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STREAMBANK EROSION PHENOMENA AND UNDERSTANDING: CURRENT RESEARCH AND FUTURE DIRECTIONS

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Collection Introduction

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HIGHLIGHTS

- High rates of streambank erosion are detrimental to the stability and function of streams.
- This collection brings together six studies that represent key advances in streambank erosion research.
- Current research directions on streambank erosion, erodibility characterization, and sediment loading are presented.
- Future research directions and challenges related to high-frequency data collection and modeling are discussed.

ABSTRACT. *Streams are in dynamic equilibrium with their environments, and as that environment is altered by human development and changing climate, streambank erosion is a common, but little understood, result. This article highlights the contributions of the special collection "Streambank Erosion, Sediment Dynamics, and Restoration (SER)," which assembled six studies that represent key advances in streambank erosion research, highlight current research in the field, and identify directions for future research. The studies in this special collection were grouped into three central themes: (1) streambank erosion monitoring, (2) streambank erodibility characterization, and (3) streambank erosion loading. In this article, key findings within each of these central themes are summarized, emphasizing the significant contributions of each study. Likewise, perspectives on future research directions are discussed, outlining important challenges that remain to be addressed. Overall, the studies in this special collection are unified in their overarching goal of improving quantitative and predictive understanding of streambank erosion phenomena.*

Keywords. *Erodibility Parameters, Jet Erosion Test, Monitoring, Sediment, Soil Erosion, Stabilization Practices, Streambank, Stream Restoration.*

Streambank erosion is a ubiquitous morphodynamic process (Zhao et al., 2022). High rates of streambank erosion are detrimental to the stability and function of streams (fig. 1) and can have severe economic and safety consequences on human riparian development. Over time, high rates of streambank erosion can lead to excessive bed erosion and deposition, reduced efficiency of in-stream structures, increased downstream loading of fine-grained material (e.g., clay and silt) and nutrients (e.g., phosphorus), and poor water quality and habitat conditions (Miller and Kochel, 2010; Fox et al., 2016; Castro-Bolinaga and Fox, 2018; Papangelakis and MacVicar, 2020). Generating an improved understanding of these impacts is critical in applications like stream restoration, stormwater management, and channel stabilization, where billions of dollars are spent annually to mitigate streambank erosion (Bernhardt et al., 2005; Fox, 2019; James, 2019). Furthermore, the occurrence of streambank erosion has been accelerated in response to climate-change induced fluctuations in the timing and intensity of hydrologic events (IPCC, 2018; Langhorst and Pavelsky, 2023). These fluctuations are rapidly altering the amount of water and sediment delivered to and transported by streams (Syvitski et al., 2022), modifying their water-sediment regimes and their capacity to resist and recover from change imposed by ensuing disturbances (i.e., the stream's resilience) (Fuller et al., 2019). Therefore, the ability to accurately quantify rates of streambank erosion is key to advancing knowledge on how climate change will impact streams in the future (Tullos et al., 2021). Yet, such an ability is constrained by the amount and quality of available streambank erosion data, as well as the effectiveness of techniques to characterize streambank erodibility and estimate downstream sediment loading.

The objective of this article is to highlight the contributions of the special collection "Streambank Erosion, Sediment

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Figure 1. Severe streambank erosion in a restored sand-bed stream in North Carolina. As a result of channel widening due to streambank erosion, the stream's sediment transport capacity has been reduced, causing bed material deposition along the bank. Flow is from right to left.

Dynamics, and Restoration (SER)," which was sponsored by the Streams, Reservoirs, and Wetlands Group (NRES-25) of the American Society of Agricultural and Biological Engineers (ASABE). The special collection brought together six studies that represent key advances in streambank erosion research, highlighting current directions in the field and identifying areas for future research. The studies in this special collection were grouped into three central themes: (1) streambank erosion monitoring, (2) streambank erodibility characterization, and (3) streambank erosion loading. In this article, key findings within each of these central themes are summarized, emphasizing the significant contributions of each study. Likewise, perspectives on future research directions are discussed, outlining important challenges that remain to be addressed. Overall, the studies in this special collection are unified in their overarching goal of improving quantitative and predictive understanding of streambank erosion phenomena.

STREAMBANK EROSION MONITORING

Knox and Mittelstet (2021) addressed a research need stated by Bigham (2020) related to assessing the spatiotemporal variability of techniques to measure the effect of streambank stabilization techniques on the local bank over time. Knox and Mittelstet (2021) developed a sediment monitoring system (SMS) using an ultrasonic sensor. The sensor was developed to take high-frequency measurements to quantify erosion and deposition. The authors compared multiple methods that are currently used to monitor erosion and deposition. Each of the current methods is limited by the frequency of measurement, total area monitored, invasiveness, or cost. While the SMS takes measurements at a high frequency and is not invasive or costly, the total area monitored was only 2,826 cm^2. The authors tested the SMS in the laboratory and at four field locations. In the laboratory, the SMS was able to record changes in erosion and deposition with high accuracy. Results showed that the soil type did not influence the results, but vegetation did. Results from the field experiments yielded greater uncertainty and variability than the experiments conducted in the laboratory. The ultrasonic sensor is dependent on the speed of sound, which the authors found was influenced by air temperature, relative humidity, and wind. The SMS successfully measured the timing and quantity of deposition for two storm events, measuring 435 mm of deposition. While the SMS has limitations, it has the potential to measure streambank, streambed, and upland erosion at a high frequency for minimal cost.

While studies have shown the effectiveness of streambank stabilization techniques at the local scale (Dave and Mittelstet, 2017), Russell et al. (2021) evaluated the impact of stabilization structures on unstabilized reaches immediately upstream and downstream. The study occurred on the Cedar River in north-central Nebraska and included streambanks stabilized and/or protected with jetties, rock vanes, root wads, and gravel. The authors measured streambank erosion and deposition at 1.5 meander wavelengths upstream and downstream from 24 stabilization structures, as well as the streambanks directly opposite the stabilized streambanks. The study quantified the erosion and deposition during the pre-stabilization (1993-2005) and post-stabilization (2005-2018) periods using historical imagery and ArcGIS. The authors rejected their initial hypothesis that local and adjacent streambank segment erosion rates would be significantly less after stabilization, and that deposition rates would be greater in stabilized locations and adjacent stream segments. Due to a breached dam on the Cedar River in 2010, several of the stabilized structures were no longer functional. Of the 24 stabilization structures, only 50% were fully functional, while six were non-functional. Each of the non-functional stabilization structures were trees or wooden jetties. The erosion and deposition for the pre-stabilization period ranged from 0.0 to 98.9 m^2 m^{-1} and 0.0 to 124.5 m^2 m^{-1}, respectively. For the post-stabilization period, the erosion ranged from 0 to 27.5 m^2 m^{-1} and the deposition ranged from 0 to 27.2 m^2 m^{-1}. Results found that the differences in erosion from the pre- to post-stabilization periods showed little or no significant statistical difference, and deposition was actually greater during the pre-stabilization period. The authors concluded that there is a need for improved streambank erosion monitoring so we can better understand how streambank stabilization structures impact an entire river system.

STREAMBANK ERODIBILITY CHARACTERIZATION

Accurate characterization of soil erodibility is central to understanding the magnitudes and rates of streambank erosion. The Jet Erosion Test (JET) (fig. 2) remains one of the most commonly used instruments for quantifying streambank erodibility parameters, namely, critical shear stress (τ_c) and erodibility coefficient (k_d). However, questions remain with regard to standard operating practices among JET users, including selecting a pressure head (h). Fox et al. (2022) performed numerical analyses and documented a procedure to provide guidance on appropriate ranges of h values for predetermined soil types and JET settings. Pre-determined soil types were selected based on the classification system proposed by Hanson and Simon (2001) using average values of τ_c and k_d for highly erodible, more erodible, erodible, and moderately resistant soils. Evaluated JET settings included the user-specified initial time intervals and total test duration, as well as the initial jet orifice height. Findings from this work indicated that both soil type and user-specified settings are important when selecting h. Results showed that the range of appropriate h values increases as soil resistance increases from highly erodible to moderately resistant. The upper limit of such a range was found to depend on the soil type and the initial time interval for data collection, with larger values of h required for more resistant soils and suitable only for shorter initial time intervals. Moreover, the lower limit was found to be sensitive to the total test duration, with longer tests requiring smaller values of h to achieve a minimum scour depth. Lastly, both the upper and lower limits of the range of appropriate h values were found to increase as the initial jet orifice height increased, with a much greater impact on the upper limit of such a range. Fox et al. (2022) recommended that JET users should select h values near the middle of the numerically derived appropriate range to account for assumptions and simplifications in the analyses (e.g., soil homogeneity). Overall, the work of Fox et al. (2022) contributes towards the establishment of more consistent standard operating practices for the JET.

Figure 2. A mini-JET device deployed on a streambank in Millstone Creek, North Carolina, to characterize its erodibility. In this setup, a constant pressure head tank is being used to drive the impinging water jet.

Streambank erodibility parameters can exhibit high variability both spatially and temporally, highlighting the role of rapidly changing environmental conditions such as moisture content and temperature (Hoomehr et al., 2018; Akinola et al., 2019). Wilson et al. (2022) investigated the causal factors influencing the spatial and temporal variability of τ_c and k_d across six streams within seven Major Land Resource Areas (MLRA) in Iowa. Specifically, they used a combination of historical data and field measurements to quantify the impact of soil properties, moisture content, and freeze-thaw cycles on τ_c and k_d. Evaluated soil properties included texture, organic matter content, water content, bulk density, pH, and Atterberg limits. Erodibility parameters were determined in the laboratory using a recirculating water-and-sediment conduit flume. Results from this work showed that spatial variability in τ_c and k_d is strongly correlated with spatial variability in soil type. Wilson et al. (2022) found that τ_c was larger and k_d smaller in the loess-derived soils in western and southern Iowa, which contain a higher amount of cohesive material, when compared to the coarser till-derived soils in the north central and northwest regions. Regarding temporal variability, findings from this work suggested that changes in soil moisture and freeze-thaw cycles impact the magnitude of τ_c and k_d, with higher moisture content and more frequent freeze-thaw cycles contributing to smaller τ_c and larger k_d values. Within the study MLRAs in Iowa, Wilson et al. (2022) reported that minimum τ_c and maximum k_d values are reached during March and April when soil moisture is high and there are several freeze-thaw cycles, with the opposite trend occurring in August when soil moisture is moderate and freeze-thaw cycles do not exist. Overall, the work of Wilson et al. (2022) contributes towards the development of regional support tools that account for soil properties and rapidly changing environmental conditions.

STREAMBANK EROSION LOADING

Quantification of instream sediment and total phosphorus (TP) at the watershed scale is lacking. To assist in managing legacy phosphorus, we must know the origin and location of the TP within a watershed. Mittelstet and Storm (2016) found that 74%-89% of all TP added to two watersheds in Oklahoma still remained in the soil and stream system as legacy TP. Understanding the source of sediment and TP is vital to validating models and identifying the best management practices to reduce soil erosion. Beck et al. (2022) addressed the lack of literature in quantifying in-channel fine sediment and TP. Their study was conducted in 2015 along 13.5 km of Walnut Creek, a perennial, third-order stream in Iowa. The authors surveyed 12 storage reaches, which represented 20% of the total channel length. Each reach consisted of 10 transects, 24 m apart. For each transect, measurements were taken at 0.5 m intervals. At each of these probe points, the depth of stored sediment was determined by pushing a 150 cm long x 1 cm wide metal tile probe downward until the resistance of the underlying Gunder member was detected. Beck et al. (2022) reported that the unique color, structure, and relatively high bulk density of the Gunder made it recognizable in comparison to sediment stored above its top. The type of sediment at each probe point was recorded and assigned to a storage feature class. Classes included loose bed sediment, side bar, point bar, mid-channel bar, debris jab, beaver dam, and streambank toe colluvium. Results showed that the total sediment storage within the study area was estimated to be 30,205 m^3, or 2.2 m^3 per m of channel length. The TP storage within the study area, which was determined from sediment samples collected from each storage feature class, was estimated to be 9.4 Mg, or 0.7 kg per m of channel length. The sinuous reaches had significantly greater mean sediment depths than the straight reaches. The majority of the total sediment storage mass was found in the feature classes streambank toe colluvium (72%), and loose bed sediment (18%). Results indicated that sinuosity was the best storage predictor, while stream power, channel gradient, and change in channel cross-sectional area were poor predictors. The authors concluded that in-channel fine sediment and TP storage were significant compared to annual loads. Quantifying in-channel sediment and TP is critical to relating source contributions to watershed loads.

Urban development has significantly altered the hydrologic response of watersheds, leading to shifts in the quantity and frequency of runoff to streams (Bhaskar et al., 2020). These shifts have increased rates of streambank erosion, impacting channel stability, reducing water quality, and increasing sediment loading to downstream waterways. Malhotra et al. (2023) performed a numerical study to identify the dominant sources of sediment loading in an urbanized watershed in eastern Alabama. Specifically, they evaluated how the application of two machine learning approaches, namely, random forest and Least Absolute Shrinkage and Selection Operator (LASSO), influence the selection of fingerprinting properties when identifying loading sources between streambanks and construction sites. Evaluated fingerprinting properties included 59 geochemical elements, whose concentrations were determined from collected sediment samples. Results indicated that sediment source apportionment was sensitive to the selected machine learning approach. Malhotra et al. (2023) reported that as the contribution of a particular source group increased, the difference between the concentration of fingerprinting properties selected by the machine learning approach and the mean value of the corresponding concentration of fingerprinting properties in that source group decreased. In general, results indicated that sediment loading from streambanks was greater than that from construction sites within the study watershed, highlighting the role of rapid urbanization in accelerating streambank erosion. Although machine learning approaches can aid in the selection of fingerprinting properties, Malhotra et al. (2023) recommended caution when selecting statistical tests to obtain optimum composite fingerprints, as sediment source apportionment is sensitive to the optimum fingerprinting properties selected.

FUTURE DIRECTIONS AND CHALLENGES

Despite substantial progress in advancing streambank erosion research (Zhao et al., 2022), there remain many challenges for further improvements in the field. Here, several key future research directions and remaining challenges in the three central themes covered by the special collection are highlighted.

Improvements in the frequency and quality of monitoring data are key for accurate estimations of streambank erosion rates. While some methods, such as the Photo-Electronic Erosion Pin (Lawler and Leeks, 1992) and LiDAR/TLS, can measure streambank erosion at high frequency, they are limited by the extent of the area that can be monitored, invasiveness, or the cost associated with acquisition and/or implementation. Since the newly developed SMS is limited in the area it can monitor, new methods are needed to monitor streambank erosion and deposition over a large area, at both low and high flows. Hatley et al. (2023) utilized new advances in fiber-optic distributed temperature sensing to develop a device capable of tracking the water-sediment interface at high spatial and temporal resolutions. The use of root dendrogeomorphology has also emerged as a bio-inspired and cost-effective monitoring technique, although its application is constrained by the availability of roots along the streambank face and the time scale associated with predictions (annual) (Dick et al., 2014). Furthermore, increasing the frequency and quality of monitoring data will enable a more effective evaluation of stabilization techniques and restoration practices. Despite an investment of billions of dollars annually, post-stabilization or post-restoration monitoring data are still limited and collected at a low frequency (typically annual), if at all. Bigham (2020) reported that since 1998, there have only been 146 peer-reviewed manuscripts on streambank stabilization, and only 32% were field studies.

Predictive understanding of streambank erosion and associated downstream sediment loading is still limited by the inability to adequately characterize and account for the inherent variability and uncertainty that mark these phenomena in nature. Such variability and uncertainty include, for example, changes in streambank erodibility parameters with environmental conditions that can vary daily and seasonally. Importantly, this limitation has translated into the widespread application of deterministic numerical models that assume stationarity, do not capture variability, and ignore uncertainty. For example, a recent survey of practitioners revealed that the main challenges to incorporating the effects of climate change in design, practice, and policy were access to numerical models that account for physics-based processes, variability, and uncertainty (Tullos et al., 2021). This is critical in applications like stream restoration, stormwater management, and riverine infrastructure construction and removal, in which the use of deterministic analyses that ignore variability and uncertainty might then lead to an increased flood risk of vulnerable communities, major economic and infrastructure losses, and long-lasting adverse environmental and ecological impacts.

Advances are still needed to improve fundamental understanding and modeling of the contribution of streambank erosion to overall watershed sediment loading (Fox et al., 2016). Process-based models that simulate streambank erosion and sediment dynamics are available, but they require extensive parameterization using site-specific data that has not been readily available (e.g., streambank erodibility parameters, root cohesion, or pore-water pressure fluctuations) (e.g., Lammers et al., 2017; Mittelstet et al., 2017). Relevant examples of available process-based models include FLUVIAL-12 (Chang, 1998), CONCEPTS (Langendoen et al., 2001), SWAT (Arnold et al., 1998), and the coupled HEC-RAS 1D with BSTEM (CEIWR-HEC, 2015). Studies from this special collection contributed to advancing data collection methods (e.g., Knox and Mittelstet, 2021; Fox et al., 2022) and characterizing the variability of site-specific parameters (e.g., Wilson et al., 2022). However, previous studies that have assessed streambank erosion simulation typically find that process-based models have difficulty capturing the complexity of erosion processes (Myers et al., 2021). An alternative approach to process-based modeling is to disaggregate long-term simulated (Wilkinson et al., 2014) or measured (Mankin and Modala, 2022) streambank erosion data for simulating daily sediment loading. However, the application of this type of approach is constrained by data availability. Research opportunities exist along the full continuum from simple, practical quantification to complex, process-based streambank erosion modeling (e.g., Zhao et al., 2022).

CONCLUSIONS

The special collection "Streambank Erosion, Sediment Dynamics, and Restoration (SER)" brought together six studies that represent key advances in streambank erosion research, highlighting current dictions in the field and identifying areas for future research. The main findings of the studies in this special collection were the following:

- A new sediment monitoring system (SMS) using an ultrasonic sensor is an effective monitoring instrument for high-frequency measurements of erosion and deposition.
- The impact of local streambank stabilization techniques on unstabilized reaches immediately upstream and downstream varies significantly depending on the location along the system and the type of stabilization technique used.
- The range of appropriate pressure heads to conduct Jet Erosion Tests (JETs) depends on the interrelated effects of soil resistance, the initial time interval for data collection, and the total test duration.
- Streambank erodibility parameters are sensitive to regional changes in soil moisture and freeze-thaw cycles, with higher moisture contents and more frequent freeze-thaw cycles contributing to smaller critical shear stresses (τ_c) and large erodibility coefficients (k_d).
- Channel sinuosity is a better predictor for estimating in-channel fine sediment and TP storage when compared to channel gradient and changes in cross-sectional area.
- Although machine learning approaches can aid in the selection of fingerprinting properties when identifying sediment loading sources, caution should be taken when selecting statistical tests to obtain optimum composite fingerprints, as sediment source apportionment is sensitive to the optimum fingerprinting properties selected.

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