**Dendrogeomorphology for *Post-hoc* Erosion Evaluation in Southern U.S. Prairie Streams**

**Running Title: Bank Erosion Derived from Tree Roots Supports Management of Rivers and Reservoirs**

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*Ethics and Integrity Statement:* All data produced and used for this study will be available through the Open Science Framework data repository through the Center for Open Science. Funding for the research was provided by the Glasscock Energy Research Endowed Scholarship Fund from the Department of Environmental Science at Baylor University. All authors listed on this manuscript that none have any conflict of interest, financial or otherwise that would inhibit their utmost objectivity regarding the data, the research, and findings of this study. All authors have approved this research as being ethical treatment of data and analysis. Figures presented in this manuscript are licensed through Joseph D. White with approval for publication.

**Acknowledgements**

We thank Mr. and Mrs. C. Gus Glasscock, Jr, that supported this research through the Glasscock Energy Research Endowed Scholarship Fund from the Department of Environmental Science at Baylor University.

**Abstract**

Streambank erosion impacts rivers and reservoirs due to bank erosion. However, little information of stream bank is available due to the need for advanced planning. Dendrogeomorphology offers a *post-hoc* method to calculate streambank erosion providing information about past erosion events and processes. Bank retreat can be calculated by dendrogeomorphology where the distance from a channel bank of an exposed live root shows anatomical changes that are dated from the root’s growth rings. We estimated bank erosion for three different sized southern U.S. watersheds ranging in area from 4 to 3781 km2 using dendrogeomorphology compared to modeled erosion based on critical velocity required for sediment transport. Erosion values ranging from 3.8 to 13.5 cm/yr for the smaller drainages with no difference found between root and modeled erosion rates. The large sub-basin had erosion ranging from 33.6 to 196.4 cm/yr with high variance associated with two prior 2-year flow events with significant differences found between root and modeled values. We also found distance to bank strongly and positively correlated with root exposure in straight sections of the channel in contrast to roots collected in meander bends attributed to erosion processes (i.e., scour, mass wasting) occurring at these locations. When compared with other erosion studies across the southern U.S. prairie, our values were similar in magnitude but with low correlation to drainage area indicating site specificity of erosion mechanisms. We confirm dendrogeomorphology provides reasonable estimate of bank erosion across multiple spatial scales, important for watershed management in areas lacking intentional and persistent monitoring.

*Keywords:* dendrogeomorphology; channel erosion; erosion modeling; Blackland Prairie; exposed tree roots

1. **Introduction**

Water scarce areas, such as the southern prairie regions of the U.S., are facing increasing pressure on water supply due to increased population and consumptive demand, climate change factors associated with precipitation and evaporation, and reservoir storage capacity. Of these, existing reservoirs capacity change is predominantly due to sediment loading from contributing watersheds (Wisser et al., 2013; Randle et al., 2021). Sediment management within the watersheds can mitigate reservoir storage decline (Aptiz and White, 2003; Noe et al., 2020) with potentially reduced nutrient loading and improved riverine and lotic ecosystem function (Erol and Randhir, 2013). However, knowledge of past and current watershed erosion and sediment yields is generally unknown.

The southern prairies of the U.S. have been historically subjected to extreme weather shifts from drought to wet, with a trend more recently for larger areas having extreme rainfall during wet periods (Flanagan and Mahmood, 2023). These prairies are water scarce with past human use mostly reliant on groundwater that, with aquifer depletion, is increasingly shifting to surface water (Zou et al., 2018). The importance of surface water in this area highlights the importance of reservoir storage capacity. Within the U.S. southern prairies region, surface reservoir storage has declined by <0.1 to 2.0 % per year as a direct result of watershed sediment yield associated with intensive agricultural land use (Graf et al., 2010). In Texas, it is estimated that major reservoirs lose up to 111.0 × 106 m3 per year due to sedimentation; an amount equal to 5.5 × 109 m3 by 2060 (TWDB, 2007). Continued climate change will likely exacerbate sediment yields as drought/wet periodicity intensifies (Rahmani et al., 2018).

Since 1992, the biennial U.S. National Water Quality Inventory Reports (Section 305(b) Report to Congress) have ranked sediment and nutrient loading as the leading causes of water-quality impairment of rivers and lakes (Langendoen et al. 2012). Studies show streambank erosion contributes 37-80% of the suspended sediment in river systems (Simon and Thorne, 1996, Walling et al., 1999, Lai et al. 2012). However, quantifying bank erosion is difficult because it requires intensive sampling, planning, and long-term monitoring.

Channel erosion rates are generally unknown for many areas as data must be collected over long periods of time. Measurement techniques, such as erosion pins, which are typically monitored less than 5 years, may be inaccurate because intermittent channel erosion events may be missed (Couper et al, 2002, Pizzuto et al., 2009, Lawler 1993). Length of observation is important because acute, low frequency erosion events, such as bank failure culminate in the observed overall changes in stream geomorphology (Hooke, 1979, Nanson and Hickin, 1983, Brasington et al. 2003, Donovan and Belmont, 2019). Longer term observation from historical aerial photography may be achieved with erosion inferred from mapped channel migration (Pyle et al. 1997; Miřijovský et al., 2015) though typically at a coarse temporal resolution. More recently, unmanned small aircraft system (i.e., drone) platforms used to capture aerial imagery, have been coupled with structure from motion image processing techniques, to refine bank mass loss estimates (Duró et al., 2018). However, this method is still limited by pre-planning required for multi-temporal monitoring.

Alternatively, dendrogeomorphology has been shown as a promising method to overcome the challenge of *post-hoc* analysis of streambank erosion. Dendrogeomorphology is the study of geomorphic processes including bank erosion that is based on analyzing growth anomalies in tree rings (Alestalo, 1971; Shroder, 1980). In tree roots, annual growth rings change appearance after exposure to dry air with vessel changing anatomically from large, dispersed, diffuse-porous vessel wood to small, dense, ring-porous vessels (Fayle, 1968). Annual growth rings in exposed roots also show higher variability in ring widths, bending rays, and scar tissue (Schweingruber et al. 2007, Stoffel & Bollschweiler, 2009). By analyzing the anatomy in cut sections of exposed roots (root slabs) collected along stream channels, dates of erosion of hydrologic paths are determined by counting growth rings from the outer most ring to the ring that shows the growth anomaly (e.g., Stoffel et al., 2013, Vandekerckhove et al., 2001, Corona et al., 2011). Tree type is important, as conifers most are frequently used for dendrogeomorphological analysis, because of the ease in identifying root anatomical changes (Franco‐Ramos et al., 2021; Gärtner et al., 2001; Malik and Matyja, 2008; Bodoque et al., 2011). For angiosperms, only ring-porous species can be used due to their characteristic ring structure in response to seasonal water availability (Tichavský et al., 2018; Dick et al., 2014; Stotts et al., 2014, Hitz et al., 2008). Dendrogeomorphology has emerged as a reliable and valuable tool for estimating channel erosion particularly in unmonitored watersheds capturing the history of stream erosion in a single sampling campaign (Stoffel at al., 2013; Noe et al. 2022).

In this study, we assess the erosion rates for three different stream systems across a broad range of contributing watershed areas. Using the dendrogeomorphic method, we estimate erosion from wood anatomy of native riparian tree roots sampled along urban and rural streams. Root-based and modeled erosion rates are then compared to assess factors influencing erosion as indicated by differences between these methods. We then compare our erosion to published values for other U.S. prairie streams to better understand regional erosion trends in this water limited area and provide consensus on stream bank loss particularly important for management of streams lacking observed data.

1. **Study Area**

Three watersheds located within the Trinity and Brazos River Basins in central Texas, USA were selected in this study. These watersheds are part of the southern portion of the Great Plains ecological region of North America that includes the Blackland Prairie and Oak Woods & Prairies natural regions (LBJ School of Public Affairs, 1978). The climate in this area is characterized as humid subtropical with annual average temperature of 19°C and 96 cm of precipitation.

The smallest watershed, Cedar Creek (32.6543°N 97.0084°W), is a first order tributary located in a heavily urbanized suburban city that is part of the Dallas-Fort Worth metroplex. Water from this drainage contributes to the Mountain Creek Lake reservoir, a small lake used for cooling a local electric generation plant. The Cedar Creek watershed covers 4.0 km2 and is underlain by a Cretaceous shale formation that dips gently to the southeast (Allen and Flannigan, 1986). The alluvial channel banks consist of cohesive silty clay (35%). The stream bottom is comprised of shale and marl bedrock fragments, limestone gravel, and cobbles that occur in riffles, while clay and sand-sized particles compose the bed material between riffle segments. The section of Cedar Creek studied is 1.1 km long with an average slope and sinuosity of 0.0058 m/m and 1.4, respectively. This section of Cedar Creek has an average channel width of 2.5 m and depth of 2.5 m.

The second watershed studied is drained by a third-order stream, Mill Creek, situated in a rural, agricultural-dominated landscape located approximately 12 km east of Italy, Texas, USA. The Mill Creek watershed has a total drainage area of 203 km2 and contributes to the Richland-Chambers reservoir, a large water body providing water to the large metropolitan city of Ft. Worth, Texas, and surrounding municipalities. The Texas Water Development Board (2009) estimates that the Richland Chambers Reservoir loses 2.5 × 106 m3 capacity a year; it is estimated that 85% of the sediment is from channel erosion such as Mill Creek (Wang, et. al. 2010). The stream segment studied for Mill Creek (32.1470°N 96.7797°W) is underlain by a Cretaceous age unit composed of calcareous clays with small amounts of fine sand that dips gently to the southeast. The soils of the channel banks are composed of fine-grained silty clays (50%) with the channel bottom largely barren and devoid of loose materials that consists of exposed clay-rich soil. The slope and sinuosity of the studied portion of the Mill Creek is 0.0021 m/m and 1.12, respectively, with an average channel width of 7.0 m and bank height of 3.5 m.

The third watershed study was in the lower section of North Bosque River, a tributary of the Brazos River, that passes through Erath, Hamilton, Bosque, and McLennan counties within the state of Texas, U.S.A. The drainage area of the watershed is approximately 3200 km2 and empties into Waco Lake reservoir. The North Bosque the watershed provides approximately 70% of the water stored in the reservoir and is the major source of drinking water for the city of Waco, Texas, and surrounding cities. The underlying geology of the North Bosque River is composed predominantly of alternating Cretaceous sand and limestone formations dipping gently to the southeast. The geologic unit of the section of the river we studied (31.8525°N 97.4886°W), located approximately 20 km upstream of the Waco Lake reservoir, is composed of marly limestones, and shell beds ( Procter, 1969). The soils of the banks of this section are composed of loamy and clay (35%) alluvium derived from overbank floodplain deposits. The channel is composed of exposed bedrock and alluvial gravel beds with an estimate slope of 0.0006 m/m, a sinuosity of 1.27, channel width of 54 m, and an approximate height of 4.0 m from the minimum thalweg depth to the top of within channel gravel beds. The height to top of the channel and floodplain is an average 8.0 m with both channel heights were derived from lidar data with a 1 m spatial resolution (StratMap, 2020).

1. **Methods and Materials**

*3.1 Tree Root Sampling, Preparation, and Analysis*

We collected samples consisting of 10 to 15 cm cross sections cut from exposed tree roots, known as root slabs, from selected sections of the three streams located near the outlet of the watersheds (Figure 1). Of these slabs, 50 were from Cedar Creek, 29 from Mill Creek, and 19 from the North Bosque River. Tree species of collected roots were identified by locating the tree closest to the cut root and by visual examination of the wood. Species included: green ash(*Fraxinus pennsylvanica*), Texas ash (*F. texensis*), cedar elm (*Ulmus crassifolia*), American elm (*U. americana*), common hoptree (*Ptelea trifoliata*)*,* net leaf hackberry (*Celtis laevigata*), burr oak (*Quercus macrocarpa*), Osage orange (*Maclura pomifera*), Eastern cottonwood (*Populus deltoides*), hardy pecan (*Carya illinoinensis*), and boxelder (*Acer negundo*). All species selected were considered to have ring-porous wood based on stem wood anatomy with well-defined annual rings suitable for chronology (Figure 2). Samples from exposed root were collected > 1 meter from the trunk to minimize tree ring distortion associated with primary stem anatomy (Bodoque et al., 2011). The horizontal distance to the streambank was recorded for each root sample as a measure of channel erosion for that location.

Next, root samples were prepared for analysis by first being placed in a drying oven at 60° C for approximately 4 days to eliminate moisture. After drying, samples were cut into 3 to 6 cm discs with a circular saw and hand sanded using continually finer grained sandpaper until ring anatomy was visible when viewed through stereo microscope (Phipps, 1985). Erosion rates were determined for each sample where exposure could be anatomically evaluated. Wood-anatomical changes were identified microscopically (Figure 3). Once this wood morphology change was identified, total years of exposure was calculated by subtracting the number of annual tree rings since anatomical change from the current year. False rings, incomplete ring triggered by an abrupt change in weather during the same year (Stokes and Smiley, 1968), were identified and excluded from the ring counts.

Samples were collected along bank heights considering to be submerged at flows associated with effective flow rates that are associated with the duration of 1-year flow events (Q1) for all streams sampled. In addition, data on height above stream bottom the root was collected, channel top width, side-slope, and height were also recorded for each channel as inputs for erosion rate modeling (Gärtner, 2007). We then estimated channel erosion rate based on the horizontal distance of the root to the channel bank, divided by the number of annual rings since root exposure; calculated as:

where (cm/yr) is the root-based erosion rate, (cm) is the horizontal distance to the streambank and is the time span of exposure (years).

*3.2 Streambank Erosion Modeling*

In the absence of other extensive erosion measurements for our study watersheds, we used modeling as an alternative method. Bank erosion modeling has a long history involving statistical, analytical, and mechanistic approaches (c.f., Borelli et al., 2021; Keane et al., 2017; Rinaldi and Darby, 2007; Rosgen, 2001). Bank erosion modeling is complex and model structure must reflect the quality and availability of spatial data. For watershed scale models, the scale of data is dependent upon regionally collected data such as the USDA, NRCS soils data, NHDplus topographic data, and NOAA weather data to populate the model. Recent work by Das et. al. 2020 illustrates the complexity of meandering channels under the action of secondary currents, flow separation, and strong intermittent turbulent stress. To simplify computations, turbulent stresses that determine erosion are a function of streamflow with streambank erosion occurring at a critical velocity associated with bank material cohesiveness (Partheniades, 1965; Schumm, 1973; Ramadan et al., 2003; Wong et al., 2015). In Briaud and Montalvo-Bartolomei (2017), bank erosion is presented as a power function representing the ratio of stream velocity ( m/s) to critical velocity ( m/s):

where is the erosion rate (m/s), is a baseline erosion rate at critical velocity (m/s), and is the power coefficient associated with erosion rates associated with stream velocity for different soil texture types presented graphically by Briaud (2013). The value of was originally estimated by Briaud and Montalvo-Bartolomei (2017) as 2.78 × 10-8 m/s and was used in this study.

Without stream gauges at each study site, stream velocity was estimated based on the flow analysis assuming a trapezoidal channel based on the method by Guo (1999) utilizing input parameters of channel width, bank slopes, the channel slope, and an estimate of the Manning’s n value for each stream section (Table *1*). These channel morphological parameters were measured in the field from the studied stream sections for the three watersheds. The Manning’s n value was assigned based on in-channel characteristics described by Chow (1959). Using the method by Guo (1999) the values for Cedar and Mill Creeks were estimated using maximum channel height on the assumption that effective flow results achieve bank full conditions resulting in the finest sediment movement over time (Sholtes and Bledsoe, 2016). This flow corresponds to a one-year frequency flood events for these relatively small watersheds (Phillips, 2015). For the North Bosque River, the 1-year flood discharge corresponded to the depth associated with the maximum height of point bars rather than the channel height given that the higher frequency lower flow events would not be displacing or moving gravels and cobbles (Naito and Parker, 2019). The average height of the alluvial point bars was determined from an airborne lidar- digital elevation model with a 1 m spatial resolution (USGS, 2016). The channel width for calculating the Q1 flow was determined from a field survey of the studied segment, measuring average widths from the point bar to the opposite bank (Table *1*). The flow velocity for the North Bosque River at the full channel height was also determined due to the occurrence of two larger (Q2+) flood events that occurred between 2018-19 in this watershed prior to the root slab collection for which stage height reached or exceeded the maximum channel height (Figure 2). The channel width for this flow was based on the average maximum width of the entire channel for the studied segment (Table *1*).

Next, critical velocity () for straight channels was calculated from Hoffmanns and Verheij (2021):

where is the flow depth (m), is the bulk density at a matric potential of -33 kPa of the bank substrate (kg/m3), is the density of water (kg/m3), is the gravitational acceleration (m/s2), and is the soil cohesion (Pa). The bulk density values of the stream segments of each studied watershed were acquired from the SSURGO soil database (Soil Survey Staff, 2022).

For meandering channels, was adjusted for increased velocity and shear associated with channels bends. This adjustment was taken from Thorne and Abt (1993) in which the ratio of the average channel velocity to the velocity at the toe of the outer bank slope is a function of the meander radius of curvature () and the channel width () calculated for meandering sections in which the upstream entry is either straight or meandering. For straight channel entry:

and for meandering entry:

Because all stream sections were composed of both interpreted straight and meandering entries, both ratios were calculated for each stream section using the measured channel widths with the calculated by the sinuosity () for each stream by (Williams,1986; Soar and Thorne, 2000):

The ratios calculated for both straight and meandering entry were then each multiplied by the for the stream sections, which then used to calculate bank erosion for both meandering entry types. The final calculated for the meander was the median of the straight and meander entry erosion values based on the two velocity calculations.

Cohesion can be determined through laboratory geotechnical testing or *in situ* testing using pocket penetrometers or vane shear (Grabowksi, et. al, 2011). Cohesion values are highly variable in river channels with natural variability approaching plus or minus 220% (Samadi, et. al., 2009). Gregory and Baryou (2010) attribute this to weathering induced “softening” of the material over time due to shrink swell and freeze thaw processes as well as more time dependent variations in soil saturation and suction (Simon and Collison, 1002; Aubeny and Lytton, 2003) Varandega and Haigh (2014) indicate that cohesion can vary from 1.7 Kpa to 83.5 Kpa as the soil consistency changes from the Liquid limit to the Plastic limit. Watershed model complexity involves relating field cohesion to erosion susceptibility. In this model this is accomplished through the use of pedotransfer functions which allow transposition of cohesion to the spatial model platform. Clay content was chosen as the best variable to predict cohesion (Schjonning et. al., 2020; Dafalla, 2013).

For soil cohesion, critical shear stress () was initially determined for a range of soil clay content ( %) for standard USDA soil textural types (e.g., sandy loam, clay load, silty clay etc.) from Smerdon and Beasley (1961).

where is the soil type clay content (%). Next, soil cohesion was solved using the derived for the USDA soil types:

where is the critical Shields parameter for incipient motion (Pa) for a given particle size (). For this study, the bank soils were dominated by clay, thus the was set to a value of 0.033 and the was set to 0.004 (fine clay aggregates; Hoffmans and Verhjei, 2021). Finally, the percent clay content for the standard USDA soil types were fit to the derived values using a third order polynomial, , with calculated values of , , , and , allowing for cohesion to be calculated from local soil clay content and bulk density values. Based on the above approach, the cohesion generated by this equation should be considered cohesion with water contents above field capacity but below saturation. It was thought that this would be the cohesion level active during flood events. For the calculation of erosion, the coefficient was solved from the Briaud (2013) data by

using clay content ( %) of importance for deriving site-specific values for each stream section based on readily available soil textural data (SSURGO; Soil Survey Staff, 2022).

For each stream using field measured inputs and SSURGO-derived clay content and bulk density, an instantaneous bank erosion value () was calculated in m/s. However, to compare with the root-based erosion estimates (), the instantaneous modeled needed to be scaled to annual rates (; cm/yr). For this we determined the number of days of Q1 flow. Without gauge data at two of the studied watersheds, we aggregated data from studies on overbank flow for U.S. streams (Andrews, 1980; Endreny, 2007; Jacobson et al., 2019). From this analysis, the mean Q1 flow duration accounted for approximately 1% of the of the year or 3.65 (± 0.97) days. Annual modeled erosion was calculated by: where is the flow duration and 86,400 number of seconds per day. Using the mean and standard deviation values of the Q1 flow duration, we estimated average using a Monte Carlo simulation (n=30) to account for variability of flow duration derived from the broad dataset.

*3.4 Special Case: Flood Event*

Initial assessment of the root cores from the North Bosque River indicated that 7 of the root slabs had a single year of exposure. This was likely due to two major flooding events (Q2 – Q5) between October 2018 and June 2019 (Figure 4), indicated by a flow gauge station (USGS #08095200; 31.66960575°N -97.4694602°W) located approximately 2 km downstream from the studied section, occurred just prior to the root collection in July 2019. The number of days that the flow exceeded Q1.5, used as a threshold, was approximately 8.5 days. Therefore, we separated analysis of the root samples that had exposure >1 year, referred to as non-flood, and those with the 1-year exposure, referred to as the flood samples.

*3.5 Regional Erosion Observations*

Reported bank erosion values were collected from the literature as a source of comparison with the root-based estimates. Data were selected where bank erosion values, drainage area, and whether data collected during non-flood or flood periods were specifically reported, using only studies conducted within the Great Plains ecoregion of the U.S. Least-squares regression analyses were performed on log base 10 transformed data for the non-flood and flood data separately.

*3.6 Analysis*

A least-squares linear regression was calculated for horizontal distance to the streambank and length of exposure for the different channel locations for each studied stream section of each watershed. We then compared the straight and meander channel root-derived erosion rates () using unpaired Student’s *t*-test to investigate differences in erosion rates between roots collected at different channel locations. Finally, root and modeled stream bank erosion rates by channel type (straight v. meander) were assessed for Cedar and Mill Creek. All root samples collected for the North Bosque River were from a meandering section of the stream. For these erosion estimates, the non-flood and flood root and model results were analyzed using a Student’s *t*-test using raw values where data were normally distributed or natural log transformed to meet normality requirements. For regional analysis, comparisons were made with the published literature erosion rates from various U.S. prairies using different measurement techniques with linear regression models calculated based on reported drainage areas and erosion values.

1. **Results**

Of the 98 root samples from the 11 different species collected, rings displaying anatomical evidence of exposure were identified in 68 roots. For Cedar Creek, a total of 24 root sections were used with 12 that were collected from straight channel sections and with the remaining 12 collected from meander sections (i.e., cutbanks). For Mill Creek, 25 total roots were used with 14 of these collected from straight portions of the channel and 11 from meanders. The remaining 19 root specimens were collected from a meandering portion of the North Bosque River approximately 3 km northwest of the torn of Valley Mills, TX, USA. No root wood anatomical change could be detected for *M. pomifera and* *Q. macrocarpa* thus samples from these species were eliminated from our analysis. In addition, some specimens of the two elm species, *U. americana* and *U. crassifolia*, had poor ring structure making age determination difficult and therefore were not used for the study.

The horizontal distance to the streambank for all exposed roots ranged from 5 to 579 cm. For Cedar Creek, the time since exposure ranged from 1 to 19 years with an average exposure time of 7 years. For Mill Creek, root time since exposure ranged from 4 to 26 years with an average of 11 years. Of the North Bosque River roots, time since exposure ranged from 1 to 30 years. For the non-flood roots from the North Bosque River, the average time since exposure was 13 years.

The root horizontal distance to the streambank was moderately correlated with years since exposure for straight channel sections of Cedar (r2 = 0.83) and Mill Creek (r2 = 0.73; Figure 5a & b). However, root samples collected from meander sections of all streams, including those from the North Bosque River, were poorly correlated with distance to bank (Figure 5c). When dendrogeomorphic erosion rates () derived from sampled roots were analyzed by height of collection above the channel bottom, no clear pattern was found, except for roots taken from Mill Creek (Figure 6b).

The values for straight portions of Cedar Creek (4.9 ± 2.3 cm/yr) were significantly less than those for the meander portions (13.5 ± 7.9 cm/yr) (p<0.05). Similarly, the average of straight portions of the Mill Creek channel were also less than the meanders, with values of 3.8 ± 1.1 and 9.7 ± 3.8 cm/yr, respectively. For the North Bosque River, the for the root specimens classified as non-flood (all acquired from the meandering portion of the channel) was 31.4 ± 28.6 cm/yr. For the roots collected from the North Bosque River streambank categorized as flood (with exposure ≤ 1 year), the average root-based erosion was 196.4 ± 124.1 cm/yr.

For comparisons between watersheds, significant differences in values were found between meander and straight channels of the smaller drainages (i.e., Cedar, and Mill). For the North Bosque River, roots were only collected from meanders which had significantly higher erosion rates than the meandering channels of either Cedar or Mill Creek (p<0.05).

For Cedar Creek, average straight channel was 6.2 ± 2.1 cm/yr and 11.8 ± 3.2 cm/yr for meanders (Figure 8a). The modeled straight channel for Mill Creek was 5.2 ± 1.1 cm/yr compared to 7.9 ± 2.1 cm/yr for the meander channels (Figure 8b). Finally, the North Bosque River, the modeled non-flood and flood average values were 26.4 ± 6.9 and 92.69 ± 10.3 cm/yr, respectively (Figure 9). No significant differences were found between the dendrogeomorphic-derived and modeled erosion () for the non-flood values. Non-flood and flood values were different for both roots and modeled rates. In addition, root and modeled erosion rates were significantly different for the flood.

Linear correlation analysis of U.S. prairie erosion rates from the literature, including the values from this study, were found to be partially explained by drainage area with a positive log-log relationship for both non-flood (r2=0.53) and flood (r2=0.55) periods (Figure 7). This also showed that our values fit within range of values expected for the varying drainage areas for the U.S. prairie ecological region for both non-flood and flood conditions. Comparison of the slope of the regression equations were different with, non-flood erosion having a lower value (0.29) than for flood erosion (0.60), indicating that erosion increased by 2× for flood events for a given drainage area. Comparison of the standard error of the estimate (SEE) of these regression models showed considerable differences with the non-flood having the lowest SEE = 0.57, equivalent to a log base 10 untransformed value of 1.73 cm/yr, compared to the flood model with SEE = 1.44, or an untransformed value of 4.24 cm/yr.

1. **Discussion**
   1. *Dendrogeomorphic Erosion*

Our results show that erosion rates determined for different channel locations likely captured different erosional processes occurring within a stream system. For the straight channels, particularly those analyzed for the smaller Cedar and Mill Creek watersheds, there is a moderate to high correlation between horizontal distance of the exposed root and the time of exposure (Figure 5a&b). This is because scour is a flow process associated with sediment detachment from combined shear and turbulence-induced pressure variations (Roy, et al., 2019) that is likely persistent from year to year in straight channels. In contrast, the high erosion estimates and the low correlation among horizontal distance and root exposure times for meanders from all streams studied implicates a different erosional process (Figure 4a-c).

For all roots used in the study, the exposure of the root to air as indicated by the root wood anatomy was for a single specific year. However, correlation of distance to bank with the age of the exposure was particularly poor for meander channel roots (Figures 4a-c) indicating sporadic , discrete mass wasting events account for a significant portion of the root exposure. In meandering channels, cutbanks develop with mass wasting occurring as stream velocity is maximized at the bank slope toe (Thorne and Abt, 1993). This leads to bank undercutting and creation of unstable channel side slopes with bank failure following (Simon et al. 2000). This process is accentuated in streams with channel banks composed of cohesive soils that increase possible channel steepness (Rutherfurd 2007). Mass wasting is also the most potent form of erosion as evidenced by the meanders having rates > 2.5× than those of the straight channels. Mass wasting was not modeled. More detailed information would be needed on variations in site stratigraphy, cohesion, groundwater flux, slope angles, and vegetative root strength as in BSTEM (Simon, 2000), to model such events.

Erosion rates estimated from the dendrogeomorphic method are point data, similar to erosion pins, as bank material lost since root exposure is measured at a specific location. This leads to variability in erosion estimates within a stream, even for a single event, For example, for root samples collected from the North Bosque River flood (Figure 9) had the highest and most variable calculated erosion. This variability may be attributed to site heterogeneity in terms of bank morphology, orientation, distance of root from channel bottom (Figure 6b). Also, riparian trees affect stream flow near banks due to exposed and submerged stem and roots (Motta et al., 2014). Root size, position, relative uplift of roots after partial exposure can influence bank failure rates affecting root anatomy formation (Stoffel at al. 2013, Bodoque et al. 2015). Lastly, the longer time between root exposure and measurement increase variability in erosion estimates (Dick et al., 2014) as channel widening affects channel hydrology non-linearly. However, the dendrogeomorphic method is better suited for estimating erosion rates dates as flood events are present in the root anatomy record for an extended time typically longer than any pin measurement.

* 1. *Comparison with Modeled Erosion*

As shown, average modeled bank erosion values were not significantly different from the dendrogeomorphic method confirming that basic characteristics of stream slope, channel morphology, bank material, and flood frequency are key drivers of bank retreat especially in channels with cohesive soils. However, differences in estimated erosion variability were higher for compared to modeled values especially for meander channels (Figure 8a&b) and the analysis of the non-flood event for the North Bosque River (Figure 9). For the model, only the time of bank full flow was allowed to vary via the Monte Carlo simulation. Our analysis of bank of full flow statistics were for a relatively large, robust dataset across the U.S. (Andrews, 1980; Endreny, 2007; Jacobson et al., 2019) with resultant relatively low variability (3.65 ± 0.97 days). For the smaller watersheds, the effect of channel sinuosity is important with meanders producing higher erosion with greater individual event variability. For the model, meander erosion was based on the Thorne and Abt (1993) empirical equation where the slope toe critical velocity is calculated solely from channel morphology including width and radius of curvature.

The significant differences in erosion from the two methods for the flood event in the North Bosque River (Figure 9) highlights the difficulty in capturing complexity of erosion processes under extreme conditions. The modeled flow velocity (2.61 m/s) based on the channel simply having a greater proportion water depth (Table *1*) was not much higher than for the Q1 flow (1.95 m/s). Our use of the simple Guo (1999) for modeling flow velocity was based on the premise of simplicity, where only basic channel dimensions are known. Clearly, with water level rise in the North Bosque River channel, the morphology of channel changes (Figure 2) leading to more complicated within channel flow patterns affecting erosion in specific locations. Heterogeneous erosion under the higher flow conditions is made evident by our finding roots exposed for >1 year and those exposed by the flood at nearly the same height in the channel. In addition, the flood roots had very high erosion with more than a meter of root exposed in this single year (Figure 6) While simple models of channel flow may not capture important hydrodynamics affecting erosion, the duration of high flow is also important to consider. At effective flow, the maximum erosion rate is applied to the maximum channel area. The duration of this flow event is therefore a major variable in increasing the amount of mass loss.

While channel slope stability is important, sub-aerial processes also influence erosion. Wynn and Mostaghimi, (2006) showed that sub-aerial processes have a greater effect on upper channel banks due to more extreme wet-dry cycles. We found evidence for this with the upper banks of the meandering sections to be more susceptible to higher and more variable erosion (Figure *6*a&b). Soil moisture in the lower channel bank is largely maintained by the hyporheic zone that leads to more consistent cohesion in lower bank sediments. Soils in the upper bank are also prone to desiccation, resulting in weakened aggregates that are more easily dislodged from the bank and loss of soil cohesion (Couper and Maddock, 2002). As desiccation cycles appear to increase temporal variability with higher mass wasting, as evidenced by the root data, greater emphasis on this mechanism should be included in future modeling.

* 1. *U.S. Prairie Stream Erosion*

The dendrogeomorphic estimated streambank erosion for all three watersheds analyzed were consistent with other methods of erosion measurement for other prairie streams located in U.S. prairies (Table 2). For measurements without flooding, mean erosion across drainage areas from 4 to 3781 km2 was 13.9 cm/yr for the accumulated dataset. By comparison, the mean of non-flood root-based erosion for all three drainages from our study was 12.7 cm/yr. For floods, the literature data had a mean value of 78.0 cm/yr for approximately the same drainage area range. Our study contained only a single estimate of flood-influenced erosion from the North Bosque River of 196.4 ± 124.1cm/yr indicating how individual flood events can produce a wide range of erosional outcomes for an ecologically similar region.

The values estimated here from roots were also similar for values derived from different drainage areas and flood conditions (Figure 7). The broad positive log-log relationship found for erosion and area across all data for both non-flood and flood data is to be expected given that channel length, hence exposure of erosive bank materials to flowing water, and contributing area are intricately linked (i.e., Hack’s Law; Veneziano and Niemann, 2000). Also, continental scale relationships between drainage area and hydrologic discharge are also positively related on a log-log basis (Finlayson and Montgomery, 2003) indicating the importance of stream power to removal and movement of eroded bank soil.

However, these regression analyses indicate that only 50% of the variability in erosion is effectively explained by drainage area, thus drainage area alone may be of limited use for sediment management. Prairies of the U.S. have gone through dramatic land use changes with surface soil erosion estimated at 1.9 mm/yr, which is indicative of higher overland flow (Hortonian) due to agricultural land use expansion during 19th and 20th centuries (Thaler et al., 2022). As natural grasslands were removed for to agriculture, a change in flow regime with increased discharge occurred leading to channel degradation as discharges exceeded the stream’s sediment transport capacity (Harvey and Watson, 1986). Such historical land use changes across U.S. prairies now have higher storm-water peak discharges resulting in greater forces exerted on the stream channel (Leopold and Skibitzke, 1967, Ferguson and Suckling, 1990, Booth and Jackson, 1997, Miller et al., 2014). In response, channel incision and widening will continue in these ecosystems until a new equilibrium is reached (Bledsoe et al., 2002, Watson et al., 2002) reducing management and mitigation options.

At smaller scales, urbanization is and will continue to play a large role in stream erosion associated with large cities in this region. This is evident from our regression analysis of the non-flood data (Figure 7) in which our average root-based erosion value was much higher for Cedar Creek (4 km2; 9.2 cm/yr), than for drainages of a similar area (4.6 cm/yr). Cedar Creek is in a heavily urbanized area with extensive stream straightening that and a storm-water drainage system resulting in peak flows at much higher discharges than prior to land use change (Miller et al., 2014). In response channel incision and widening are occurring with over-steepened banks, extreme scour of straight channel banks (Figure 10a), slumping trees and visible indications of mass wasting on channel cutbanks (Figure 10b). While the evidence for stream deterioration is clear, quantification of erosion from *post-hoc* dendrogeomorphology, as demonstrated here, is essential for determining engineering solutions related to bank stabilization and down-stream sediment loading from small drainages under the influence of urban flow inputs.

1. **Conclusion**

This study confirms the value of dendrogeomorphology as a rapid and accurate method for evaluating streambank erosion in watersheds without antecedent monitoring. The method can be applied with sufficient spatial resolution to discern differences in erosion processes between small and large river basins, and between straight and meandering stream segments. We conclude that: 1) the dendrogeomorphic method provides a reliable historical record of erosion for straight channels dominated by scour, 2) erosion estimated from roots in meandering channels is highly variable related to mass-wasting; however, mean erosion values are likely representative of actually erosion where numerous samples are collected, and 3) root-based erosion methods are potentially important for providing forensic evidence of rapid channel degradation in unmonitored watersheds.

The model used here for comparison also showed high correspondence with the root-based estimates of erosion supporting the generalization that stream erosion in low slope watersheds is dominated by soil cohesiveness, flow, and channel migration. Critical velocity is an efficient way to identify erosion potential with inflow into streams most affected land use changes involving alteration in impervious cover.

With surface water storage limiting supply with ever increasing demand, especially in water-scarce regions, more information on stream sediment supply to reservoirs is needed. Dendrogeomorphic methods provide a longer historic perspective on changes streambank erosion, that when coupled with implementation of best management practices, provide a rapid and economic means for assessing future erosion mitigation.

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**Data Availablity:**All data produced and used for this study will be available through the Open Science Framework (<http://osf.io> ) data repository through the Center for Open Science.

Table 1 – Parameter values used for modeling bank erosion (cm/yr) for each of the watersheds studied. For the North Bosque River, values used for the non-flood and flood erosion are provided. Details of the individual parameters are found in the text.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Cedar Creek | Mill Creek | North Bosque River | |
|  |  |  | *Non-flood* | *Flood* |
| Channel bottom width (m) | 2.5 | 7.0 | 23.0 | 23.0 |
| Average bank slope (m/m) | 0.2 | 1.0 | 1.0 | 1.0 |
| Manning’s n | 0.050 | 0.030 | 0.035 | 0.035 |
| Average channel slope (m/m) | 0.0058 | 0.0021 | 0.001 | 0.001 |
| (m/s) | 1.51 | 2.58 | 1.95 | 2.61 |
| (m/s) | 0.75 | 0.85 | 0.68 | 0.74 |
| (m) | 2.5 | 3.5 | 4.0 | 10.0 |
| (kg/m3) | 1541 | 1370 | 1435 | 1435 |
| (%) | 31 | 49 | 37 | 37 |
| (Pa) | 1928 | 4996 | 2672 | 2672 |
| (dim) | 1.4 | 1.1 | 1.3 | 1.3 |
| (dim) | 2.84 | 1.55 | 2.38 | 2.38 |

Table 2- Erosion rates (cm/yr) estimated by this study for different U.S. streams and rivers in the Great Plains ecoregion within the U.S. located in withing drainages of varying size (km2) from this and other studies. Where available, one standard deviation from the study data is shown unless indicated by the not available (na) abbreviation. For some studies, data collected from flood events and bank location (upper/lower) are indicated. The measurement technique is also specified for those that utilized erosion pins (Pin), dendrogeomorphic (Dendro), photographic structure from motion(SfM), field mapping, or laser scanning.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| U.S. Stream/River | Drainage Area  (km2) | Mean Erosion Rate  (cm/yr) | Standard Deviation  (cm/yr) | Measurement Technique | Reference |
| Chariton River (flood), IA | 3 | 3 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Chariton River (flood), IA | 4 | 4 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Cedar Creek, TX | 4 | 9.2 | 7.1 | Dendro | This study |
| Chariton River (flood), IA | 4 | 4 | *na* |  | Tüfekçioğlu et al., 2019 |
| Kings Creek upper bank, TX | 5 | 3.1 | 1.9 | Pin | Capello, 2007 |
| Kings Creek lower bank, TX | 5 | 4.1 | 1.0 | Pin | Capello, 2007 |
| Chariton River (flood), IA | 6 | 37 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Chariton River (flood), IA | 7 | 9 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Kings Creek, KS | 11 | 5.8 | *na* | SfM | Marcotte, 2020 |
| Chariton River (flood), IA | 20 | 0.5 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Timber Creek upper bank, TX | 22 | 8.7 | *na* | Pin | Coffmann, 2009 |
| Timber Creek lower bank, TX | 22 | 8.9 | *na* | Pin | Coffmann, 2009 |
| Walnut Creek, IA | 52 | 4.2 | *na* | Field mapping | Schilling and Wolter, 2000 |
| Walnut Creek, IA | 52 | 18.8 | *na* | Pin | Palmer et al., 2014 |
| Chariton River (flood), IA | 56 | 40 | *na* | Pin | Tüfekçioğlu et al., 2019 |
| Wilson Creek, TX | 132 | 13.3 | *na* | Laser scan | Nettles, 2009 |
| Mill Creek, TX | 203 | 6.4 | 3.9 | Dendro | This study |
| Big Brushy Creek upper bank, TX | 239 | 33.5 | 9 | Pin | Capello, 2007 |
| Big Brushy Creek lower bank, TX | 239 | 9.3 | 4.6 | Pin | Capello, 2007 |
| Rathbun Lake, IA | 1433 | 38 | *na* | Pin | Tüfekçioğlu et al., 2020 |
| Illinois River, OK (flood) | 2300 | 408.3 | *na* | Pin | Harmel et al., 1999 |
| North Bosque River | 3781 | 31.4 | 28.6 | Dendro | This study |
| North Bosque River (flood) | 3781 | 196.4 | 124.1 | Dendro | This study |

Figure 1 - Map of three watersheds studied located in the north and central part of the U.S. state of Texas. Location of watersheds are shown with major waterways, lakes, and prairie sub-regions of the Great Plains ecoregion. The insert map shows the three drainages at high resolution with red symbols showing erosion was estimated by dendrogeomorphology and modeling.

Figure 2 - Idealized cross-sections of the a. Cedar Creek, b> Mill Creek, and c. the North Bosque River. Mean channel dimensions are shown used for modeling effective flow (Q1). For the North Bosque, the flow for Q2+ is also shown representing the “flood” conditions for this stream during 2019.

Figure 3 – Images of representative root cross-sections collected in the three watersheds of this study. Arrows shown in all images indicate the imterpreted morphological change associated with root exposure to air. From the top left, a) is from F. texensis showing the change in wood porosity associated with large diameter xylem vessels in the center of the root to the low porosity small diameter xylem in the outer section of the root, b) is another sample of F. texensis showing similar change in root wood porosity from large to small diameter xylem vessels, c) is also from F. texensis showing a trasnsition in the wood anatomy change from medium density of large dimater xylem, to a typical wood anatomy indicating large diamater xylem isolated in each single ring typcially associated with early growing season, and d) a section of U. americana showing a wounding event and resultant scar tissue development that conincides with a xylem morphological change. Such wounding is likely on ly to have occurred following soil removal around the root.

Figure 4 – Discharge (m3/s) for July 2018 through August 2019 measured at the U.S. Geological Survey station #08095200 (31.66960575°N -97.4694602°W) located near the town of Valley Mills, Texas, on the North Bosque River. Shown are the different flood return discharges for the one-year (Q1), one and one-half-year (Q1.5), two-year (Q2), and five-year (Q5) floods. For the year prior to root collection (August 2019) in this watershed, two discharge events exceeded the Q2 level.

Figure 5 - Data from sampled roots with measured distance to bank (cm) and years since exposure are shown for the a. Cedar Creek, b. Mill Creek, and c. the North Bosque River watersheds. Root samples are separated into those collected from straight and meander portions of the channels. For the North Bosque River, root samples were only collected from meandering channels.

Figure 6 – Erosion rates are shown derived from the dendrogeomorphic method with the associated height above the channel from which the root was collected for a. Cedar Creek, b. Mill Creek, and c. the North Bosque River. Data are separated into straight and meander channels for Cedar and Mill Creek. For the North Bosque River, calculated erosion from non-flood and flood roots are shown.

Figure 7 - Correlation of log base 10 transformed drainage area (km2) and erosion rates (cm/yr) for various studies in the Great Plains ecoregion of the U.S. (Table 2). Values for erosion measured for non-flood events and flood are presently separately. Symbols with red indicate those data used in the regression analyses from this study.

Figure 8 - Comparison of mean bank erosion (cm/yr) for straight and meander channels for a. Cedar Creek and b. Mill Creek watersheds from the dendrogeomorphic and modeled estimates. Error bars represent one standard deviation of the erosion values. *S*ignificant differences (p<0.05) are indicated by the \* and †symbols and were found among the erosion rates for the straight and meander channels but not between the among root- and modeled-based values.

Figure 9 - Comparison of non-flood and flood mean bank erosion (cm/yr) for North Bosque River watershed watersheds from the dendrogeomorphic and modeled estimates. Error bars represent one standard deviation of the erosion values. Significant differences (p<0.05) are indicated by the \*, †, and ‡ symbols. For the non-flood estimates, no differences were found between the among root- and modeled-based values. Significant diffferences were found betweem both root- and modeled-based erosion values for the non-flood and flood values. Also the flood erosion for root- and modeled-based values were different.

Figure 10 - Photos taken of Cedar Creek in July 2015. In photo a., the straight channel scour is shown with roots and fallen trees. In photo b., cutbank erosion is evident.