.6. The channel gradient is very low, having a measured slope of 0.02% to 0.04%. Given the gradient and the bed sediment composition, the bed consists of a low energy, ripple-dune topography (Bigham et al., 2020).

3 | METHODS

To determine if observed changes in bank erosion rates (response variable) were due to the implementation of deciduous tree revetments rather than some other outside factor, the monitoring study followed the Before-After-Control-Impact (BACI) approach. BACI enables evaluation of human-induced perturbations on measurable field variables when restoration sites cannot be randomly chosen (Green, 1979; Underwood, 1992). To improve the statistical power of BACI results, the beyond BACI approach was employed by incorporating more than one control site (Underwood, 1992).

Bank erosion rates were determined prior to implementation of the four deciduous tree revetment projects, as well as after (before-after). In addition, bank erosion rates were measured at four nearby control sites and compared to the stabilized sites (control-impact). Control sites were selected based on the following criteria: (1) landowner permission, (2) actively eroding meander bends, (3) vegetation and bank stratigraphy qualitatively appeared to be similar to the stabilized streambanks (prior to construction) and (4) meander radius of curvature to bankfull width ratios (R_c/W_{bkf}) were similar to those of the stabilized streambanks. Table 1 summarizes site information related to the eight assessed streambanks. Reported ratios of R_c/W_{bkf}

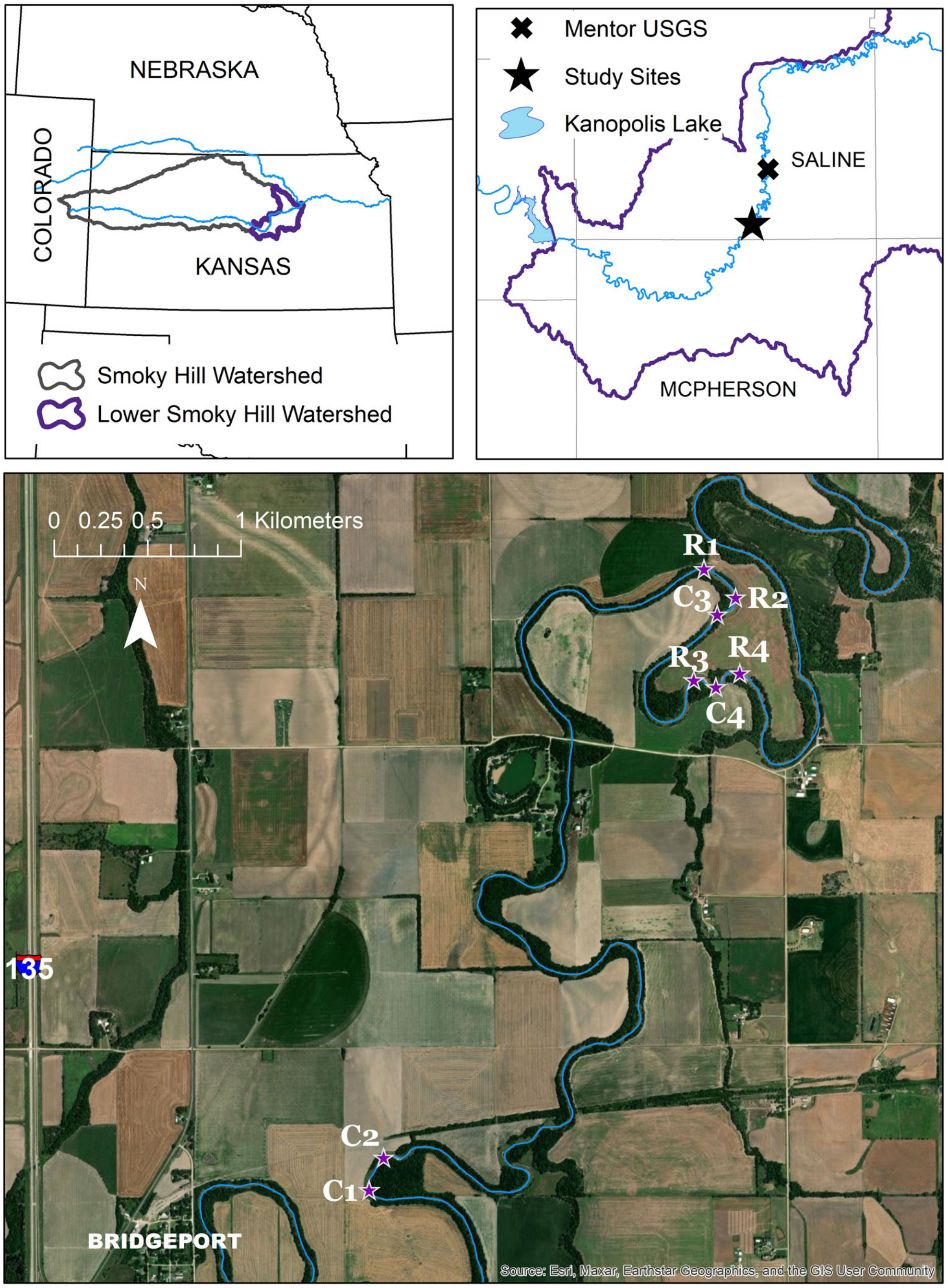


FIGURE 2 Site map of study sites of interest, relative to Smoky Hill River and Lower Smoky Hill River watersheds. R: Revetment, stabilized streambank, C: Control, natural streambank. [Color figure can be viewed at wileyonlinelibrary.com]

were measured by drawing a circle that matches the centerline of the stream channel, as described by Lagasse et al. (2009). W_{bkf} was measured at the crossover between meander bends near the eroding streambank of interest and is based on the stage of the bankfull discharge and its coinciding floodplain (Bigham et al., 2020).

To calculate streambank erosion rates, repeated cross sections were conducted annually when flow and site conditions allowed. In general, at least two cross sections were placed per assessed streambank, one located upstream of the apex of the meander, and another located downstream. If the eroding streambank was long (e.g., R2, R3 and C1), an additional cross section was installed near the apex of the meander. Streambanks C3 and C4 are exceptions to this; given their short lengths, only one cross section was installed at each of these streambanks and were located near the apex of the meander.

These cross sections were surveyed with total station equipment referenced to at least two control points identified by a steel rebar and cap. In total, 17 cross sections were installed, 10 of which were located on deciduous tree revetment sites and the remaining at nearby control sites (Figure 1 and Table 2). If possible, permanent, monumented points identified by steel rebar and cap were placed at cross section end points to expedite future surveys. Each cross section was surveyed and resurveyed during similar time periods (Table 1).

Streambank erosion rates were calculated based on the change in area between each survey period using an established bank toe station and top of bank elevation of the eroding streambank of interest.

TABLE 1 Site information for the deciduous tree revetment (R) and control (C) streambanks of the Lower Smoky Hill River, Kansas in the United States.

Streambank	Coordinates	R_c/ W_{bkf}[a]	# of revetments	# of cross sections	Installation month/year	Survey month/year	
						Pre-install	Post-install
R1	38.661228, −97.579805	2.4	3	2	12/16	3/16, 11/16	3/17, 3/18, 9/20
R2	38.659025, −97.578013	3.0	7	3	1/17	3/16, 11/16	3/17, 3/18, 9/20
R3	38.656131, −97.580767	2.1	9	3	1/17	3/16, 12/16	3/17, 3/18, 5/20
R4	38.656357, −97.577677	1.5	3	2	1/17	3/16, 12/16	3/17, 3/18
C1	38.631229, −97.601264	3.3	0 (Control)	3	—	3/16	3/17, 3/18
C2	38.633081, −97.599687	2.0	0 (Control)	2	—	3/16	3/17, 3/18
C3	38.658807, −97.579848	3.9	0 (Control)	1	—	3/16, 11/16	3/17, 3/18, 9/20
C4	38.655176, −97.579050	1.8	0 (Control)	1	—	3/16, 12/16	3/17, 3/18, 5/20

[a] R_c/W_{bkf}: Ratio of meander radius of curvature (R_c, m) to bankfull width (W_{bkf}, m).

TABLE 2 Summary of average lateral retreat rates measured along 10 deciduous tree revetment sites (treatment, R prefix) and seven control sites (C prefix) along the Smoky Hill River, 2016–2020. Revetments were installed in 2017.

Streambank	Average lateral retreat rate (m/yr)		
	2016–2017 (pre)	2017–2018 (post)	2018–2020 (post)
R1-1	−0.10	0.07	0.46[a]
R1-2	0.58	0.04	0.91[a]
R2-1	0.09	0.06	0.22
R2-2	0.51	0.77	1.25[a]
R2-3	0.57	0.17	0.22[a]
R3-1	−0.01	0.01	0.11
R3-2	0.42	0.11	1.27[a]
R3-3	1.24	2.27[a]	3.05[a]
R4-1	0.38	0.54	-[a]
R4-2	0.31	1.92[a]	-[a]
C1-1	0.14	−0.07	-
C1-2	0.41	0.08	-
C1-3	0.54	0.17	-
C2-1	0.18	0.29	-
C2-2	0.80	0.87	-
C3-1	0.09	0.80	0.73
C4-1	4.41	2.14	4.15

Note: - indicates re-surveys were not possible due to loss of control pins; negative values represent deposition.

[a] Revetments were washed away in the vicinity of the cross sections;

An example of this process is provided in Figure 3. Based on the change in area between overlays, average lateral retreat rates (or bank erosion rates) were calculated using the following equation (Equation (1)):

$$\text{Avg. Lateral Retreat Rate}\left(\frac{\text{m}}{\text{yr}}\right) = \frac{(\Delta\text{Cross Sectional Area at Bank of Interest, m}^2)}{(\text{Bank Height, m})(\text{Time Between 2 Surveys, yrs})} \tag{1}$$

To assess change in bank erosion rates following the installation of deciduous tree revetments, the following questions were addressed:

1. Are the control sites representative of bank erosion rates occurring at the stabilized sites, prior to installation, and over the course of the study period?
2. Are there detectable differences in bank erosion rates between control sites versus stabilized sites?
3. Are there detectable differences in bank erosion rates pre- versus post-installation at stabilized sites?

A total of nine hypotheses were formulated based on these questions and are summarized in Figure 4. Erosion rate data were not normally distributed, thus non-parametric tests were required to assess change. In all control-impact comparisons, the non-parametric Mann–Whitney *U* test was used to compare changes in streambank erosion rates at a 10% significance level. In all before-after treatment comparisons, the non-parametric Wilcoxon Signed-Rank Test was used to compare changes, also at the 10% significance level. The Wilcoxon Signed-Rank Test is best suited in situations where repeated data are collected on the same experimental unit, as is the case in the before-after comparisons, while the Mann–Whitney *U* test is best suited for assessing differences in two independent groups, such as the control-impact scenario. The null hypotheses tested by the Mann–Whitney *U* test and the Wilcoxon Signed-Rank Test were that the bank erosion rate samples are from the same population and are not different (Weaver et al., 2017). Because the erosion data were not normally distributed, median values are presented and compared rather than average rates.

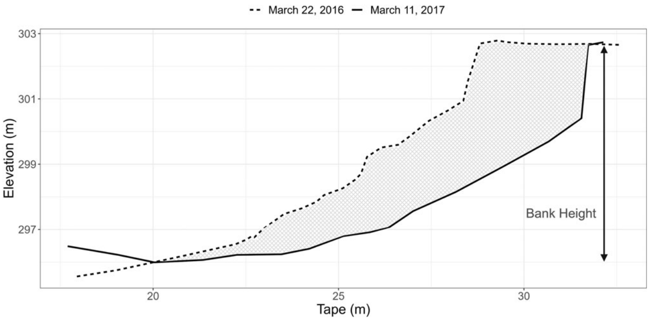


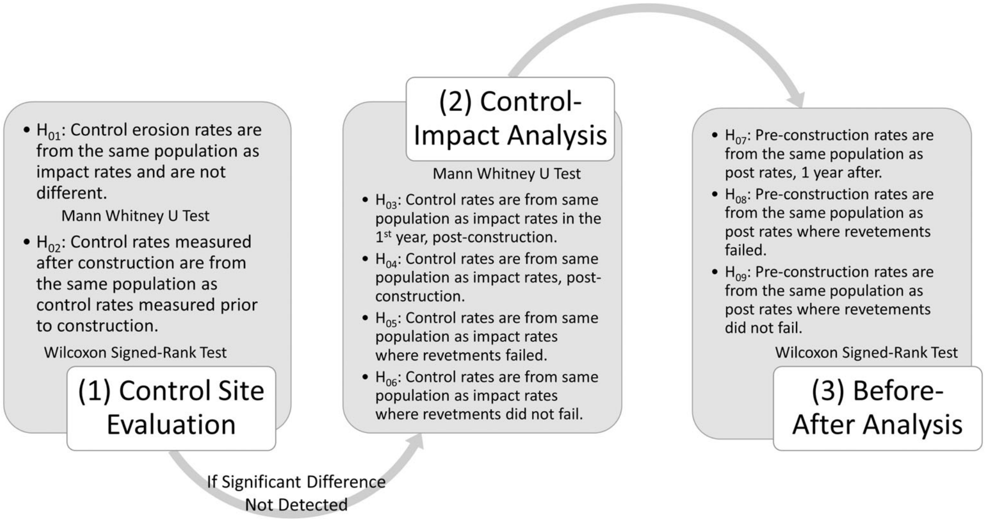
FIGURE 3 Example of area (in crosshatch fill) between two surveys of an eroding streambank (solid and dashed lines), bank height and dates used to calculate the average lateral retreat rate at site C4 on the Lower Smoky Hill River.

3.1 | Flow analyses

The Mentor USGS stream gage (USGS 06866500), located 17 river km downstream from the last measured cross section (R4-2), was used to evaluate flows experienced during the study period. Flow data were downloaded in 15-min intervals from the start of the study period (14 March 2016) to the end (7 September 2020) and divided into the three assessment periods: 2016–2017 (pre, period 1), 2017–2018 (post, period 2) and 2018–2020 (post, period 3). In addition, 15-min increment flow data were downloaded from 1 October 2007 (start of data collection at the Mentor USGS gage) until 30 September 2020. These flow data were denoted as period 4 to quantify and compare long-term median flows to those experienced during the assessment period. Since flow data were not normally distributed, the Kruskal–Wallis test was used to determine if there was a significant difference in median flow across the three study periods (Weaver et al., 2017). In addition, a flood frequency analysis was conducted to determine the annual exceedance probability of the largest flow that occurred during the study period. The observed annual peak flows from 1949 to 2021 at the Mentor USGS gage were used to determine peak flow return intervals, based on a Log-Pearson Type III analysis.

3.2 | Streambank stratigraphy

Since streambank stratigraphy and physical properties have a large effect on bank erosion rates (Simon et al., 2000), soil properties of



(1) Control Site Evaluation

- H_{01}: Control erosion rates are from the same population as impact rates and are not different.

Mann Whitney U Test

- H_{02}: Control rates measured after construction are from the same population as control rates measured prior to construction.

Wilcoxon Signed-Rank Test

If Significant Difference Not Detected

(2) Control-Impact Analysis

Mann Whitney U Test

- H_{03}: Control rates are from same population as impact rates in the 1st year, post-construction.
- H_{04}: Control rates are from same population as impact rates, post-construction.
- H_{05}: Control rates are from same population as impact rates where revetments failed.
- H_{06}: Control rates are from same population as impact rates where revetments did not fail.

(3) Before-After Analysis

- H_{07}: Pre-construction rates are from the same population as post rates, 1 year after.
- H_{08}: Pre-construction rates are from the same population as post rates where revetements failed.
- H_{09}: Pre-construction rates are from the same population as post rates where revetements did not fail.

Wilcoxon Signed-Rank Test

FIGURE 4 Null hypotheses and statistical tests applied to evaluate effectiveness of deciduous tree revetments in reducing streambank erosion rates.

representative streambanks were collected to obtain soil texture (USDA classification), bulk density, cohesion, friction angle, critical shear stress and erodibility. A Gidding's soil probe was used to obtain a core sample of streambank material down to a depth of about 4 m at one control site (C1), and three stabilized sites (R1, R2 and R3). These sites were selected as they appeared to be most representative of all cross-sectional stratigraphy, with R1 being representative of C2 and C3, and R2 being representative of C1, and R3 and R4 being representative of C4. A Borehole Shear Tester (BST), developed by Handy Geotechnical Instruments, was then used to obtain in situ shear strength measurements of cohesion. The BST was operated at 20, 30, 40 and 50 kPa normal stress to obtain the resultant maximum shear stress (kPa) for each observed layer. Data were then graphed with normal stress on the x-axis and shear stress on the y-axis to obtain the Mohr–Coulomb failure criterion using linear regression. The fitted line through the measured points provides the cohesion (c', y-intercept) and the friction angle (Φ', slope of the line in degrees). Erodibility parameters of the two streambank layers were also obtained in situ using a mini-JET. A mini-JET is a smaller version of the original Jet Erosion Test (JET) developed by Hanson (1990), and can obtain in situ estimates of critical shear stress (τ_c) by impinging a jet of a known pressure perpendicular to an erodible surface and measuring the scour hole depth the jet creates overtime until an equilibrium depth is obtained. Two mini-JET tests were conducted per streambank layer at 13.8 kPa to obtain average erodibility parameters. Scour over time measurements were then converted to erodibility parameters using the Blaisdell method (Hanson & Cook, 2004).

3.3 | Force balance assessment

Improper anchoring of large wood structures has been reported as the primary failure mechanism in several case studies of large wood structures (e.g., Miller & Kochel, 2013; Russell et al., 2021; Shelley et al., 2022; Shields et al., 2006). Therefore, a large wood (LW) design spreadsheet developed by Rafferty (2017) was used on the designed deciduous tree revetments (Figure 1) to assist in conducting vertical (i.e. buoyancy), horizontal (i.e., drag) and moment force balance analyses. A LW structure is considered stable based on a user-selected safety factor (SF, ratio of resisting to applied forces). Rafferty (2017) recommends using a SF of at least 1.5 for low-energy systems, such as the Lower Smoky Hill River. The tool requires field data input such as flow parameters (e.g., design discharge, maximum depth, average velocity, meander radius of curvature, bankfull width), streambed and bank material gradations, LW species and their associated dry and green unit weights, type(s) of wood structure (e.g., flow deflector, jam, etc.) and geometry and proposed channel geometry. With these inputs, a SF can be computed and then adjusted, if necessary, by adding specified anchoring techniques (e.g., ballast, mechanical anchors, etc.).

For this analysis, the highest flow event during the study period was used as the design discharge. In addition, measured flow velocity and discharge data from the downstream Mentor USGS gage were used to estimate the average velocity during the selected design discharge. The Rafferty (2017) tool incorporates the average velocity to estimate the expected velocity at the meander bend using the Lagasse et al. (2009) equation that accounts for the R_c/W_{bkf} ratio of the meander bend of interest. Each deciduous tree revetment system used hackberry (*Celtis occidentalis*) footer logs with at least one of the following as the protruding deciduous tree revetment throughout the reach: black walnut (*Juglans nigra*), Osage orange (*Maclura pomifera*), American elm (*Ulmus americana*), green ash (*Fraxinus pennsylvanica*) and/or hackberry trees. Each footer log was anchored with an American Earth Anchor 3AL-60CC duckbill anchor. This information was input into the Rafferty (2017) tool to assess deciduous tree revetment stability.

4 | RESULTS AND DISCUSSION

Table 2 summarizes streambank erosion rates measured at four reaches stabilized with deciduous tree revetments (10 cross sections total) and within four control reaches (seven cross sections total), both pre- and post-installation. Deciduous tree revetments began to wash away within the first year following installation on Sites R3 and R4 (5 of the 10 stabilized cross sections). Within 3 years post-installation, all four treatment sites had been completely washed out (Sites R1 and R4) or damaged (Sites R2 and R3). Resurveys could not be conducted at all sites in 2020 due to system-wide lateral retreat, resulting in loss of monumented control pins. Figure 5 provides a time-lapse photo series of Site R3, which had lost five of nine deciduous tree revetments by 2020 (3 years post-installation).

Since deciduous tree revetment projects were damaged or destroyed within 3 years following installation, it was apparent that using these structures in this manner was not a long-term solution to manage bank erosion on the Lower Smoky Hill River. However, the question remained: Did the tree revetments result in a temporary decrease in bank erosion rates prior to being damaged? In addition, a new research question was raised in observance of revetment failure: Did installing deciduous tree revetments cause bank erosion rates to increase? To answer these questions, pre- and post-installation bank erosion rates were analyzed, as summarized in Figure 4. Results of these analyses are provided in Table 3.

The control site erosion rates were first evaluated to determine if measured rates were representative of the stabilized sites (pre-installation, H_{01}), as well as over the entirety of the study period (H_{02}). Results indicate that erosion rate differences between control sites and stabilized sites prior to installation, as well as erosion rates at the control sites from the pre- to post-installation periods were not statistically significant (Table 3). This lack of difference allows for a more robust comparison of erosion rates between control and stabilized (post-installation) sites, as control sites are representative of natural erosion rates.

Next, the measured lateral retreat rates between the control sites and the tree revetment sites were evaluated. Statistically significant differences in bank erosion rates were not detected between the

FIGURE 5 Deciduous tree revetment site R3 (a) Pre-installation in 2016, (b) Immediately following installation in 2017, (c) 1-year post-installation in 2018 and (d) 3 years post-installation in 2020 with only four deciduous tree revetments (of nine) remaining. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Results of statistical analyses conducted to detect significant changes in bank erosion rates pre- to post-installation of deciduous tree revetments.

	Hypothesis	Observations (from years)	Population medians	Test	*p*-value
Question 1	H$_{01}$	Control (16–17)	Control: 0.41 m/yr	Mann–Whitney *U* test	0.6961
		Stabilized (16–17)	Stabilized: 0.40 m/yr		
	H$_{02}$	Control$_B$ (16–17)	Before: 0.41 m/yr	Wilcoxon Signed-Rank test	0.4688
		Control$_A$ (17–20)	After: 0.29 m/yr		
Question 2	H$_{03}$	Control (17–18)	Control: 0.29 m/yr	Mann–Whitney *U* test	0.6254
		Stabilized (17–18)	Stabilized: 0.14 m/yr		
	H$_{04}$	Control (16–20)	Control: 0.48 m/yr	Mann–Whitney *U* test	0.7170
		Stabilized (16–20)	Stabilized: 0.34 m/yr		
	H$_{05}$	Control (16–20)	Control: 0.48 m/yr	Mann–Whitney *U* test	0.0708
		Stabilized (17–20)	Stabilized: 1.26 m/yr		
	H$_{06}$	Control (16–20)	Control: 0.48 m/yr	Mann–Whitney *U* test	0.0327
		Stabilized (17–20)	Stabilized: 0.07 m/yr		
Question 3	H$_{07}$	Before (16–17)	Before: 0.40 m/yr	Wilcoxon Signed-Rank test	0.5173
		After (17–18)	After: 0.14 m/yr		
	H$_{08}$	Before (16–17)	Before: 0.54 m/yr	Wilcoxon Signed-Rank test	0.0938
		After (18–20)	After: 1.08 m/yr		
	H$_{09}$	Before (16–17)	Before: 0.40 m/yr	Wilcoxon Signed-Rank test	0.5469
		After (17–18)	After: 0.09 m/yr		

Note: Rates that were significantly different (*p*-value <0.1) are highlighted in grey. Hypotheses (H$_0$) are provided in Figure 4. $_B$: Rates observed prior to installation of stabilized sites; $_A$: Rates observed after installation at stabilized sites.

control sites and all of the tree revetment sites during the 2017 to 2018 post-installation monitoring period (H$_{03}$). Furthermore, erosion rates measured at control sites and the tree revetment sites for the entire post-installation monitoring period were not statistically significant (H$_{04}$). This suggests that installing tree revetments did not substantially reduce bank erosion rates overall. However, since some deciduous tree revetments failed early on, the question arose if these failures may have skewed the control versus treatment analysis. Therefore, two more hypotheses were tested to determine how measured bank erosion rates at cross sections with revetment failures and cross sections without revetment failure compared to control site erosion rates (H_{05} and H_{06}). Both of these tests indicated there was a significant difference in bank erosion rates between tree revetment cross sections and control cross sections. At stabilized cross sections where tree revetments remained intact, bank erosion rates were significantly lower (*p*-value <0.05) than control cross sections. Conversely, at stabilized cross sections where tree revetments were washed away, bank erosion rates were significantly higher than control cross sections (*p*-value <0.1). These results indicate tree revetments are capable of reducing bank erosion rates on the Lower Smoky Hill River but only while revetments are in place. However, once tree revetment failure occurs, tree revetments cause bank erosion to worsen.

Finally, average lateral retreat rates were compared pre- to post-installation of deciduous tree revetments at stabilized cross sections. The assumptions of the Wilcoxon Signed Rank Test require paired data comparisons, meaning that the same number of observations are compared across the before and after categories. To maximize the number of observations in the statistical analysis, the study periods with the most observations before (2016–2017) and after (2017–2020) revetment installation were used. With respect to the latter, the 2017–2018 timeframe was chosen for comparison as all cross sections were surveyed and paired with measurements from the before time range (2016–2017). The results from this comparison show that there was not a detectable difference between erosion rates before and after tree revetment installation (H_{07}), similar to the control-impact analysis discussed previously. However, given the results of separating failure and no failure cross sections in the control-impact analysis, bank erosion rates were also separated to compare sites with and without failures.

Pairing erosion rate data, as well as maximizing the number of observations, is important to implement the Wilcoxon Signed Rank Test to effectively detect change. Because the 2017–2018 timeframe had the most revetments still intact, this timeframe was used to compare to pre-installation rates at the same cross sections. Alternatively, the 2018–2020 timeframe had the most revetment failures. In the comparison of before to after bank erosion rates at cross sections with revetment failures, the 2018–2020 rates were compared to the 2016–2017 pre-installation rates at the same cross sections (H_{08}). The results from this analysis agree with the control-impact analysis for cross sections with revetment failures in that the erosion rates before installation of tree revetments were significantly less than at sites where tree revetments failed (*p*-value <0.1). By contrast, while the median erosion rate at stabilized sites with tree revetments still intact was less than the median before-installation rate, it was not significantly different (H_{09}, *p*-value> 0.1). These results support the previous finding from the control-impact analysis that installing tree revetments may or may not cause bank erosion to decrease prior to failure but following failure, causes accelerated lateral retreat that likely would not have occurred otherwise.

These results are similar to those obtained by Russell et al. (2021) on the Cedar River in Nebraska in the United States, where tree revetments (or jetties), similar to those installed on the Lower Smoky Hill River, were monitored over a 12-year period. The researchers found that if tree revetments remained fully or partially functional, bank erosion decreased following installation, supporting the finding that deciduous tree revetments installed on the Lower Smoky Hill River may have decreased bank erosion in the short term. However, in the case of revetment failure, Russell et al. (2021) also found that bank erosion was exacerbated, above pre-installation rates. To further evaluate the results obtained on the Lower Smoky Hill River, flow events experienced, bank stratigraphy differences, meander planform characteristics and structure force balance assessments are discussed and incorporated into this analysis in the following discussion sections.

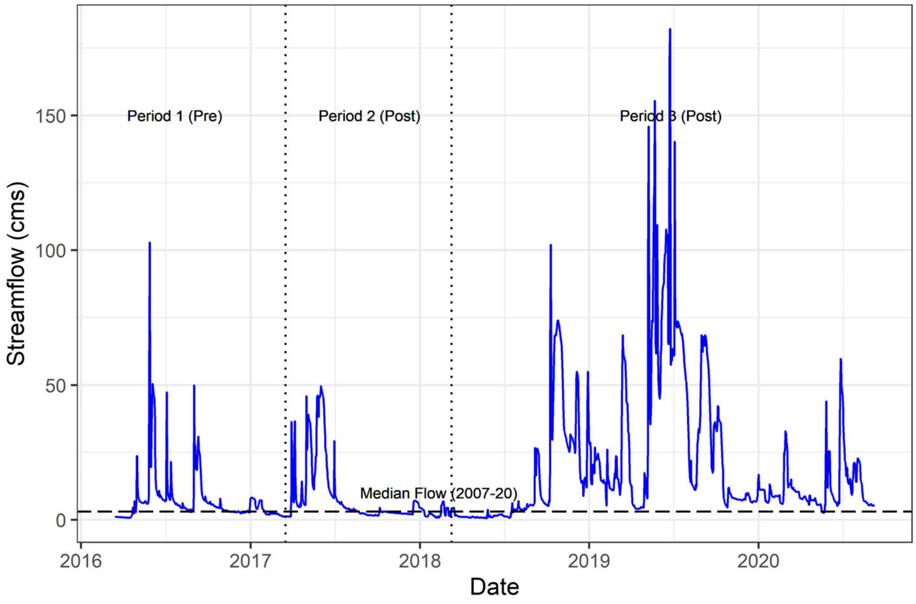


FIGURE 6 Flows experienced (blue, solid line) during the study period, March 2016 to September 2020. Dashed line represents median flow (2007–2020, 3.03 m^3/s) and the dotted lines mark survey dates. [Color figure can be viewed at wileyonlinelibrary.com]

5 | FLOWS EXPERIENCED

The flows experienced during the study period are graphed in Figure 6. Based on Kruskal–Wallis test, there was a significant difference in median flows between one or more assessed periods (*p*-value <0.01). The pairwise Wilcoxon test was used to further assess differences between the assessed periods. The pairwise Wilcoxon test is similar to the Mann–Whitney *U* test but incorporates the Benjamini and Hochberg (1995) adjustment for multiple treatments. The pairwise Wilcoxon test indicated that median flows of all four periods were significantly different from each other (*p*-value <0.01), with the highest observed flows occurring in the 2018–2020 post-installation period (median = 7.87 m^3/s, period 3), followed by 2016–2017 (median = 5.44 m^3/s, period 1), followed by the long-term median flow from 2007 to 2020 (= 3.03 m^3/s, period 4) and finally 2017–2018 (median = 2.27 m^3/s, period 2). In addition, the highest flow experienced during the study period (191 m^3/s, Figure 6) occurred in the summer of 2019 and was estimated to be a 5-year return interval discharge based on a Log-Pearson Type III flood frequency analysis.

The control-impact assessments shown in Table 3 are inherently robust against flow variability as erosion rates from control-impact assessments are typically measured during the same time periods with generally the same flow events. Alternatively, the before-after assessments may have been affected by observed flow events. For example, the significant increase in erosion rates observed on streambanks with deciduous tree revetment failures (H_{08}) could be due to (1) the installation of the revetments, (2) the observed flow events during this timeframe or (3) both. Observed erosion rates at stabilized sites were lowest during the 2017–2018 period, or the timeframe with lowest observed flow events, and highest during the period with the highest observed flows (2018–2020), which could have affected the results of the statistical analyses for H_{07} through H_{09}.

6 | STREAMBANK STRATIGRAPHY

Site characteristics, primarily bank material composition, would have also affected observed erosion rates. Figure 7 summarizes the bank stratigraphy analyses. Based on these results, the control sites, C1 and C2, were characterized by the highest values of cohesion and critical shear stress, meaning that these streambanks were inherently more resistant to fluvial erosion than all other sites evaluated. The other two control sites, C3 and C4, were more like R1 and R3, respectively, with similar bank stratigraphy as these two stabilized sites. However, as indicated in Table 3, when conducting the control site evaluation

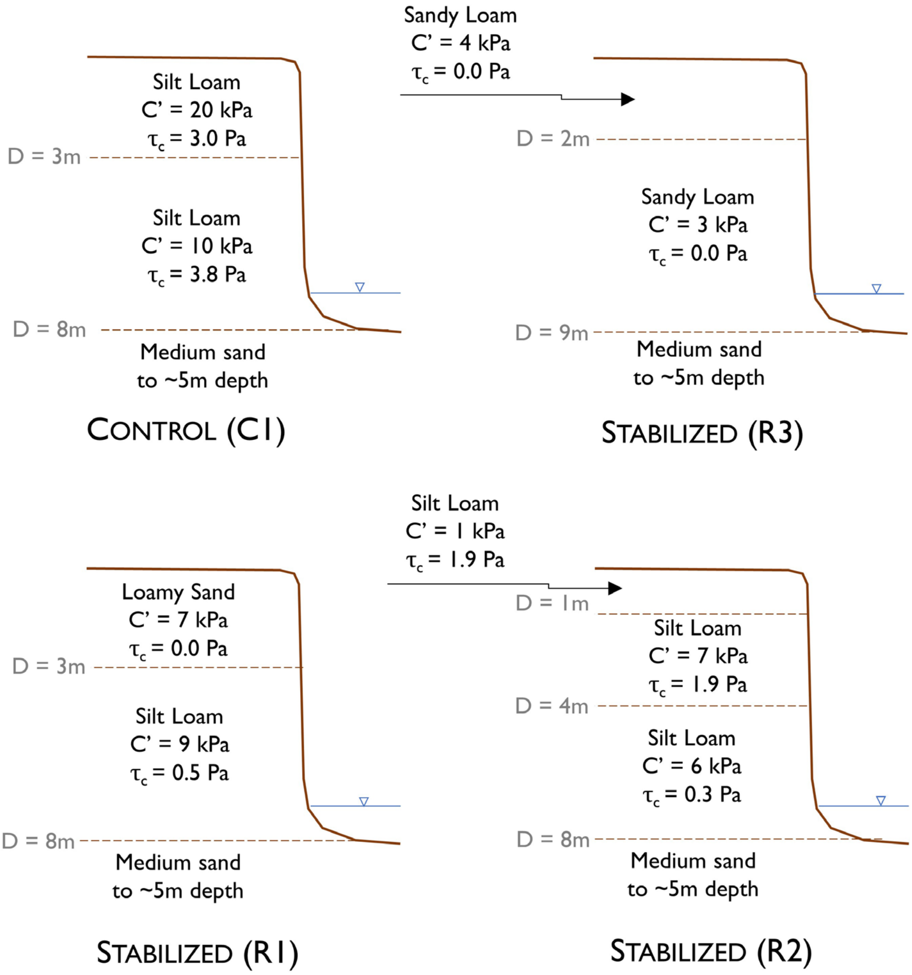


FIGURE 7 Streambank stratigraphy and streambed sediment profiles for representative streambanks on the Lower Smoky Hill River, Kansas. R1 is most similar to C2 and C3, R2 is most similar to C1, R3 and R4 are most similar to C4. Soil texture: USDA classification; c': Effective cohesion; τ_c: Critical shear stress; D: Depth. [Color figure can be viewed at wileyonlinelibrary.com]

(H_{01} and H_{02}), significant differences in bank erosion rates were not observed, suggesting that the mixture of control sites was suitable for the purpose of this comparison.

When considering the soil physical properties at the stabilized sites, low cohesion values (3–9 kPa), as well as low estimated critical shear stresses (0.0–1.9 Pa), explain both the need for streambank stabilization at these sites as well as their susceptibility to project failure. The sites containing higher percentages of sand are especially vulnerable (sites R3 and R4). Construction activity that involves filling excavated trenches with compacted lifts, as was the case for this project, may have unintentionally accelerated bank erosion along sites with sandy loam or loamy sand soils. In other words, these data support the observation in Table 3 that the installation and failure of deciduous tree revetments resulted in accelerated bank erosion, especially along sites with high sand content soils, as construction activities would have disturbed the overall soil structure increasing its susceptibility to fluvial erosion. Erosion rates measured at Sites R3 and R4 provide an example of this. Erosion rates prior to construction activities at these sites were comparable to sites containing more silt and clay material (2016–2017, Table 2). However, following installation of woody revetments, erosion rates increased at both sites during the 2017–2018 period (the lowest median flow during the overall study period) while they decreased at C4, the control site containing the most similar materials.

7 | MEANDER PLANFORM

Past research has explored how meander planform (i.e., meander radius of curvature) affects stream migration and bank erosion rates by increasing applied hydraulic shear stresses (Lagasse et al., 2009; Moody, 2022; Zhao et al., 2021). Often, the R_c/W_{bkf} ratio is used to quantify the effects of meander planform on bank erosion rates (e.g., Lagasse et al., 2009; Moody, 2022; Rosgen, 2009). Rosgen (2009) notes that meander bends having a R_c/W_{bkf} of less than 2 tend to have a high applied shear stress. Table 1 provides a summary of these ratios for each meander bend assessed. Low R_c/W_{bkf} ratios of 2.1 and 1.5 provide further explanation as to why structures began to fail after the first year at sites R3 and R4, respectively.

8 | FORCE BALANCE ASSESSMENT

The highest discharge that occurred during the study period was used as the design discharge (191 m^3/s, Figure 6), which represented a 5-year return interval discharge. Using measured flow velocity and discharge data from the downstream Mentor USGS gage, an average velocity of 1.4 m/s was used to estimate expected velocity around a meander bend of interest. The Rafferty (2017) tool showed that all 22 installed revetments were predicted to have at least one force balance below a SF of 1.5 following a 5-year return interval flow event, with the moment force SF being less than 1.5 for all revetments. In addition, 10 of the 22 revetments had a SF less than 1.5 for buoyancy; however, it is noted that the majority of the structures containing hedge trees were not predicted to fail due to buoyancy, as these trees contain the highest wood density (55 and 65 lb/ft^3 for the specific dry and green weights of the wood, respectively) compared to the others used (typically 40 and 55 lb/ft^3 for dry and green weights of the wood, respectively). Finally, two of the 10 revetments that had SFs less than 1.5 for both moment and buoyancy forces also had a SF less than 1.5 due to drag. However, it is noted that a SF of less than 1.5 does not necessarily mean the structure will move but a SF of less than 1 does (applied forces > resisting forces). A total of eight of the 22 revetments had a SF less than 1. When comparing these predictions to what was observed, only six of the 22 revetments did not fail (two on R2 and four on R3) following the 5-year return interval flow in 2019, showing the validity of using the Rafferty (2017) tool in designing LW structures.

While a more comprehensive design (e.g., using the Rafferty (2017) tool) would have increased upfront costs, it would have saved money on maintenance or, in this case, replacement costs in the long run. Application and continued improvement of stream numerical modelling tools, such as the Rafferty (2017) tool, is imperative to advance the design of streambank stabilization projects, while also minimizing project failures and unintended impacts to streams on a reach- to watershed-scale (Bigham, 2020).

9 | CONCLUSION

Can deciduous tree revetments reduce streambank erosion rates on a sand-bed stream? In the case of the Lower Smoky Hill River and in the current design form, the answer is simply no. This case study showed that the use of deciduous tree revetments to stabilize streambanks, as described here, may reduce overall bank erosion in the short term (prior to failure) but likely accelerated bank erosion following failure, especially on streambanks containing a higher sand content. Accelerated bank erosion can be attributed to the disturbance of the bank profile through the revetment installation cut and fill process, increasing the bank profile's susceptibility to fluvial erosion, as well as improper anchoring to counter applied forces.

Even though the deciduous tree revetements described herein did not work in their present form, the use of wood structures cannot yet be ruled out as a possible, low-cost technique to stabilize streambanks along the Lower Smoky Hill River or similar river systems. Future designs should incorporate collecting in situ bank stratigraphy properties and using these data to assess design alternatives in numerical modelling software, such as HEC-RAS and the Rafferty (2017) LW design tool. These tools can be used to test various flow scenarios and to estimate in-channel shear stresses and thus, wood anchoring requirements. This case study establishes the importance of collecting and integrating site and flow condition analyses early on in the design phase to minimize failure. While costs of these additional analyses may be high upfront, proper use of available numerical modelling tools to test streambank stabilization designs should reduce overall maintenance or project replacements in the future.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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