Investigating the Dynamics of Meandering River Cutoffs: Relationships with Discharge, Land Cover and Spatial Clustering

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

As climate change has become one of the major concerns across the globe, investigating the dynamics of meandering river evolution is substantial for urban river management and flood mitigation plans. In recent years, the study on river cutoff has been given lots of attention, as its occurrences and impacts were unpredictable and catastrophic. This study investigates its relationship with high-flow events, land cover and spatial clustering through flood frequency analysis, cutoff ratio criterion and spatial cluster analysis. 1,186 river cutoffs across the United States are located and identified based on Google Earth Imagery. 12 highly sinuous rivers with high cutoff occurrences are then selected and processed through R Studio and ArcGIS. The results show no strong correlation between high-flow events and cutoff occurrence across the study areas. Discharges with an average of approximately eleven-year return period are associated with cutoff occurrences. With the installation of the cutoff ratio in the dataset, it is found that chute cutoffs with higher CR_m values are likely to occur on land cover types with lower erosion resistance. Neck cutoffs are usually found in floodplains less susceptible to erosion, particularly in undisturbed vegetated areas. Spatial cluster analysis shows that neck cutoffs are significantly clustered at all scales, whereas chute cutoffs exhibit relatively lower clustering tendencies and tend to be more event-driven. Minimizing the random disturbances in the analysis, this study collectively validates the non-random behaviour of cutoff occurrences, which further calls attention to the importance and viability of assessing and predicting cutoff evolution in urban planning and flood management.

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Chapter 1
Introduction

1 Background

Rivers meandering through terrains such as mountains and deserts create a natural landscape that can be observed across the earth and play a significant role in distributing rainfall to various water bodies on Earth (Akay et al., 2020; Greenberg & Ganti, 2024; Kiss & Blanka, 2012). Unlike other natural river shapes seen in nature, meandering rivers follow a twisting course that helps to reduce the speed of water flow by lengthening the river channel and forming curves to enable water to release its energy and reduce sudden changes in water flow patterns (Czuba et al., 2019). Meanwhile, meandering rivers also serve as abundant resources and natural habitats supporting a large range of wildlife and ecosystems. As water flows through meandering channels, sediments and natural materials accumulate at riverbank edges, resulting in hotspots that nurture vegetation growth alongside the riverbanks (Camporeale & Ridolfi, 2010; Perucca et al., 2007; van Oorschot et al., 2016).

The natural form of a meandering river is often characterized by certain geomorphic features like river cutoffs and point bars. Despite their residence time in rivers, these features usually play fundamental roles in maintaining stream power and providing resources for surrounding aquatic and land species. The formation of cutoffs often causes fluctuations in channel stability or triggers new patterns of instability. In most cases, cutoffs tend to straighten the meander river channel, reduce its sinuosity and simplify the river planform; however, its consequences often vary differently in terms of different allogenic and autogenic factors involved (Hooke, 2004; Raj et al., 2015). Other than that, the high uncertainty in river cutoff formation often poses risks to the communities and ecosystems situated in proximity. Therefore, it is essential to possess the ability to manage and predict instances of cutoffs effectively, for the purpose of preventing and managing floods in regions where human activities converge with meandering river networks (Coomes et al., 2009; Kiss & Blanka, 2012).

Due to its high potential and relevance in managing rivers and lands, the study of river cutoffs has captured scientists' interests from various fields such as engineering (Han & Endreny, 2014; Hooke, 1995), hydrology (Van Dijk et al., 2012), biology (Perucca et al., 2007) and geomorphology (Kastha & Khatun, 2022). Research on meandering cutoffs has shown advancements over years through the use of a variety of approaches (Douglas Shields & Abt, 1989; Erskine et al., 1992; Hooke, 1995; Stølum, 1996). Each of these approaches has provided evidence that has deepened our knowledge of cutoff evolution and its impacts on nature and human activities. Initially, it was viewed as a factor linked to channel lateral migration at a local scale in several studies (Camporeale et al., 2005; Hooke, 1995, 2004; Zinger et al., 2011); however, the concept of cutoff formation later revealed its high unpredictability and potential threats of sudden effects on broader scales as well (Schwenk & Foufoula-Georgiou, 2016). Overall, this ongoing discussion regarding the evolution of meandering rivers has influenced many decision- and policy-making processes on flood controls, conservation area protection and urban land planning.

Successful research on river cutoffs is usually conducted and proceeded depending on its practical and scientific values. Given the overall change in river planforms, cutoff occurrence and evolution often serve as a mirror of traits observed in meandering river networks. This information helps urban planners monitor and control current river conditions accurately, even forecast future changes. The speed at which migration and infilling occur can be managed and used in various fields, like building artificial barriers, setting up protected areas for nature conservation and urban land planning (Douglas Shields & Abt, 1989; Han & Endreny, 2014; Le Coz et al., 2010; Piégay et al., 2008; Raj et al., 2015). Apart from that, many studies focus on investigating and advancing the theoretical understanding of river cutoffs. For example, scientists generally categorize river cutoffs into chute and neck cutoffs, which are the two most commonly observed cutoffs in meandering river systems. Since then, they have been the focus of numerous studies. The formations of different cutoff types often reveal their correlations with a variety of internal and external determinants, such as land cover, sediment transport, erosion resistance, leading to changes in river dynamics. Understanding the correlation and compatibility among these forces builds the foundation for further studies and potential river management practices (Fuller et al., 2003; Li et al., 2019; Richards & Konsoer, 2020; Van Dijk et al., 2012; Viero et al., 2018).

In 1996, Stølum introduced the theory that cutoff is considered an integral part of the self-organizing processes in meandering rivers. As channel migration and sinuosity increase gradually, meandering river systems become more complicated, eventually reaching the chaotic threshold. Surpassing this threshold, the sudden formation of cutoffs disrupts the continuing entangling process and pushes the river system back to the previous state between equilibrium and chaos. This process ultimately stabilizes and simplifies meandering river systems. A few years later, this theory was supported and confirmed by several studies. The long-term evolution of meandering rivers can be determined and explained by a certain threshold in channel sinuosity that balances between equilibrium and chaos states (Asahi et al., 2013; Hooke, 2004; Stølum, 1997; Van Dijk et al., 2012). This result further uncovers the potential and feasibility of predicting cutoff occurrence over a certain timeframe. For instance, by obtaining the particular hydrological parameters, such as cutoff length, migration rate, sinuosity, Constantine and Dunne (2008) have successfully simulated and predicted the temporal evolution of river cutoffs. Other than that, the occurrence of river cutoffs is not merely affected by fluvial characteristics and external environmental factors, but also by their internal spatial clustering. The initial formation of a cutoff can often act as a trigger that increases soil erodibility and instability in the meander bends, resulting in the avalanche effect of cutoffs and the complexity of meandering river systems (Schwenk & Foufoula-Georgiou, 2016). And the presence of these clustering patterns is often found to continuously impact the meandering dynamics in various processes in both downstream and upstream directions. Specifically, the higher erosion rate found at the clustering zone can increase the bedload and sediment flux along the stream bed. And the meandering bed-slope rate can be significantly intensified at the local scale. The clustering can also steepen the local drainage corridor and increase its bed stresses, resulting in adjustments in meander cross-sections. Lastly, integrating the force of backwater effects, initial cutoffs can even trigger nonlocal cutoff clustering in the upstream direction, resulting in nonlocal instability in the river (Ielpi et al., 2021). Therefore, the distribution and clustering of cutoffs can collectively affect meandering river dynamics at multiple spatial scales, resulting in the formation or vanishing of future cutoffs. However, until now, these studies have only been conducted based on a relatively limited number of cutoff events occurring over limited timescales, which constrains the understanding and prediction of cutoffs in the long-term analysis and misleads the long-term strategies for river management.

Studying the evolution and formation of river cutoffs can be beneficial for advancing science of river systems as well as provide contributions to effective river management, particularly in relation to implementing conservation measures. This thesis is conducted to meet these requirements by focusing on three objectives: 1) examining how high-flow discharge can affect river cutoff occurrences using data about twelve meandering rivers with frequent cutoffs in various locations across the United States; 2) investigating the relationship between land cover type and cutoff events; 3) assessing the connection between neighbouring cutoffs to reveal the processes that control their clustering. By attempting to achieve these objectives, this study aims to clarify and improve our understanding of the interactions between river dynamics and its allogenic and autogenic factors. The results of these efforts have the potential to help structure and design approaches for future river management and flood mitigation plans.

2 Thesis Structure

This thesis combines concepts from the fields of geomorphology and hydrology to increase our understanding of the mechanisms behind meandering river cutoffs formation and their dependence on variables, such as flow events and land cover patterns. Until now meandering rivers have been a subject of research due to their significance in affecting river restoration efforts and decision-making processes regarding land management and water resource development. However, gaps remain in our knowledge about the scales and factors that trigger cutoffs and their clustering. In this chapter, we will demonstrate the importance of meandering river cutoffs at local and broader scales by focusing on the geomorphic activities and the subsequent impacts of these cutoffs on shaping meandering river networks.

In Chapter 2, we identify and assess a large dataset of cutoffs that occur in twelve meandering rivers in the United States over time. Through processing in-field hydrological measurements and conducting flood frequency analysis to explain the relationship between high-flow events and cutoff formations. A metric, known as the meandering cutoff ratio, is introduced and ANOVA test and Mann-Whitney U test are then applied to assess the statistical differences among the land-cover types. Moreover, the research evaluates the potential indicators of the spatial clustering of cutoffs using the K function and discusses the triggers leading to chute and neck cutoff clustering. Results from these efforts highlight the relationship between local hydrological factors and geomorphic features that influence these clustering patterns. The implications of these relationships are then discussed within the context of managing rivers and reducing flood risks.

In the last section of this thesis, Chapter 3, the broader implications of the results from Chapter 2 are discussed as well as how these results can help in long-term development strategies and mitigation plans under the impact of climate change. The significance of this study is not merely for protecting natural habitats but also for human communities in its vicinity, which are all dependent on a sustainable meandering river ecosystem.

3 Meandering Cutoff Mechanisms

3.1 The Evolution of River Meandering Theories

Meandering rivers flowing through floodplains are one of the most common but unique landforms observed on Earth. They are usually seen as channels of water flowing in a sinuous pattern along a relatively flat terrain (Seminara, 2006). The meandering path of these rivers can be affected by a wide range of factors such as river discharge, erosive capacity of the floodplain and land-cover change (Frascati & Lanzoni, 2009; Seminara, 2006). Given the high variations in meandering rivers, they are also treated as non-deterministic systems (Klaver, 2018). Specifically, higher discharges in rivers tend to occur along the curves of meanders, which causes higher bank erosion and the creation of riverbanks. Inner curves in rivers usually contain lower water flow, resulting in sediment accumulation and the creation of point bars (Rinaldi et al., 2008; A. Sukhodolov & Kaschtschejewa, 2010). The processes of sediment movement and redistribution in river systems are fundamental in determining the dynamics of meandering rivers (Iwasaki et al., 2016).

The unique pattern and evolution of meandering rivers has attracted significant scientific inquiry across world since 1926 (Einstein, 1926). Due to limited data and technology in the 1800s, the Coriolis Effect was claimed as a contributing factor driving the meandering pattern of rivers. For example, Baer-Babinet’s law stated that rivers in the northern hemisphere tend to erode towards the right of the flow direction, while the southern hemisphere appears in the opposite direction (Babinet, 1859; Baer, 1860). This phenomenon was later proved less significant compared to other allogenic and autogenic processes involved (Kleinhans, 2010; Słowik et al., 2024). With evidence observed during the early to middle Palaeozoic Period, it was proposed that vegetation cover substantially affects river meandering, which brought up the theory that river planforms would be straight and uniform in the absence of vegetation (Corenblit & Steiger, 2009; Thomas et al., 1987). After comparing pre-vegetation rock records and modern stages, it was revealed that the evolution of vegetation cover indeed stabilizes meandering planforms by strengthening riverbanks and increasing sediment retention, but natural meandering rivers can remain consistently stable across both unvegetated and vegetated landscapes (Ielpi et al., 2022). This latter finding suggests that vegetation cover alone is insufficient to explain the phenomena of river meandering. The cause of meandering initiation and evolution remained the subject of ongoing debate until the early 21st century. Integrating evidence from historical records and simulated models, it was stated that floodplain heterogeneity and surface barriers on Earth create abnormalities in river channels and complicate river processes; therefore, forcing river channels to bend, migrate and relocate (C. R. Constantine et al., 2009; Güneralp & Rhoads, 2011). Specifically, the initial widening tendency of straight and fast river channels is often caused by the absence or vanishing of cohesive banks. Until the widening process reaches a certain point, the formation of bars and pools forces the water to flow towards one side, resulting in an increase in bank erosion and channel perturbation; in the end, the meandering movement starts to govern and complicate the river systems (Kleinhans et al., 2024).

3.2 Erosion and Deposition Dynamics

The pattern and magnitude of erosion and deposition in meandering rivers can be influenced by a complex interplay of factors, including climate, vegetation cover, topography, and human activity among others, which makes the prediction and understanding of meandering processes challenging (Blanckaert, 2018; J. A. Constantine et al., 2014; Greenberg & Ganti, 2024). For example, water flow serves as one of the most direct ways through which climate influences river meandering. In areas with high precipitation, meandering rivers tend to exhibit high and intense discharge, which significantly increases channel erosive capacity, particularly at the outer bends of meanders (Masuya et al., 2024; Plink-Björklund, 2015; Williams, 1989). The persistent intensification of erosion accelerates lateral migration and is often followed by the undercutting of riverbanks and the development of cut banks, which, over time, contribute to more pronounced meandering patterns and potentials of river cutoffs, oxbow lakes or other related landforms (Akay et al., 2020; J. A. Constantine, Dunne, et al., 2010; Güneralp & Rhoads, 2011). Conversely, in channels where water flow is lower, the erosive capacity of the river decreases, leading to slower rates of meander migration. More importantly, studies highlight that infrequent but intense precipitation events, like flash floods, can still cause catastrophic and enormous changes in the patterns and magnitudes of erosion and deposition. The sudden surges in water flow can provoke rapid erosion and deposition, temporarily altering the meandering patterns, instigating cutoffs and potentially causing long-term shifts in meandering river dynamics (Shiklomanov et al., 2007; Steiger et al., 2022).

It is commonly acknowledged that in meandering rivers, erosion on the outer banks of bends, driven by the higher flow velocities, is typically accompanied by sediment deposition on the inner banks, where flow velocities are lower. The formation of point bars on the inner banks and cut banks on the outer banks determines the channel capacity to redistribute sediments across its floodplain, contributing to the heterogeneity of the landscape (Eke et al., 2014; Güneralp & Rhoads, 2011; Zhao et al., 2021). Particularly during the formation of river cutoffs, sediment deposition not merely often occurs in the abandoned meander bend and along the new channel, but also spreads and deposits more widely across the floodplain, leading to the accumulation of sand and silt downstream that helps stabilize the entire floodplain (Schwenk & Foufoula-Georgiou, 2016; Tang et al., 2022). These dynamics are fundamental in reshaping the floodplain landscape and affecting the evolution and migration of meandering rivers over time. Research indicates that the transport capacity of sediment in rivers can reduce progressively as with distance from the riverbed and results in the reduction in sediment accumulation in floodplains (Huffman et al., 2022; van de Lageweg et al., 2016). Coarser particles like sand and gravel tend to settle near the riverbank; and finer materials like silt and clay tend to be carried away by the main stream. Hydrological features, such as point bars, crevasse splays, and former meander bends, are the products of past river activities and they often preserve in the river channel. As over time goes, they may gradually get buried under sediment layers during the deposition process. Closer to the main river channel, these features tend to get fully buried by the thicker sediment layers in rivers,and this can lead to the preservation of more sediments in the floodplain. In contrast, since features located on the edge of the floodplain can experience slower sediment deposition and thinner sediment layers above allowing them to, they can remain exposed for extended periods (Szmytkiewicz & Zalewska, 2014; Thonon et al., 2007; VandenBygaart, 2001). Overall, the gradual burial of these features along with the channel lateral migration contributes to the overall complexity of the floodplain. Sediment accumulation creates a complex structure in soil stratigraphy that leaves significant evidence for the historical evolution of meandering rivers.

3.3 The Role of River Cutoffs

River cutoffs are of particular importance as they are sudden and unpredictable events which cause rapid changes to river planforms. The formation plays an essential role in human activities, as it contributes significantly to the introduction of sediment loads originating from the floodplain. The accumulation of sediment can trigger extensive clearing efforts to ensure a river's navigability and operational safety for human use (Zinger, Rhoads, Best, & Johnson, 2013). Cutoffs occur from the bypass of a meander loop, usually followed by the formation of an abandoned meander called an oxbow lake (Carlo Camporeale, Perucca, & Ridolfi, 2008). Oxbow lakes and their relative meander scars, which occur when lakes have filled with sediment due to overbank floods and no longer hold standing water, are important pieces of heterogeneity within floodplains. Thus, they are important for providing natural habitats for fish, birds, and vegetation, and are important sediment and water sinks that can lessen the impacts of floods along meandering rivers (Camporeale et al., 2008).

River cutoffs are commonly classified based on the mechanisms of their formation, which are chute and neck cutoffs. A chute cutoff emerges as the shortcut forms on one bend initially and then reaches the other bend (Figure 1). Chute cutoffs are usually found in relatively lower sinuous rivers, typically triggered by overbank flows and high-flow events (Ghinassi, 2011; Hooke, 2004; Howard & Knutson, 1984). The sudden increasing discharge in rivers amplifies stream power and floodplain erosion on the inner banks, resulting in the creation of a short path between meandering loops. The overall developing process is relatively more abrupt and efficient compared to neck cutoffs (Hooke, 2004; Van Dijk et al., 2012). Neck cutoffs form as two adjacent bends are too close to each other; thereby, a new direct shortcut forms bypassing the original meander loop (Figure 2). Neck cutoffs are often observed in highly sinuous rivers, resulting from channel elongation and migration. As adjacent meanders approach each other progressively over time, ultimately they merge into one single channel and create a new course in between, which could potentially transform old meanders into oxbow lakes (Lewis & Lewin, 2009; Micheli & Larsen, 2011). In other cases, the indicators leading to chute and neck cutoffs are always site-specific and vary significantly considering a variety of hydrological and geomorphological characteristics, such as bank erosion, land cover and soil composition. The heterogeneity of these factors across different landscapes reveals the absence of a singular, universally applicable driver for the formation of chute and neck cutoffs. Instead, each cutoff event is a unique occurrence, reflecting the specific hydrological and geomorphological context of its site (Gautier et al., 2007; Ielpi et al., 2021; Konings et al., 2012).

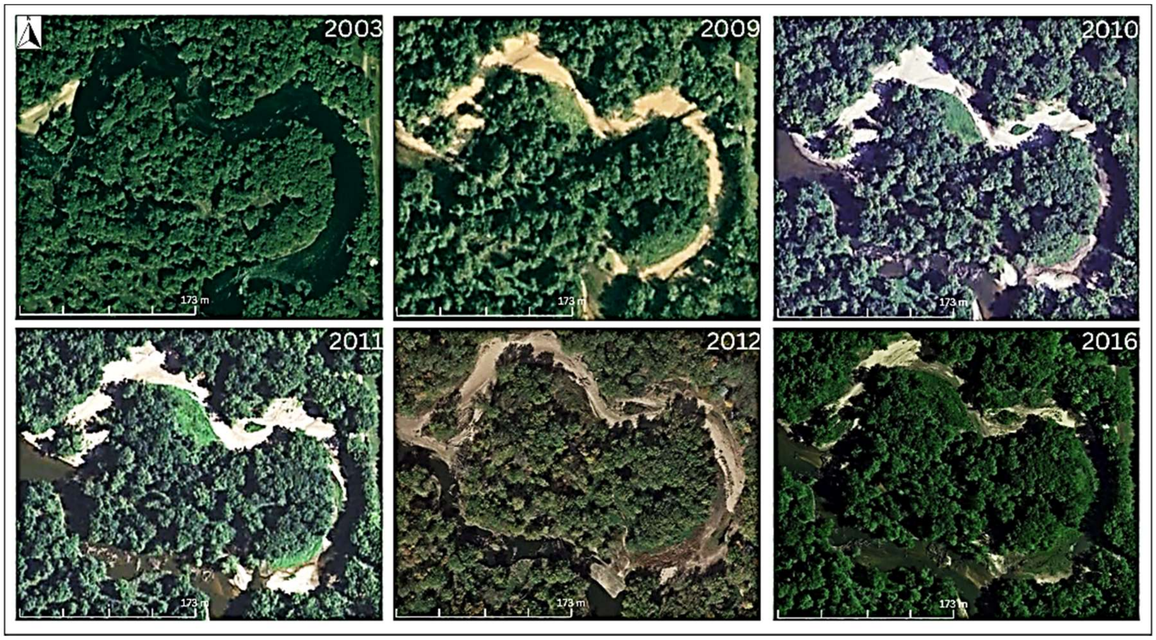


Figure 1: Meander Cutoff Evolution: an example of a chute cutoff formation in the Wapsipinicon River, Iowa, USA

Figure 2: Meander Cutoff Evolution: an example of a neck cutoff formation in the Buffalo River, Minnesota, USA

4 Spatiotemporal Factors Impacting Cutoffs

4.1 The Role of Climate and Floods

The relationship between climate variability and the formation of meandering rivers is the primary driver in influencing meandering river evolution over time, particularly through the frequency and magnitude of cutoffs. In 1960, Wolman and Miller (1960) introduced the concept of effectiveness in geomorphology studies, and this theory was later expanded upon and validated by Brunsden and Thornes in 1979 and Newson in 1980. The concept of this effectiveness focuses on how much a geomorphic event, like a flood can change the shape of the floodplain and how long these subsequent changes persist and last, despite the natural processes trying to bring geomorphic and hydrological features back to their original states. Research indicates that large and rare events tend to cause the most persistent and significant changes in landforms (Mitchell et al., 2020; Steiger et al., 2022). Specifically, climate-triggered floods are occurrences known for their rarity and intense impact, which are widely considered events with high geomorphic effectiveness. When these events occur, the rising water flow instantly accelerates hydrological processes such as lateral migration, bank erosion and cutoff development in rivers, resulting in the formation of new geomorphic features throughout the floodplain. This could cause permanent changes to the river systems or require significant time and effort for natural processes to return the river to its initial condition. As a result of climate-induced floods occurring in meandering rivers, can cause significant and long-lasting impacts on the shape and structure of rivers (Miller, 1990).

Additionally, the magnitude and frequency of floods in meandering river mechanisms have been consistently investigated and well-documented over time. A study conducted in 1960 by Wolman and Miller revealed that infrequent severe floods tend to have a greater effect on altering river channels, compared to frequent but less severe floods. And this argument was supported by various subsequent studies later. For example, Gay et al. (1998) noted that the Powder River, in Montana experiences cutoff formations and expansions primarily linked to multiple occurrences of flooding events. The floods exert power to break through the bends in the river course, leading to alterations in its shape and direction. Flow patterns change frequently in periods of intense flooding, as observed in research conducted on the Lower Mississippi River (Matthes 1948). During these high-flow stages, floods tend to overtop the riverbank and develop new river channel between the meander bend. In the Meshwa River located in North Gujarat, India (Raj et al., 2015), a flood in 2009 resulted in around 1.75 kilometres of channel movement at a rate of approximately 250 meters per year. The consequence of these changes brought about the formation of cutoffs, which significantly affected the meandering river course. Similarly, research focusing on a 1-in-100-year flood in the South Saskatchewan River in Alberta demonstrated how infrequent but high-magnitude floods can affect sediment characteristics in meandering rivers. These floods have sufficient stream power to initiate and accelerate the formation of cutoffs by eroding channels at bends along the river path (Hagstrom et al., 2018). Overall, these findings point out the significance of high-magnitude but rarely occurring floods in shaping meandering river channels and contributing to the formation of cutoffs.

4.2 The Role of Landscape Drivers

Establishing vegetation along the riverbanks can promote the formation of meandering river channels (Huthoff, 2012; Raupach, 1992). This process can help restrict the channel movement and its erosive capacity in rivers (Kyuka et al., 2021). The presence of vegetation cover in rivers can reduce river flows through increasing its resistance to form and pressure drag effects. This decrease in flow velocity reduces shear velocity and rivers' erosive capacity over time, thereby leading to fewer cutoff formations (Aberle, 2012). A study shows that even if the width of the neck cutoff is decreased to 40 percent of the channel width, the complete formation of a neck cutoff takes longer. In this case, the impact of increased discharge, on this process is very minimal (Li et al., 2022). However, floodplains that have shallow-rooted plants can increase channel movement and migration. The formation of cutoffs improves rivers' ability to store sediment. The influence of vegetation on river meandering can differ based on various factors, such as its characteristics, age and structure (Nikora, 2010; Yang & Choi, 2009). When the water depth surpasses the height of vegetation growth significantly, the flow behavior can vary greatly.

Therefore, this disparity highlights the use of different flow modelling methods, specifically for non-submerged and submerged conditions (Finnigan, 2000; Nepf & Vivoni, 2000; A. N. Sukhodolov & Sukhodolova, 2010).

The presence of plants typically decreases the creation of channels, in rivers like braided river systems (Ielpi et al., 2021). As plants grow and take root in the sediment bars along the riverbanks, the braided channels tend to merge into meandering channels over time (Gran & Paola, 2001; Van Dijk et al., 2012). Plant stems play an important role in increasing flow resistance and reducing erosion by facilitating transpiration and interception processes, which results in promoting the settling of fine cohesive sediments along riverbanks (Camporeale et al., 2013). On the other hand, the growth of plant roots helps in soil compaction which leads to improved bank cohesion (Simon & Collison, 2002). Specifically, riparian vegetation such as trees, bushes and grasses located along riverbanks substantially help stabilize river banks through their root networks that bind soil and sediment particles together. The existence of riparian vegetation helps prevent erosion along riverbanks, resulting in a gradual development of meandering patterns in the riverbeds. Vegetation roots serve functions in stabilizing the riverbanks and reducing channel migration as time progresses (Crosato & Saleh, 2011; Kyuka et al., 2021; Tal & Paola, 2010). On the other hand, multiple studies suggest that, instead of simplifying multi-channel systems into single-thread channels, the presence of immature, erosion-resistant and extensive vegetation can promote flow bifurcation and increase the complexity of the overall meandering patterns (Coulthard, 2005; Kyuka et al., 2021). In instances of currents or high-water levels in rivers and streams, the existence of trees or dense shrubs extending into the flowing water may cause localized turbulence, altering the flow pattern and intensifying hydraulic pressure along certain parts of the riverbank. This can result in bank erosion and decreases in the stability of those sections along the riverbanks cama; van Oorschot et al., 2016).

5 Spatial Clustering of Cutoffs

The phenomenon of cutoff clustering is often observed in diverse natural landscapes where multiple cutoffs occur closely together in a short spatial and temporal proximity. Their occurrences are typically affected by a combination of allogenic and autogenic forces, such as land cover, water flow patterns and human interventions (Slowik, 2016). However, the triggers and mechanisms of these events can be site-specific and vary significantly through time and space (Ielpi et al., 2021). Accordingly, they often cause marked changes in the shape and structure of meandering rivers at both local and regional scales and create complex feedback mechanisms and long-lasting influence in meandering networks (Schwenk & Foufoula-Georgiou, 2016). Understanding the mechanisms and causes of locally clustered cutoffs is especially important for meandering river system monitoring, flood prevention and natural habitat protection.

5.1 Clustering of Cutoffs

Clustering of cutoffs usually happens because feedback mechanisms are activated by the initiation of one single cutoff formation causing changes in hydrological processes and geomorphic features (Van Dijk et al., 2014). Clustering starts when the initial cutoff disrupts the river's natural flow balance, leading to water movement and a steeper riverbed slope. These changes in water flow patterns can reduce the stability of local meander bends, causing them to be more prone to erosion and creating more cutoffs (Ielpi et al., 2021c; Morais et al., 2016). Specifically, the formation of cutoffs is often a result of frequent occurrences of high flows that maintain sufficient shear stress and stream power in rivers for extended periods. These intense events provide the conditions for carving out bends in the river within the same section (Hooke, 2004). If the natural river systems are not capable of restoring hydraulic balance after the occurrence of the first cutoff, subsequent high-flow events will continue to exert or even increase the shear stress on the remaining bends in the river. Due to the long-term periods of constant high-flow events in rivers, the cumulative impacts of these floods can progressively destabilize these sections of the river and trigger the development of clustered cutoffs. For instance, the Lower Mississippi River is highly prone to cutoff clustering due to its intense flood events during peak flow seasons (Biedenharn et al., 2000).

When considering river geomorphology as a factor, patterns of floodplain spatial heterogeneity, such as land cover, sediment composition and surface elevation, can also influence cutoff clustering (Güneralp & Rhoads, 2011; Zinger et al., 2013). Research shows that cutoff clustering tends to occur in flood-prone areas which contain fine-grained materials like sand and silts that are easily washed away by high-flow events (Gay et al., 1998). And the absence and vanishing of vegetation cover can decrease riverbank stability, resulting in a significant increase in the likelihood of cutoff clustering. Over time, the weakening of riverbanks due to vegetation loss makes them more prone to erosion and subsequent cutoff events (Van Dijk et al., 2013). Besides, studies also found that clusters of cutoffs tend to be more prevalent in rivers with high sinuosity and low slopes (J. A. Constantine & Dunne, 2008; Hooke, 2004). As the first cutoff occurs in such rivers, they allow a higher rate of energy transport capacity, which can easily transport energy and cause instability along the floodplain. These changes can worsen meander bend migration and erosion over short distances, ultimately triggering and accelerating the cutoff clustering process (Zinger et al. 2011).

5.2 Single vs. Clustered Cutoffs

The creation of a single cutoff is often influenced by the conditions at a local meander bend where the interaction among hydraulic forces, sediment movement and land cover create the ideal conditions for a meander to breach its neck (Hooke, 2004; Zinger et al., 2011). For example, single cutoffs typically occur as incidents during high flow periods when specific localized factors promote the erosion of meander necks. These occurrences usually happen within a local section of a river. They are influenced by short-term hydrodynamic factors like peak discharge during flood events (Raj et al., 2015). On the other hand, the clustering of cutoffs often represents a larger-scale hydrologic response to meandering river dynamics. They often occur gradually over extended periods of time and experience multiple flood cycles or prolonged periods of high discharge events. The continuous occurrence of flow events triggers a cascading effect leading to the formation of clustered cutoffs that reshape the river channel and floodplain over an extended duration (Schwenk & Foufoula-Georgiou, 2016; Slowik, 2016). Overall, single cutoffs are usually caused by bend features and immediate hydrodynamic pressures, while clustered cutoffs tend to be affected by long-term systemic processes that impact broader sections of the river.

Chapter 2
Assessing Discharge, Land Cover Influence and Clustering Mechanisms in River Cutoffs

1 Introduction

Numerical models and experiments demonstrate that a river cutoff is a phenomenon that demonstrates that a meandering river is a self-organized process. The state of meandering rivers typically fluctuates between equilibrium and chaos. Simulated rivers (e.g., Stolum, 1996) typically start in their most stable state, a straight channel. Channel migration and sinuosity begin to occur and increase, eventually reaching a chaotic state where major changes to the river's structure occur, the occurrence of cutoffs ends the continuing meandering tendency and pushes the river system back to a temporary equilibrium (Asahi et al., 2013; Stølum, 1996; Van Dijk et al., 2012). The occurrence of a river cutoff acts as a trigger to stabilize its shape and reduce the impact of short-term fluid dynamics on long-term meandering development (Frascati & Lanzoni, 2009; Stølum, 1996). Specifically, the occurrence of river cutoffs removes old meanders, and reduces meander elongation caused by bend erosion, resulting in the reduction of planform complexity (Frascati & Lanzoni, 2009).

Stolum's simulations (1996) also demonstrated that the presence of cutoff clustering reduces the sinuosity of rivers. And the formation of one cutoff is usually accompanied by a cluster of other cutoffs in its vicinity due to the decrease in channel length and increase in sediment transport. While the direct impact of river cutoffs reduces sinuosity, the long-term effect of river cutoffs can vary significantly depending on their current states. In an ordered state, cutoff clustering can intensify bend asymmetries, whereas it can also reduce asymmetries and restore order to the channel during a chaotic state. In summary, the clustering of cutoffs plays a key role in the transition between chaotic and ordered states in meandering rivers (Camporeale et al., 2008; Schwenk & Foufoula-Georgiou, 2016; Slowik, 2016; Van Dijk et al., 2012; Viero et al., 2018).

Three developmental phases in the meandering of rivers have been identified: elongation of bends, migration of channels and formation of cutoffs (Camporeale et al., 2008). Elongation usually occurs as the outer banks are worn away by increased river flow, while sediment builds up along the banks with lower flow rates leading to the gradual formation of bends over time. As the elongation process progresses down the river path, the meander loop begins to shift more prominently over time until it eventually completes a full shift along its meandering course. This transformation not merely changes the flow patterns of water, but also redistributes and pushes sediments downstream, which has a significant impact on the landscapes and ecosystems in their vicinity. This shifting of sediment in river systems has the potential to create habitats for both land and aquatic species but also has the capacity to disrupt and damage established environments, such as flooding plant species, changing river channel structure and damaging human infrastructure (Shankman, 1996). In the stage of cutoff formation, the existing meandering river planform keeps evolving as elongation and migration processes are intensified and accumulated over time. This leads to the creation of a shortcut that bypasses meanders and allows water to flow through a more direct downslope path (Hooke, 2004; Slowik, 2016). The further development of cutoffs typically exhibits variations based on the allogenic and autogenic processes involved in the case. The former meandering path often transforms into an oxbow lake disconnected and isolated from the main river channel (Hudson et al., 2000). And over time, oxbow lakes become and serve as distinctive habitats for certain wildlife species (Ward, 1998).

Despite the implementation of advanced technologies and methodologies since the 19th century, scientists are still confronting various challenges in studying river cutoffs due to the complex meandering river systems (J. A. Constantine et al., 2014; J. A. Constantine, McLean, et al., 2010; Konsoer et al., 2016; Peakall et al., 2007). It is widely recognized that the indicators for river cutoff occurrence are not universal or consistent at different scales, even within the same river network. The high temporal and spatial variation in the occurrence of river cutoffs complicate and lengthen the data collection and analysis processes, making it difficult to generate a particularly accurate and standardized model to generalize and represent river cutoffs across different river systems (Gao & Li, 2024; Konsoer et al., 2016). And predicting the occurrences is even harder considering the large number of indicators involved.

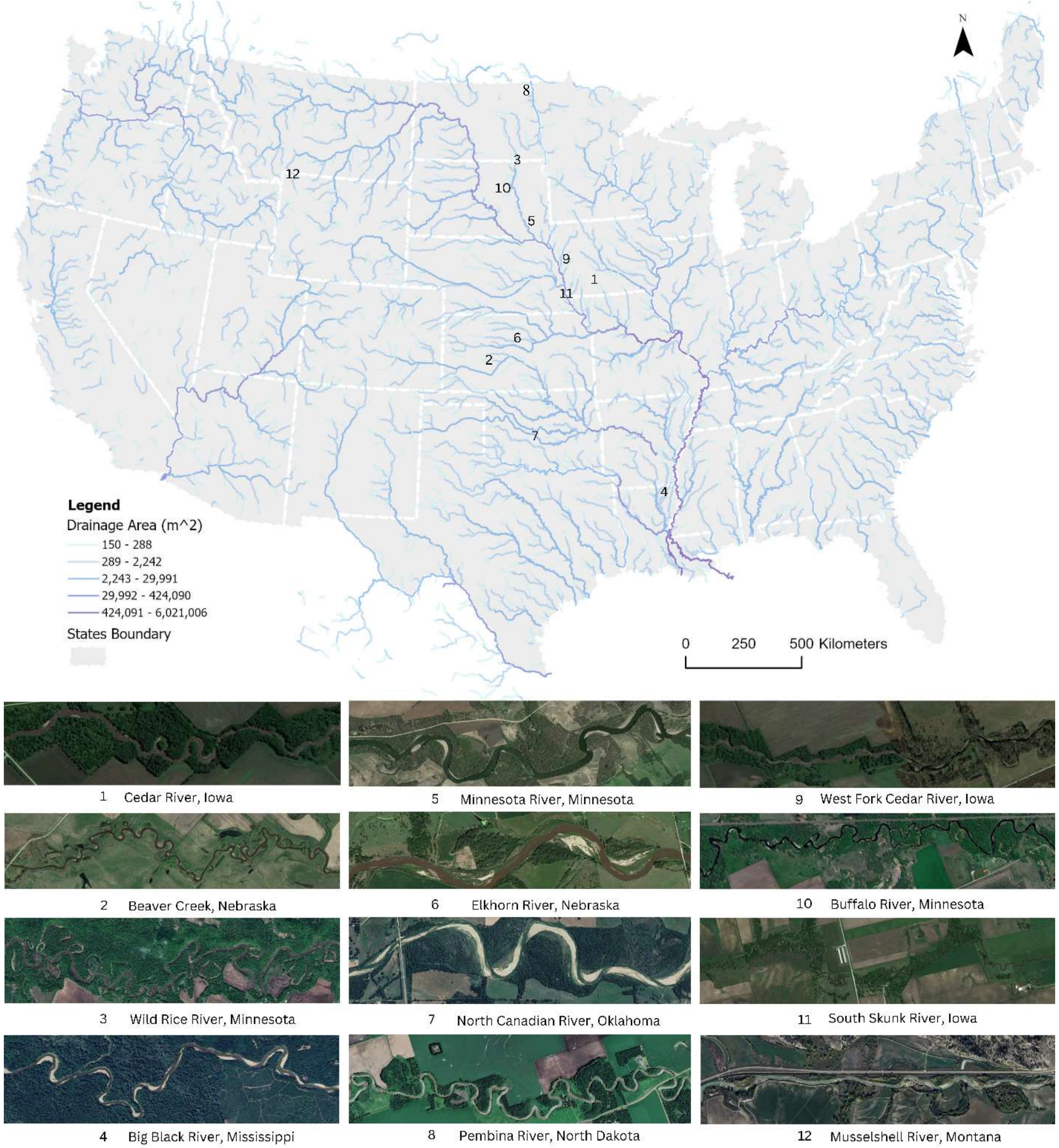
The hydrological conditions necessary to trigger cutoff occurrences remain a topic of debate. Many studies indicate that high-flow events are the primary driver, whereby high precipitation leads to bankfull or near-bankfull discharge that can generate the shear stress and stream power needed to force overbank flow, thereby leading to the formation of cutoffs (Hooke, 2004; Maitan et al., 2024). However, others point out that the amount of flow required to initiate the cutoffs can vary significantly and can occur before streams reach bankfull discharges (Van Dijk et al., 2014; Viero et al., 2018). To better understand the factors contributing to cutoff formation, long-term extensive spatial datasets, quantifiable methods and cross-regional analyses are used to 1) determine the relationship between high-flow events and cutoff occurrences, using data from twelve meandering rivers with large numbers of cutoff occurrences across the United States; 2) investigate the impact of land cover on cutoff formation; and 3) assess the connection between neighbouring cutoffs to reveal the clustering mechanisms behind cutoff formations.

2 Methods

2.1 Study Area

To investigate the relationship between discharge and cutoff formation, twelve meandering rivers with high sinuosity and frequent cutoff occurrences across the United States are investigated (Figure 3): Cedar River (Iowa), Beaver Creek (Nebraska), Wild Rice River (Minnesota), Big Black River (Mississippi), Minnesota River (Minnesota), Elkhorn River (Nebraska), North

Canadian River (Oklahoma), Pembina River (North Dakota), Buffalo River (Minnesota), South Skunk River (Iowa), Musselshell River (Montana).



1 Cedar River, Iowa

5 Minnesota River, Minnesota

9 West Fork Cedar River, Iowa

2 Beaver Creek, Nebraska

6 Elkhorn River, Nebraska

10 Buffalo River, Minnesota

3 Wild Rice River, Minnesota

7 North Canadian River, Oklahoma

11 South Skunk River, Iowa

4 Big Black River, Mississippi

8 Pembina River, North Dakota

12 Musselshell River, Montana

Figure 3: The locations of 12 meandering rivers, used in this study, within the United States with corresponding satellite imagery demonstrating adjacent land-cover types.

The study areas of this research focus on 12 meandering rivers across the United States, which are selected based on their data availability, geographical diversity and the presence of active cutoff occurrences. Specifically, this research prioritizes study areas with three key datasets: extensive USGS discharge records, which provide long-term hydrological data for understanding flow dynamics in rivers; historical satellite imagery from Google Earth, which provides the time slider function for cutoff identification in rivers; and comprehensive NLCD land cover data, which allows further statistical analyses on the relationship between cutoff occurrences and their land cover types in proximity. Detailed descriptions of these three datasets are explained in the following section. Secondly, the study areas are distributed across the United States, which captures variabilities in land cover type, climatic conditions, and geological settings. Lastly, a number of cutoff occurrences greater than 10 is observed in each river. Overall, the selection criteria above ensure that these selected study areas are suitable for representing and investigating the complexity and interactions associated with river cutoff processes.

Furthermore, the physical and hydrological characteristics of the 12 rivers are summarized in Table 1, including river length, river sinuosity, adjacent ecoregions, cutoff starting and ending points and river primary source. River sinuosity is calculated by dividing the river length by the straight-line distance between its source and mouth (Barman & C.Goswami, 2015; Yu et al., 2023). And the straight-line distance is measured manually on ArcGIS. The adjacent ecoregions indicate the geographical diversity of the 12 rivers, contributing to variabilities in land cover types, climate conditions and geological settings. Additionally, the cutoff starting point and ending point highlight the precise spatial coordinates of the first and last cutoffs occurring within the river. Lastly, the primary source identifies the dominant hydrological driver contributing to changes in the hydrological condition for each river, categorized into precipitation, groundwater and snowmelt (Benson & Thomas, 1966; Li & Quiring, 2021). Specifically, based on the USGS streamflow data in each river, rivers exhibiting high discharges during or immediately after major rainfall events are primarily sourced from precipitation and classified as precipitation-fed rivers. Snow-fed rivers are identified while gradual seasonal increases observed in river flow during spring or early summer. Despite the influence of seasonal precipitation patterns, rivers showing consistent water flow year-round are classified as groundwater-fed rivers (USGS, 2024).

Table 1: Summary of the study areas

River	River length (km)	River sinuosity	Adjacent ecoregions	Cutoff starting point	Cutoff ending point	Primary source
Beaver Creek	27	3.37	Central Great Plains, Western Corn Belt, Sand Hills	41°57'5.06"N, 98°27'49.46"W	41°25'59.28"N, 97°42'32.06"W	Precipitation
Big Black River	530	5.41	Southeastern Plains, Mississippi Valley Loess Plains	33°15'30.32"N, 89°43'18.09"W	32°36'14.62"N, 90°21'33.68"W	Precipitation
Buffalo River	224	5.60	Northern Lakes and Forests, North Central Hardwood Forests, Red River Valley	46°53'51.46"N, 96°36'27.13"W	46°56'59.35"N, 96° 6'27.79"W	Precipitation

Cedar River	20	1.92	Central Great Plains, Nebraska Sand Hills	41°57'17.12"N, 98°52'9.60"W	41°42'38.36"N, 98°26'48.73"W	Groundwater
Elkhorn River	470	1.90	Nebraska Sandhills, Western Corn Belt Plains, Central Great Plains	42°30'59.68"N, 98°58'2.53"W	41°28'53.00"N, 96°24'55.39"W	Groundwater
Minnesota River	534	2.48	Northern Glaciated Plains, Western Corn Belt Plains, North Central Hardwood Forests	44°42'55.17"N, 95°23'45.63"W	44°12'31.57"N, 94°13'35.13"W	Snowmelt
Musselshell River	550	2.53	Northwestern Great Plains, Missouri Plateau	46°26'38.25"N, 110°24'19.33"W	47°16'20.73"N, 107°57'39.20"W	Snowmelt
North Canadian River	710	1.90	Central Great Plains	35°30'21.36"N, 97°13'29.12"W	35°20'6.05"N, 96°11'17.91"W	Precipitation
Pembina River	513	2.14	Southwest Manitoba Uplands (Canada), Northern Glaciated Plains (United States)	48°53'47.44"N, 97°55'54.20"W	48°56'36.43"N, 97°20'39.59"W	Precipitation
South Skunk River	298	1.58	Des Moines Lobe, Central Irregular Plains	42°24'20.51"N, 93°35'43.18"W	41°58'47.95"N, 93°35'8.58"W	Precipitation
West Fork Cedar River	68	1.48	Des Moines Lobe	42°55'50.97"N, 93°21'18.34"W	42°37'45.23"N, 92°37'44.86"W	Precipitation
Wild Rice River	404	4.12	Northern Lakes and Forests, North Central Hardwood Forests, Lake Agassiz Plain	47°17'7.70"N, 96°23'22.51"W	47°24'50.83"N, 95°36'34.68"W	Precipitation

Notes: Data for river length from Esri et al. (2023); Data for adjacent ecoregions from Level III Ecoregions of North America (EPA, 2024); Data for primary river source from Li & Quiring (2021) and USGS (2024).

2.2 Data

Three datasets are used to investigate the relationships of river cutoff occurrences with discharge, land cover and spatial clustering (Figure 4). First, hydrological data were acquired from the United States Geological Survey. The USGS data provide detailed historical records of river discharge, flood stage, and gage height across the United States (USGS, 2020). Annual average discharge data are chosen for conducting flood frequency analysis and return period and exceedance probability for cutoff discharge data are calculated. Second, landscape imagery ranging from 1985 to 2023 were acquired from Google Earth, which is sourced from the Airbus satellites called Pléiades Neo. It is an optical constellation with two identical 30 cm resolution satellites (Airbus, 2024). Satellite imagery is used to closely identify cutoff locations and catch the time frame of each cutoff event. Using this approach a novel dataset comprising 1,186 river cutoff occurrences across the United States was created (Figure 5). Spatial clustering analysis and meandering cutoff ratio were then conducted and calculated using this dataset. Third, the 2021 National Land Cover Database (NLCD), with a spatial resolution of 30 meters, are the land cover products created by the Multi-Resolution Land Characteristics (MRLC) consortium, which provide spatially accurate and detailed information regarding land cover types at a national scale (Dewitz, 2023). In this research, this dataset was first clipped and reclassified into four land cover types in ArcGIS. Integrating the meandering cutoff ratio generated from Google Earth imagery, statistical analyses were conducted to investigate the relationship between cutoff occurrences and their land cover types in proximity. Overall, this thesis uses freely available data that enable the methods to be employed by others.

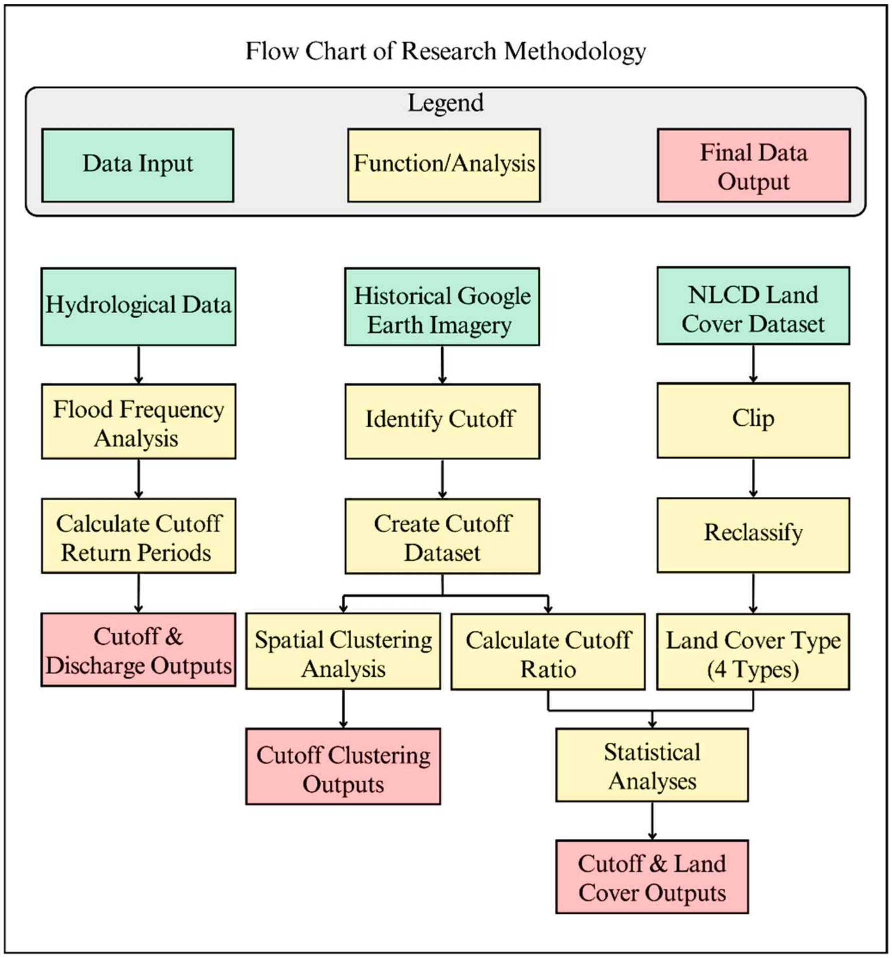


Figure 4: Data flow diagram

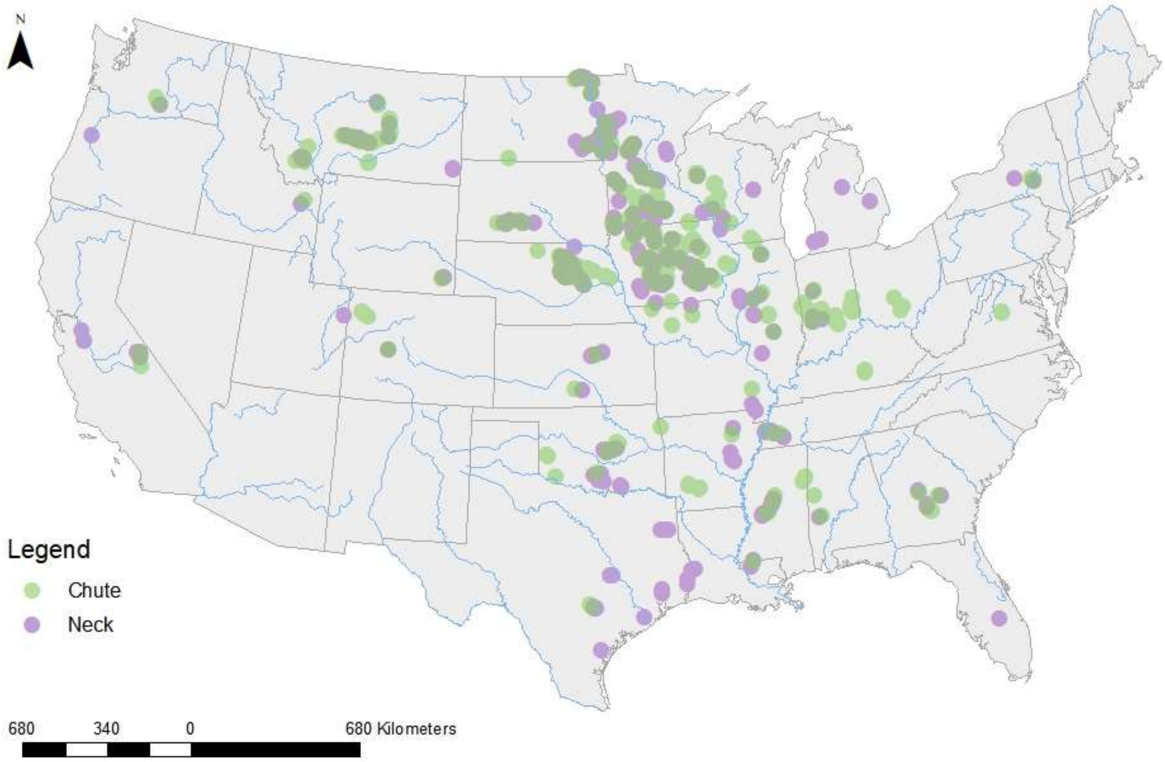


Figure 5: The geographic distribution of chute and neck cutoffs across United States. The locations of these cutoffs are marked using two distinct colors: green circles represent chute cutoffs, which occur when a river forms a new, shorter channel, bypassing the older meandering loop. Purple shows neck cutoffs, which occur when the narrow neck between two bends of a river is eroded, allowing the river to cut through and abandon the meander loop.

2.2.1 Hydrological Data

In this research, hydrologic data are retrieved from the closest gauging stations to the identified cutoff locations, which are recorded in the National Water Information System of the United States Geological Survey (USGS). Based on the USGS-provided discharge data, the maximum discharge values occurred during the cutoff occurrences are assigned as the most likely flood event responsible for the cutoffs. These values are collectively referred to as the “cutoff discharge data”. Flood frequency analysis is then applied in each river to determine discharge data corresponding to specific return periods along rivers and the recurrence interval (T) and probability of exceedance (P) are calculated using the Weibull equation:

$$T = \frac{(n+1)}{m_i} \tag{1}$$

$$P = \frac{m_i}{(n+1)} \tag{2}$$

where n is the total number of discharge events and m_i represents the rank of the ith event. Scatter plots are made where discharge (cfs) is on the y-axis and recurrence intervals are on the x-axis. The trendline equations represent the lines that best fit the relationship between discharge and return periods, thereby the USGS cutoff discharge data are plugged in for y in the equations, resulting in x, which shows how often the floods of these given cutoff discharge data would occur throughout the entire available time frame.

2.2.2 Google Earth Imagery

This study uses Google Earth (GE) imagery for cutoff identifications. It not merely offers geospatial information for identifying river cutoffs over time but is also effective for inspecting different river systems and detecting chute and neck cutoff points. The accessibility and extensive temporal coverage of Google Earth imagery, which dates back to the 1990s, benefit researchers by providing us with a comprehensive dataset for detailed cutoff analysis.

The approach used to extract data from Google Earth involves a hands-on review of satellite images to detect and record cutoff events. By using the Time Slider bar, it starts with inspecting different river sections for indicators of chute and neck cutoffs where a shorter channel forms to bypass a bend in the meander. A comparison of pre- and post- occurrence imagery is performed to verify the cutoff formation aligning with geomorphological changes. Before a potential cutoff event is spotted, observations are made at a consistent zoom level for all the study areas, with the imagery set to a scale of 1:170 to ensure accuracy and consistency across different study areas. Once a cutoff event is spotted, its location is identified and labelled at the midpoint between the inlet and outlet of the newly formed shortcut, aligned with the centerline of the river channel. The assignment also involves identifying the latitude and longitude of the cutoff and making sure that their spatial precision is preserved (Figure 6). The geospatial information is recorded and structured correspondingly, which allows it to be combined and integrated with other spatial datasets, like hydrological and land cover data. After identifying the first cutoff occurrence, the same methodology is applied to the next one until no additional cutoffs are observed among the historical Google Earth imagery for each river.

Meanwhile, the estimated date of each cutoff event is determined by examining the imagery before and after the formation of the cutoff point, which helps in providing an estimate of when the cutoff took place, and it is essentially important for correlating these occurrences with hydrological and geomorphological information. Since cutoff events on this platform are restricted to those observable within the timeframe covered by Google Earth imagery, only cutoff events happening after the earliest available images are taken into account in this dataset. Lastly, the average upstream river width is also generated by calculating the mean of the upstream river widths located near each cutoff occurrence. And the river widths are measured perpendicular to the water flow within 100 meters upstream of the cutoff locations and collected prior to cutoff occurrences, using the ruler tool with a scale of 1:170 on Google Earth. Overall, this collection of dataset helps in visualizing and comprehending how cutoff occurrences are spread out through space and time.

Figure 6: An example of the evolution of a chute cutoff in the Cedar River, United States (2011, 2015, 2020)

2.2.3 Land Cover Data

To conduct land cover analysis near river cutoff points, this study processes the NLCD dataset on ArcGIS, which starts with extracting spatial land cover data for the identified 12 research sites, specifically with a focus on the river sections surrounding the identified chute and neck cutoffs. This extracted data are then processed and reclassified through ArcGIS tools. Specifically, the land cover dataset with the default NLCD land cover categories is clipped and allocated into the twelve study areas. The NLCD categories are then aggregated and reclassified into broader land cover types to simplify the analysis while preserving key features that could impact river behaviour. The aggregation and reclassification processes concentrate on those land cover categories with levels of surface roughness and vegetation density that are known to significantly influence hydrological processes and the creation of river cutoffs. It consists of croplands, forests (deciduous and coniferous trees), unvegetated areas (such as open water, and developed land), and woody wetlands. This categorization system aims to highlight the variations in flow resistance among distinctive land cover types, indicating the significance of land cover on sediment movement and erosion that leads to the creation of cutoff channels.

2.2.4 Meandering Cutoff Ratio

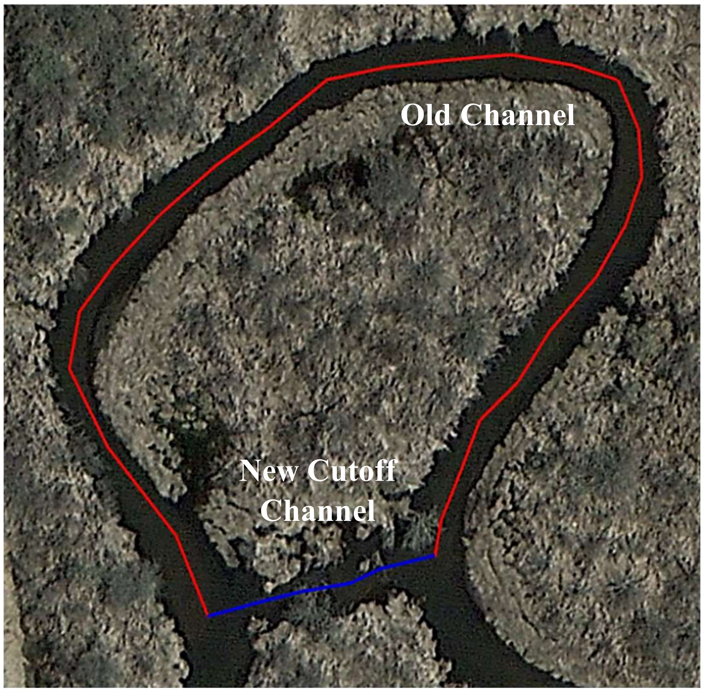


Figure 7: Schematic diagram of cutoff ratio

The cutoff ratio criterion is commonly used to characterize the length of cutoffs and the length of old channels in rivers, which is significantly influenced by the floodplain erodibility (Joglekar 1971). It is defined as:

$$CR = \frac{ol}{cl} \tag{3}$$

where the cutoff ratio (CR) equals the length of the old bypassed channel (ol) divided by the length of the new cutoff channel (cl) (Figure 7). Due to the high sinuosity in meandering rivers, the length of the new cutoff channel is always found to be smaller than the old channel length (Jagers, 2003). In this study, we modified Joglekar's equation by swapping the numerator and denominator in the fraction to find its reciprocal. And the results are displayed as decimal numbers to better represent the variations in the context of meandering rivers, which is expressed as:

$$CR_m = \frac{cl}{ol} \tag{4}$$

The value of CR_m ranges from 0 to 1 and is tightly associated with floodplain erodibility, where high CR_m indicates that the floodplain is more susceptible to erosion and low CR_m value suggests its high resistance to erosion (Jagers, 2003).

2.3 Statistical Analysis

2.3.1 Assessing the Impact of Land Cover on Cutoffs

Given the categorized variable (land cover type) involved in this study, we applied a One-way ANOVA Test to assess the differences in the cutoff ratio means among different land cover types. F statistic and p-value are calculated to determine whether there is a significant difference between the group means, which is defined as:

$$F = \frac{MST}{MSE} \tag{5}$$

where F is the F test statistic, MST is regression mean square, MSE is error mean square. A p-value of 0.05 or greater indicates that there is no association between land cover type and cutoff ratio; whereas a p-value lower than 0.05 means that we reject the null hypothesis that the group means are equal.

To further identify and compare the differences between specific land cover types, the Mann-Whitney U test is performed in R using “pairwise.wilcox.test” function with “paired = FALSE” since the land cover types and cutoff ratio are two independent variables. The Mann-Whitney U statistic is defined as:

$$U_1 = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1 \tag{6}$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2 + 1)}{2} - R_2 \tag{7}$$

where U_1 and U_2 are the U statistics for the individual groups, n_1, n_2 are the sample sizes and R_1, R_2 refers to the sum of the ranks for each group respectively. And the distributions of both variables are considered identical under the null hypothesis, whereas the alternative hypothesis assumes that their distributions are not identical.

Additionally, boxplot and bar chart are generated to visualize and discover the impact of land cover on meandering cutoff ratio and cutoff type. The boxplot highlights the distribution of cutoff ratio across different land cover types and the bar chart represents and compares the quantities of chute and neck cutoffs across different land cover types.

2.3.2 Spatial Clustering Analysis

In meandering rivers, the formation of river cutoffs can occur somewhat instantaneously or over long time periods depending on the allogenic and autogenic factors involved. Due to the lack of consistent historical data records and the rapidity of some cutoff formations, satellite imagery data within a certain time frame cannot always be used to specify the timing of their occurrences within a river channel. In most cases, channel elongation and migration can be observed over time, but the next phase of cutoff formation might only be identified based on the non-existing old river channel and new shortcut formation on a map. As a river continues evolving over time, the location of cutoff occurrence might also be pushed away from the main river channel, resulting in the vicinity of the original river network. Instead of intersecting with the river network itself, river cutoff occurrences are often found in proximity to it. When considering statistical measures for this case, this study accepts that the distribution of cutoff occurrences should be affected by river networks, but cannot be confined.

To study the cumulative distribution patterns of cutoff occurrences, the multi-distance spatial cluster analysis called the K function is used in R Studio (Equation 5, Ripley, 1977), where r is the search radius, a indicates the selected study area, n is the number of data points within the study area, d_{ij} represents the distance between the i and j points, $I(d_{ij} \leq r)$ is the indicator equals to 1 when d_{ij} is smaller than or equal to r, otherwise, it equals 0; and e_{ij} represents the weight of edge correction.

$$\widehat{K}(r) = \frac{a}{n(n-1)} \sum_{i} \sum_{j} I(d_{ij} \leq r) e_{ij} \tag{8}$$

In a case with random Poisson distribution, the expected $\widehat{K}(r)$ should be close to the value of πr^2. Given the difficulty with interpreting the K function, it is often normalized to aid interpretation and represented visually using the L function (Besag, 1977), which is defined as:

$$L(r) = \sqrt{(\widehat{K}(r)/\pi)} \tag{9}$$

where r is the search radius and $\widehat{K}(r)$ represents the Ripley's K function value. L function is basically the square root of K function divided by π and the expected L function value should equal the radius r.

The L function can be used to assess the cutoff clustering or dispersion as distance increases among their occurrences. To improve result interpretation, this spatial clustering analysis is also performed and generated with complete spatial randomness and confidence envelopes. The same statistical measure is employed in both ArcGIS and R Studio, allowing comparison between their performances in K functions and evaluation of their compatibility with this river cutoff dataset. Specifically, distance bands are selected and 99 sets of points are randomly placed to compute the confidence envelope. Given the high spatial coverage of this dataset, the minimum enclosing rectangle is identified as the study area method, which generates the smallest possible rectangle enclosing all of the identified cutoff points across the United States. Ripley's edge correction formula is then selected as the boundary correction method to fit the rectangular-shaped study area.

3 Results

3.1 Summary of Cutoffs

The analysis of cutoff dynamics provides valuable evidence for studying river morphology and the mechanisms governing channel evolution. Among the 12 rivers analyzed, a total of 418 cutoff occurrences are identified, including 154 chute cutoffs and 151 neck cutoffs (Table 2). Results show that most cutoff ratios range between 0.1 and 0.3 and the frequency decreases significantly as the ratio increases beyond 0.3 (Figure 7). The distribution of neck cutoffs is more concentrated at lower cutoff ratios with minimal occurrences above 0.4, whereas chute cutoffs tend to display a broader frequency distribution compared to neck cutoffs. The frequency of chute cutoff ratio extends more evenly toward higher ratio values from 0.4 to 0.7, indicating that they can occur at a wider range of values than neck cutoffs.

Table 2: Summary of cutoff information for each river

River	Total cutoffs	Number of chute cutoffs	Number of neck cutoffs	Average upstream river width (m) in proximity
Beaver Creek	81	15	47	14.97
Big Black River	24	5	11	43.75
Buffalo River	27	2	15	16.67
Cedar River	44	11	23	17.83
Elkhorn River	29	17	4	44.52
Minnesota River	25	22	1	82.80
Musselshell River	79	54	6	26.75
North Canadian River	27	5	6	62.04
Pembina River	16	2	11	32.81
South Skunk River	15	5	6	24.12
West Fork Cedar River	16	10	1	17.38
Wild Rice River	35	6	20	25.29
Total	418	154	151	

Notes: The river widths were measured within 100 meters upstream of the cutoff occurrences, using a scale of 1:170 on Google Earth.

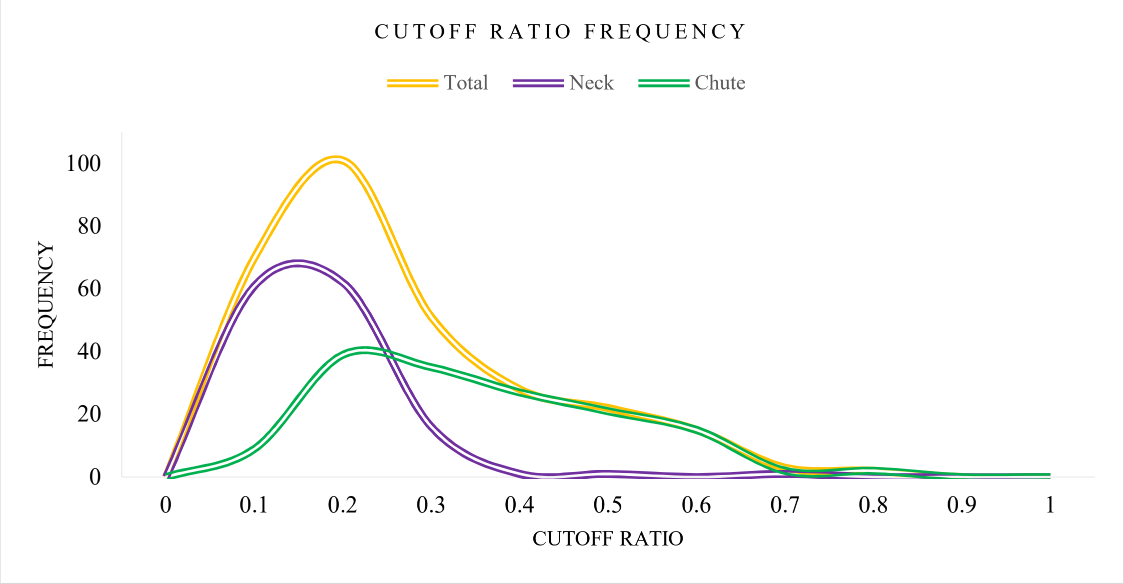
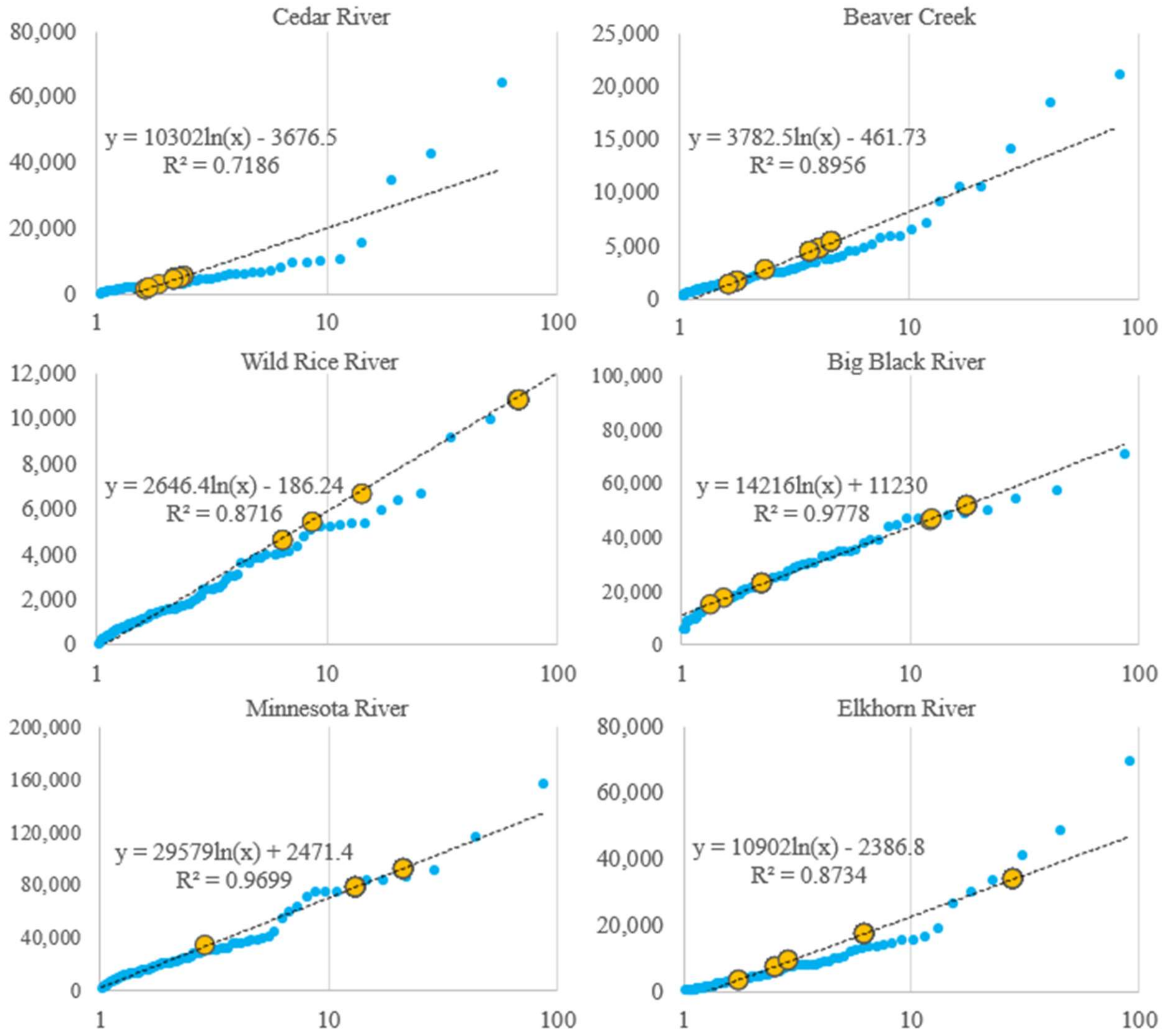


Figure 8: Cutoff Ratio Frequency

3.2 Flood Frequency Analysis

To determine if higher discharges with longer return periods tend to cause river cutoff occurrences a flood frequency analysis was conducted using the observed discharge data from the United States Geological Survey (USGS). The results demonstrate that, across the 12 rivers comprising our study area, the average return period for cutoff discharges is approximately 11 years (Table 3) and there is a strong positive correlation ($R^2 \geq 0.7$) between the return period and discharge for most rivers (Figure 9). Notably, floods with return periods of equal to or less than 10 years are responsible for 291 (78%) of 375 cutoff occurrences. These results contrast with the hypothesis that high discharge events are driving cutoff occurrences.



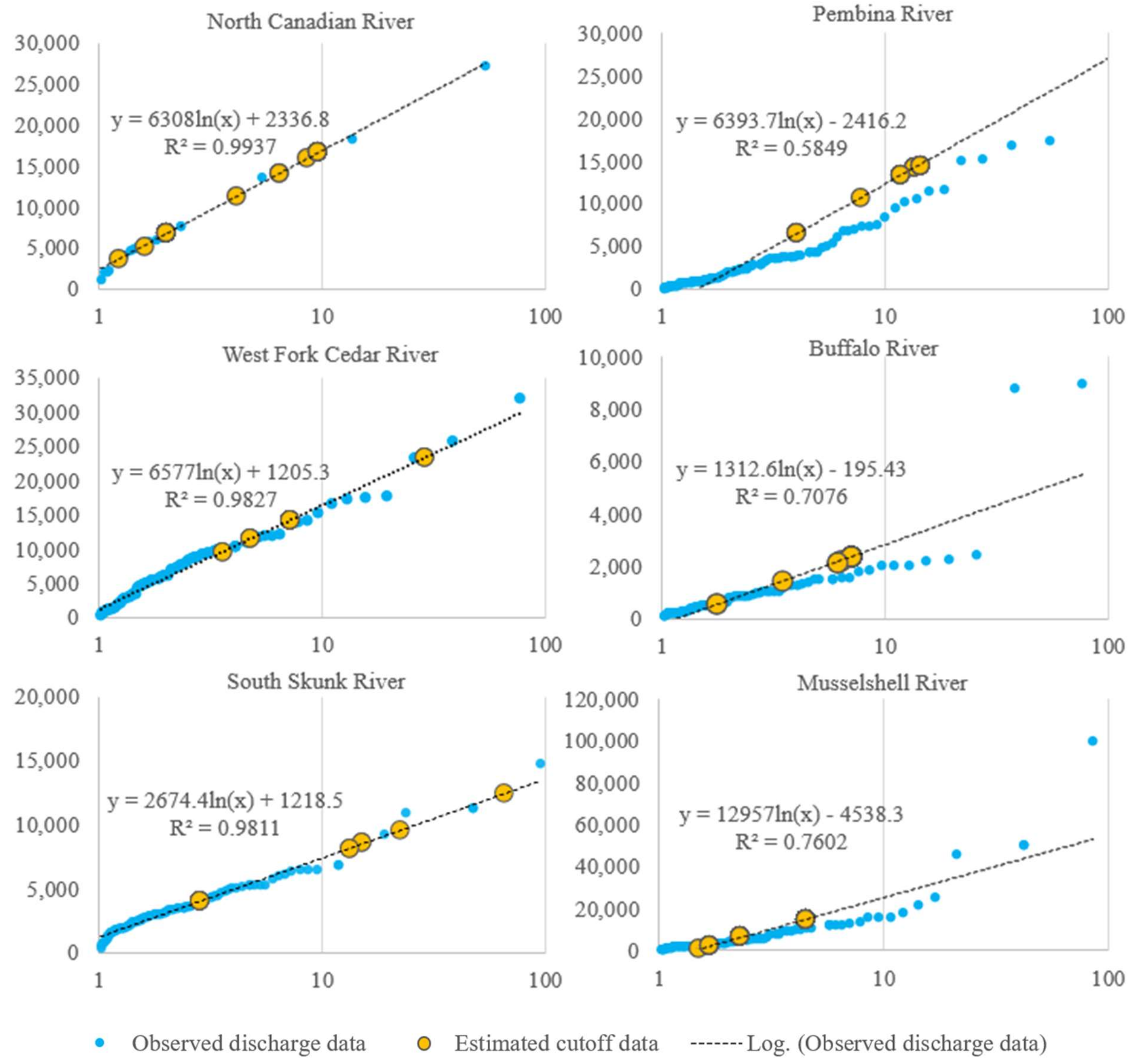


Figure 9: Flood frequency curves illustrate the relationship between flood discharge (y-axis, in cubic feet per second) and the recurrence interval (x-axis, in years) on a logarithmic scale. The yellow circles represent estimated discharge data for specific recurrence intervals, while the blue indicates observed discharge data. The black dashed line shows the fitted logarithmic regression curve for each river. The high R² values in each plot suggest stronger correlations between the variables.

Table 3: Summary of cutoff discharge, average return period, and percent chance of corresponding cutoff discharge being exceeded for the twelve study rivers. Total average return period is predominately affected by Wild Rice River since given its removal the average return period would be 8.34 years.

River	(a) Cutoff discharge (cfs)	(b) Average return period (year)	(c) % Chance of cutoff discharge (a) being exceeded
Beaver Creek	4105.42	3.55	28.2%
Big Black River	37681.25	10.06	9.9%
Buffalo River	2159.39	6.34	15.8%
Cedar River	4122.31	2.06	48.4%

Elkhorn River	19922.07	11.71	8.5%
Minnesota River	81366.67	14.75	6.8%
Musselshell River	12508.79	3.92	25.5%
North Canadian River	10458.80	4.49	22.3%
Pembina River	12466.25	11.21	8.9%
South Skunk River	6608.33	13.50	7.4%
West Fork Cedar River	14792.94	10.16	9.8%
Wild Rice River	8755.17	45.36	2.2%
Average	17912.28	11.43	16.2%

3.3 The Influence of Land Cover

To determine if there is an association between land cover type and the cutoff ratio, a one-way ANOVA was conducted. The results of the ANOVA test (p-value of 0.00035) demonstrate significant differences in the mean cutoff ratio for cutoffs located in proximity to different land-cover types (Table 4).

Table 4: The results of one-way ANOVA test between land cover type and cutoff ratio

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Cropland	122	20.83516513	0.170780042	0.014846498
Forest	54	8.546867799	0.15827533	0.013907634
Wetland	147	39.0795413	0.26584722	0.10413592
Unvegetated	52	14.36683842	0.276285354	0.027975562

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	0.974733962	3	0.324911321	6.289985921	0.000358495
Within Groups	19.16412874	371	0.051655334		
Total	20.1388627	374			

Given the results of the ANOVA test suggesting differences among the land-cover types, individual pairwise comparisons between each land-cover type were performed using a Mann-Whitney U test (Table 5). The results from these pairwise comparisons indicate that significant differences in cutoffs occur between wetland and cropland, unvegetated areas and forest, wetland and forest, with the greatest difference occurring between unvegetated areas and cropland.

Table 5: The results of the Mann-Whitney U test between land cover types

	Cropland	**Forest**	**Unvegetated**
Forest	0.68	-	-
Unvegetated	8.9e-06	8.7e-06	-

Wetland	1.2e-05	7.2e-05	0.19

Our results show that the median cutoff ratio is the highest for unvegetated areas, which also exhibit the widest interquartile range, indicating its significant variability and reduced resistance to erosion (Figure 10a). The median cutoff ratios for forest, cropland, and woody wetlands are comparatively lower, suggesting greater resistance to erosion. Generally, higher cutoff ratios ($CR_m > 0.2$) are predominantly observed in areas with lower erosion resistance and fewer natural barriers, highlighting the influence of land cover on the susceptibility to river cutoffs.

This result supports the hypothesis that land cover influences the geomorphological processes governing river meandering and cutoff channel formation. The high variations of cutoff ratio observed in cultivated croplands and unvegetated areas (Figure 10a) suggest that these areas may experience more dynamic or unpredictable cutoff behaviour, potentially leading to increased river channel instability and altered sediment transport regimes.

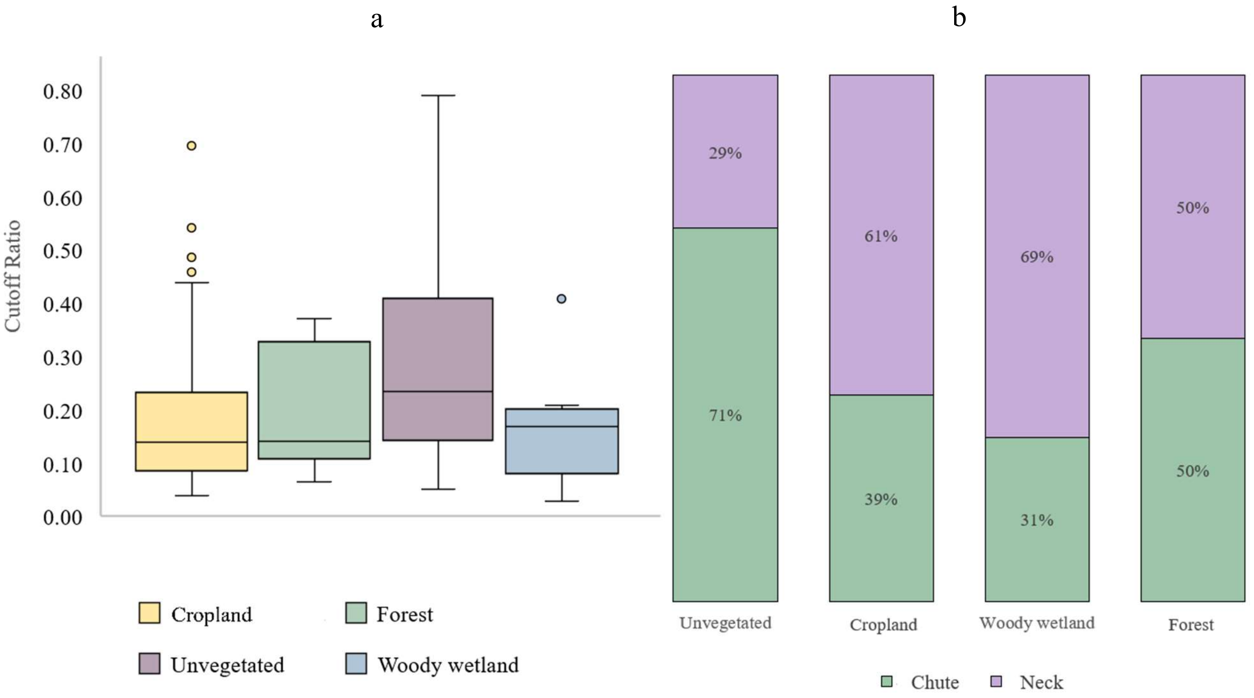


Figure 10: a) distribution of cutoff ratios by land cover type (the box plot displays the variation in cutoff ratios (CR) across four different land cover types, cropland, forest, unvegetated and woody wetland. The y-axis represents the cutoff ratio, while the x-axis lists the corresponding land cover types); b) distribution of chute cutoffs (green) and neck cutoffs (purple) across different land cover types (unvegetated, cropland, woody wetland, and forest)

Our results show that in unvegetated areas, 71% of occurrences appear to be chute cutoffs and neck cutoffs account for the remaining 29% (Figure 10b). In contrast, the opposite composition is found in woody wetlands, with neck cutoffs taking up 69% of the total occurrences, and chute cutoffs are responsible for the remaining 31%. Given the overall patterns across the four land cover types, neck cutoffs tend to occur on floodplains with higher resistance to erosion, such as woody wetlands and croplands. The presence of vegetation and other natural barriers increases floodplain stability, resulting in less frequent formation of chute cutoffs. Conversely, chute cutoffs are found to be more prevalent in unvegetated surfaces with lower resistance to erosion, where limited vegetation cover and natural barriers promote the development of chute cutoffs.

Our results show that chute cutoffs exhibit an average cutoff ratio of around 0.3, whereas neck cutoffs show a relatively lower ratio of 0.1 (Table 6). Specifically for neck cutoffs, the highest cutoff ratio is observed in the Beaver Creek at 0.33 and the lowest appears in the Minnesota River at 0.04 (Figure 11); however in the context of chute cutoffs, the Cedar River has the highest ratio up to 0.62 and its lowest is at 0.10 in the Pembina River. The disparity of cutoff ratio between chute and neck cutoffs indicates the significant impact of cutoff types on cutoff ratio in meandering rivers, which is tightly associated with channel erosive capacity and landscape heterogeneity.

Table 6: The Average cutoff ratios for neck cutoffs and chute cutoffs across the twelve rivers in the study

Cutoff Type	Average Cutoff Ratio
Neck	0.1
Chute	0.3

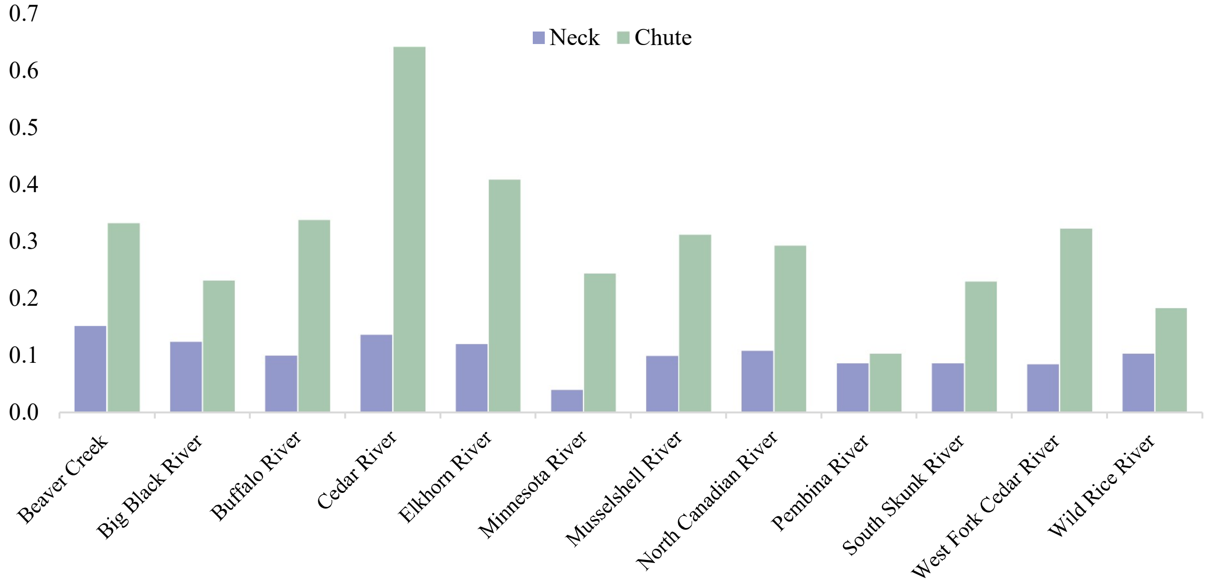


Figure 11: Cutoff ratio distribution across the 12 study areas in the United States. The bar plot indicates the cutoff ratio of chute cutoffs (green) is generally higher than neck cutoffs' (purple).

3.4 Cutoff Clustering in River Networks

To determine if different types of river cutoffs are clustered spatially, their locations were compared against complete spatial randomness implemented along the river structure using

Ripley's K ("Kest" in the spatstat R package). The K function estimates the presence of clustering using a range of distance intervals, which we evaluated from 0 to 20 kilometres, with 5-kilometer increments (Figure 12). In particular the K function for chute cutoffs shows an increase throughout all distance bands and displays a significant increase beyond the 5-kilometer mark. The gradually rising pattern shows that chute cutoffs are closely clustered together across all spatial levels and exhibit stronger clustering over greater distances (more than 5 km). The ongoing growth in the K value implies the relationship among chute cutoffs, indicating that these occurrences are not randomly spread but tend to happen close to each other. The notable difference between the K function and the CSR throughout confirms a strong clustering. The projected K function shown as the red dashed line shows a constant level across all distance ranges, whereas the observed K values are much higher and notably keep increasing with distance.

Neck cutoffs exhibit an increasing trend in their K function similar to chute cutoffs; however, the values are much higher at all spatial scales, especially at greater distances beyond the 5-kilometer mark (Figure 12). The steeper increase in the K function for neck cutoffs implies a stronger degree of clustering than chute cutoffs. This clustering pattern is noticeable at all distances, which suggests that neck cutoffs are interconnected spatially and can occur in close proximity over a wide range of distances. The difference between the observed and expected K functions is more pronounced for neck cutoffs than for chute cutoffs. And its expected K function also stays relatively constant and close to zero in all distance categories. Therefore, this significant difference implies that neck cutoffs may exhibit clustering behaviour that can extend over greater distances than chute cutoffs.

Overall, the result shows strong clustering in both types; however; the extent and intensity of clustering vary between chute and neck cutoffs. Chute cutoffs appear to rise in K values as they intensify over larger distances, whereas neck cutoffs show much stronger clustering (higher K values) at both small and large distances. The higher K values for neck cutoffs indicate that these occurrences are tightly clustered and more spatially dependent compared to chute cutoffs.

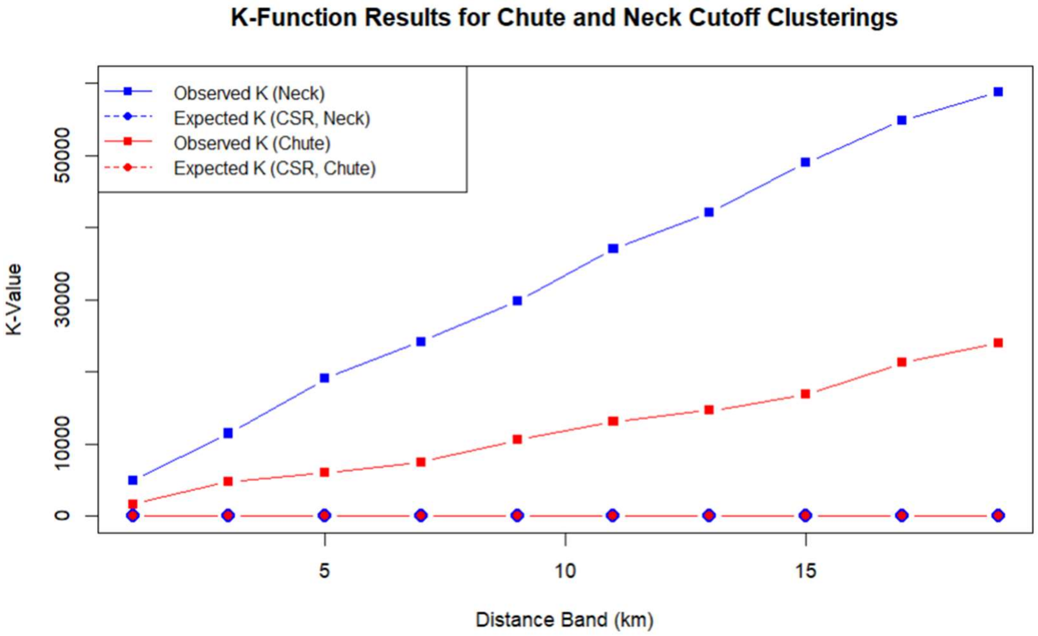


Figure 12: The plots present the results of K-function analyses generated by R Studio for chute and neck cutoffs across the United States; distance bands: 0 - 20 km with intervals of 5 km

The results show that these spatial patterns of clustered cutoffs align with the research hypothesis, indicating that the occurrences of clustered cutoffs can be spatially dependent on each other in various meandering river systems despite the influence of landscape heterogeneity and climate variability (Figure 13). Nevertheless, the extent and intensity of clustering differs between chute and neck cutoffs. In particular, the formation of neck cutoffs displays the effect as seen in the K function values surpassing the expected values across all distance ranges, notably within distances less than 200 kilometers. Figure 14 and 15 show that neck cutoffs have stronger clustering tendency within distances less than 200 kilometers than chute cutoffs. This tendency for clustering is likely associated with the formation of neck cutoffs where meander bends are highly sinuous and can result in rapid lateral migration and sudden occurrences. In comparison to Figure 14, chute cutoffs also show a tendency to cluster closely together at all distances; however, its clustered intersection is lower than 500 kilometres, indicating that the clustering impact lessens over distances compared to neck cutoffs. Chute cutoff occurrences are usually triggered by the formation of new and steep shortcuts that bypass the meander bend, as a result of intense high-flow events. Consequently, chute cutoff clustering may be confined to local areas and their clustering pattern may be affected by local hydrological conditions and surrounding landscapes.

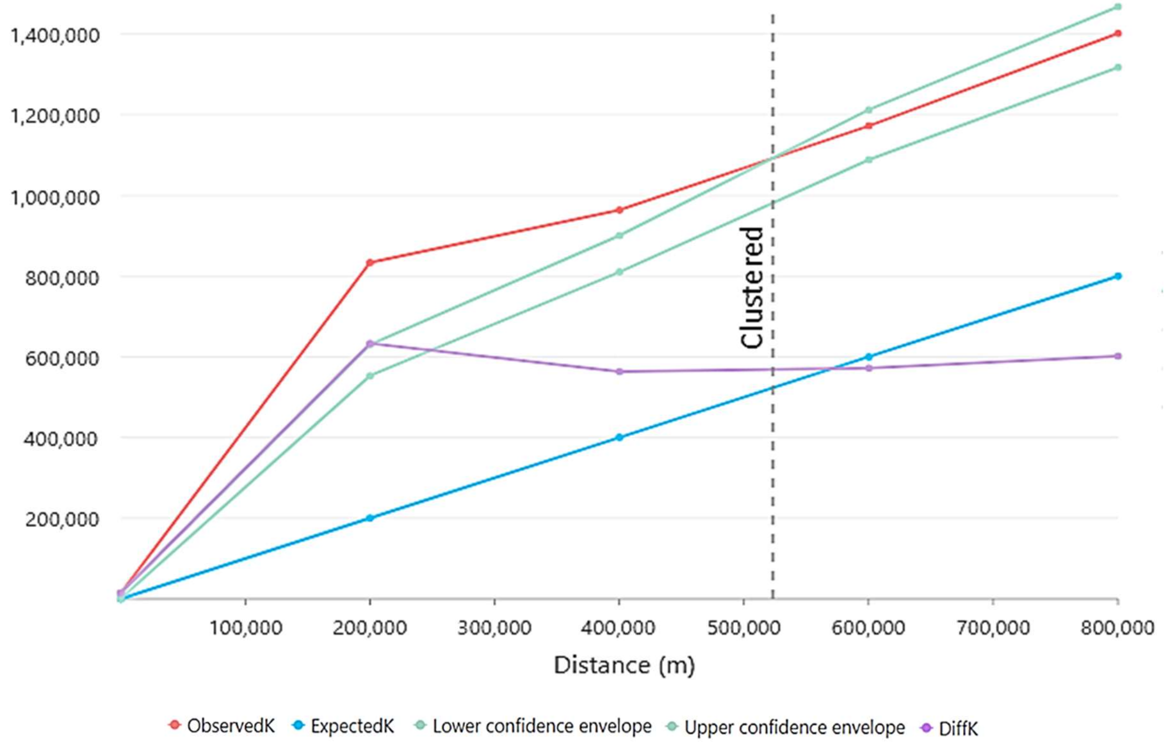


Figure 13: This plot represents the K-function analysis for all observed cutoff events in the study. The Observed K-function (red line) shows the actual spatial clustering of cutoffs, while the Expected K-function (blue line) represents the distribution expected under Complete Spatial Randomness (CSR).

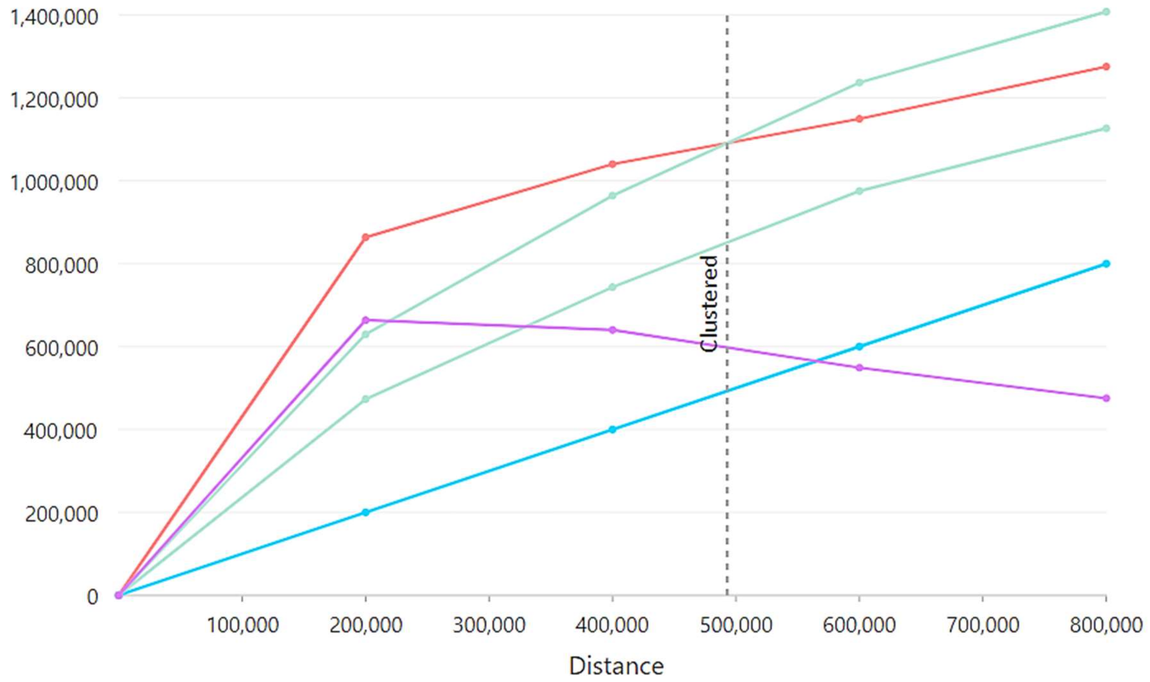


Figure 14: This plot illustrates the K-function analysis for chute cutoffs specifically. The Observed K-function (red line) is compared to the Expected K-function (blue line) under CSR, with confidence envelopes providing a range for randomness

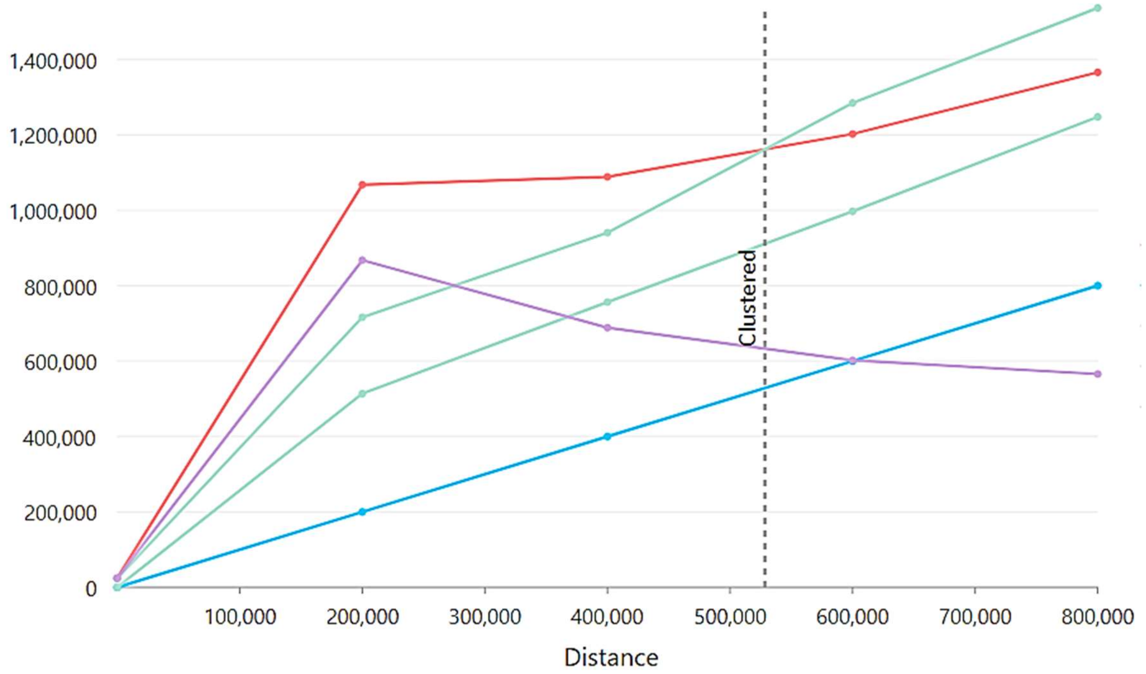


Figure 15: This plot illustrates the K-function analysis for neck cutoffs specifically. The Observed K-function (red line) is compared to the Expected K-function (blue line) under CSR, with confidence envelopes providing a range for randomness

4 Discussion

4.1 Relationships between Discharge and Cutoff Occurrence

The effect of discharge in the river systems is determined by its frequency and magnitude, both have a significant impact on the geomorphic features and hydrological processes (Wolman & Miller, 1960). A flood frequency analysis was performed to examine the intensity of discharge events (Figure 9) since magnitude and frequency of discharge can both determine the impact of cutoff discharge to river planform. For example, it was found in Table 3 that the return periods of the Musselshell River (3.92 years) and Pembina River (11.21 years) differ greatly, even though they share similar average cutoff discharge. Among 12 selected study areas in the United States, a high correlation between discharge and cutoff occurrence is observed in the Wild Rice River, Minnesota. More than half of its river cutoffs since 1991 occurred under the same discharge event with approximately 68 years of return period. This result further supports and confirms Stolum's simulations (1996) that flood events with high discharge and low frequency can lead to a cluster of cutoff formations. On the other hand, the result also shows that in most rivers, their cutoffs tend to occur during discharge events with less than 5 years of return period. Thus, it is suggested no strong correlation between high discharge and cutoff occurrence, which contradicts many current studies on river cutoffs (Gay et al., 1998; Hagstrom et al., 2018; Matthes, 1948; Raj et al., 2015). Wolman and Miller (1960) stated that sediments in meandering rivers have a low resistance threshold, making them extremely sensitive to floods of low magnitude and high frequency. During heavy rainfall, a rapid response occurs in terms of river morphology and bed roughness but then follows a swift readjustment to lower flow conditions after the rainfall (Zakwan, Ahmad, & Sharief, 2018). Comparatively, this study pointed out that in some cases, high flood magnitude may not be the primary factor triggering cutoff occurrences. Other factors may play a more significant role in the formation of river cutoffs than previously thought. For instance, the river cutoffs since 1996 in the Musselshell River, Montana all occurred during the discharge events with less than 5 years of return period. A few studies also indicate that moderate-magnitude floods with frequent occurrences control the shape and form of channels because they transport the greatest amount of sediment over a long period of time (Benson & Thomas, 1966; Pickup & Warner, 1976). The research by Langbein and Leopold (1964) showed that for most rivers that flow through temperate low-relief terrains, the return period of the discharge that transports the maximum sediment load is around 1.5 years. However, in this study, it may not be appropriate to assume a precise recurrence period for effective and bankfull discharges because they can be affected by various factors such as river morphology, hydrologic regime, sediment transport, and river planform area (Citterio & Piégay, 2009; Nash, 1994; Orndorff & Whiting, 1999).

4.2 Relationships between Land Cover and Cutoff Occurrence

This research uses and applies a metric called the cutoff ratio to better understand how the new cutoff channel relates to the previously bypassed channel under the influence of various land covers. The results indicate that chute cutoffs generally exhibit higher cutoff ratios compared to neck cutoffs. This suggests that chute cutoffs are more prone to develop in meandering rivers with lower flow resistance, while neck cutoffs are typically found in regions where the floodplain is more resistant to erosion. Additionally, many studies have also found that the angle at which a new cutoff diverts from the old channel can determine the morphological developments of these new channels (J. A. Constantine, Dunne, et al., 2010; Douglas Shields & Abt, 1989). It has been observed that neck cutoffs tend to have greater diversion angles compared to chute cutoffs since these wider angles are associated with rates of sediment deposition or blockage in the abandoned channel (Fisk, 1947; Gagliano & Howard, 1984). This blockage often occurs in flow separation and recirculation areas at the old meander bend, which results in a decrease in water velocity and shear stress within the abandoned channel (J. A. Constantine, Dunne, et al., 2010).

Moreover, this study further confirmed that the formation of river cutoffs can be greatly impacted by vegetation cover and its subsequent fluvial sediment processes along the riverbanks since they act as natural barriers to the geomorphic changes in the river channel (Hooke, 1995; Schwendel et al., 2015; Schwenk & Foufoula-Georgiou, 2016). Compared to chute cutoffs, it is also found that the development of neck cutoffs can be significantly affected by vegetation cover. The result shows that in areas without vegetation cover, there is a significant decrease in the occurrence of neck cutoffs. Among the twelve study areas, it is generally indicated that the presence of vegetation along riverbanks can help slow down the narrowing process of river necks through increasing stability and preventing erosion at these points of confluence. Overall, the presence of vegetation cover can reduce bank erosion and extend the time frame before a cutoff occurs naturally over time. Therefore, the study highlights that the formation of cutoffs can occur in a gradual and slow process under conditions where erosion happens gradually, and vegetation cover remains stable over time. Specifically, the process of how land cover affects the formation of cutoff is depicted in four stages by Li et al. (2022). As shown in Figure 16, firstly, continued erosion along the riverbanks leads to the narrowing of the neck, resulting in a smaller width than the average channel width. When the water level between the upstream and downstream of the neck increases, the seepage pressure within the neck also rises. Over time the neck breaks apart and paves the foundation for the creation and development of the cutoff channel.

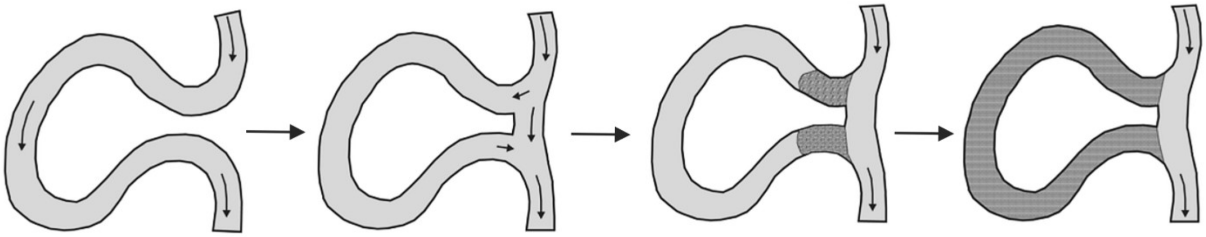


Figure 16: Conceptual model showing the long-term evolution of cutoffs in meandering rivers ((Li et al., 2022)

Despite the gradual inhibitory impact of vegetation cover discussed in this study, human interventions, such as cutting down trees for development purposes, farming, expanding and building barriers can also influence how natural meandering rivers migrate and evolve over time. The loss or destruction of vegetation cover by the riverside can increase bank erosion since it makes riverbanks exposed and easily affected by water flow (Crosato & Mosselman, 2020; Kiss & Blanka, 2012; Słowik et al., 2018). Agricultural expansion in areas prone to flooding or near riverbanks increases the vulnerability of river systems to geomorphic changes because converting natural lands into farmlands usually requires the removal of native plants and adjustment of natural water flow patterns. Consequently, this process can result in excessive surface runoff and decreased water-absorbing capacity in the soil, thereby causing more flooding incidents in the area (Knox, 2001; Rhoads et al., 2024). Additionally, the operation of large farm equipment can compress the soil, reduce its ability to absorb water and thereby raise the risk of overland flow. This situation can increase soil erosion and accelerate sediment transport into waterways (Obour & Ugarte, 2021; Parvin et al., 2022). Meanwhile, agricultural practices usually include the application of fertilizers and pesticides. These substances may get washed away into rivers when it rains heavily, leading to a decline in water quality, loss of biodiversity, and potentially higher risk of eutrophication. This process can worsen the impact of loss of vegetation cover along river banks and further contribute to the complexity and instability of river meandering (Soroush et al., 2012; Trout & Neibling, 1993).

In order to control and mitigate unintended consequences caused by hydrological processes in meandering rivers, scientists and engineers usually suggest and implement artificial cutoffs and other flood control structures like levees and dams. Specifically, artificial cutoffs can be designed for various engineering purposes, such as shortening river paths, lowering flood risks and improving navigation (Arnez Ferrel & Shmizu, 2021; Harmar et al., 2005). However, without proper hydrological risk assessment, they can cause unintended consequences. Several studies show that shortening the river channel artificially can instantly increase water flow and accelerate hydrological processes in rivers, resulting in worse bank erosion and the creation of new cutoffs downstream (Li & Gao, 2019; Schwenk & Foufoula-Georgiou, 2016; Smith & Winkley, 1996). This, in turn, leads to an increase in the frequency and intensity of cutoff events that have the potential to disrupt the natural water flow and result in the degradation of floodplain ecosystems (Qiao et al., 2022).

4.3 Spatial Clustering of Cutoffs

Based on the results from ArcGIS and R Studio, the variation in the intensity of clustering between chute and neck cutoffs can be explained by the hydrologic processes that influence how they form. Neck cutoffs occur when a meander bend becomes unstable and eventually breaks through to create a more direct and steep channel for the river to flow through. This phenomenon is driven by the sideways movement of meanders and is often linked to the long-term evolution of landforms. This helps to clarify why we consistently observe clusters of neck cutoff occurrences at a broader scales (Lewis & Lewin, 2009; Micheli & Larsen, 2011). Chute cutoffs are often caused by high discharge events when floods overtop the riverbank and create a new and shorter channel in the floodplain area. The hydrodynamic forces driving chute cutoff formations tend to be localized to certain areas, which also explains their clustering at shorter distances (Ghinassi, 2011; Hooke, 2004; Howard & Knutson, 1984).

The clustering of neck cutoffs at both local and broader scales has significant impact on the stability of meandering river systems. As several neck cutoffs occur and develop across areas, this clustering tends to cause reductions in river meandering and increase the possibility of channel avulsion. These changes can cause large disturbances in sediment movement and channel evolution, which can affect the dynamics of floodplains and reshapes the river channel over time (Schwenk & Foufoula-Georgiou, 2016; Slowik, 2016). Conversely, even though chute cutoff clustering could be more confined in local areas, it can cause greater instant consequences in floodplain river dynamics, particularly changes in sediment deposition in the new shortcut channels and abandoned meanders (Ielpi et al., 2021; Schwenk & Foufoula-Georgiou, 2016). These localized impacts are specifically important in managing flood risks and protecting natural habitats in local river systems. Regulating clusters of chute cutoffs is necessary in order to maintain local channel stability and prevent sediment accumulation in rivers.

4.4 Future Avenues for Investigation

Three potential variables, high-flow events, land cover and spatial clustering, affecting the cutoff occurrence are considered and investigated in this study. While these factors are commonly known to be important, they are still accounted for a very limited extent to explain the specific formation of a river cutoff. In pursuit of understanding the relationship with high-flow events and land cover types, the study focus is limited to a sample size of 12 rivers. The small sample size in the study might not capture sufficient situations and complexities where cutoffs occur in nature. Therefore, expanding the data collection to incorporate a larger and more diverse selection of rivers would strengthen the reliability of the results and improve the feasibility of its implications. Accordingly, a larger dataset would also support investigating variations in cutoff behaviour to potentially reveal its trends and connections at a larger spatial or temporal scale. Furthermore, future studies should take into account a variety of factors that impact cutoff formation. For example, the meandering channel slope has an influence on how rivers flow and the erosion mechanisms that result in cutoffs forming (Frasson et al., 2019; Petrovszki et al., 2012). Rivers with higher slopes may trigger and accelerate cutoff processes when compared to those in flatted areas. Meanwhile, high-flow events are tightly associated with precipitation patterns and extreme weather occurrences under the influence of climate change. Integrating the concept of the atmospheric river and climate change scenarios can help understand the frequency and severity of floods and consequently its influence on the formation of cutoffs in real life (Dettinger, 2011; Kim et al., 2021; Neiman et al., 2011; Ralph & Dettinger, 2011).

Our study highlights the significance of studying meandering rivers over a longer period of time in order to fully understand and predict their functioning and evolution across time and space effectively. In particular, investigating the mechanisms that lead to river cutoffs through long term research can present and result in a more thorough and reliable evidence of channel movement and development, in contrast to studies focusing solely for a short-term event. Rivers typically evolve over time depending on a variety of factors like water flow patterns and changes in climate and land use that shape their river courses naturally. These variables tend to cause long-lasting impacts that go beyond short-term events in rivers. Despite the lack of historical data records, it is always suggested to perform studies and observations over a longer period of time in order to study the long-term impact of geomorphic and hydrological factors on channel migration and cutoff evolution. For example, the impact of climate change on meandering river networks and the creation of cutoffs can occur and take effect slowly over a long period of time, over years or even centuries. A long-term investigation can monitor how the changes in rainfall patterns and temperature affect the flow of rivers and the transportation of sediments, which leads to changes in the frequency and magnitude of cutoffs. To sum up, this paper provides an assessment and discussion on a few limited factors that can cause uncertainty and instability in the development of river cutoffs. This highlights the need for conducting future research that takes into account a wider range of factors and uses more extensive data sets, in order to improve our understanding of meandering river behaviors and formation of cutoffs at a more extensive and deeper level.

5 Conclusion

This thesis assessed the magnitude and frequency of flooding events occurring in the twelve rivers in the United States since the 19th century. The return period for each cutoff discharge is estimated based on the flood frequency curve and the meandering cutoff ratio is calculated for each cutoff occurrence. The impact of land cover type on cutoff ratio and cutoff types is evaluated and visualized through statistical analysis and charts. The spatial clustering analysis uses Riley's K function to study the patterns of cutoff clustering. And the results are compared with the other studies. Based on the results and discussions in this study, the following conclusions are presented:

i. Contrary to the hypothesis, the study shows that there is not a strong correlation between high-flow events and cutoff occurrences. Most cutoff events among the twelve rivers can be explained by more moderate discharge events with approximately 10 years of return periods. Despite the commonly acknowledged impacts of extreme events, this result highlights the fundamental long-lasting impact of moderate flood events on meandering river systems and their cutoff formations.

ii. Chute cutoffs with higher CR_m values tend to develop in landscapes with lower erosion resistance. And neck cutoff occurrences are likely to occur in floodplains with larger erosion resistance. These variations between chute and neck cutoffs highlight the significance of the use of CR_m and land cover impact on the location, frequency and categorization of cutoff events, as well as studying the geomorphic processes behind them.

iii. Spatial cluster analysis provides effective evidence and traces of how chute and neck cutoffs are spread out spatially in the study areas. Chute cutoff clustering shows a pattern that is more event-driven and has a lower clustering tendency than neck cutoffs. This result indicates that chute cutoffs are more likely to be affected by local meander bend characteristics and short-term hydrological conditions. Neck cutoffs exhibit stronger clustering at both local and broad scales since their formations are greatly impacted by allogenic and autogenic factors, like sinuosity, riverbank stability and vegetation cover.

Overall, this research confirms the theory that the formation of river cutoffs is not a random occurrence. Instead it can be influenced by various factors in this study, such as moderate flow events, land cover patterns and spatial clustering effects. These are all significant indicators to consider in urban river management and flood prevention strategies. Through understanding the environmental and spatial factors that contribute to cutoff formation, models and solutions can be created and improved to predict and reduce the unintended consequences of river cutoffs, especially in highly sinuous meandering rivers.

Chapter 3
Future Work

1 Studying the Role of Moderate Discharge Events

Given the significance of long-lasting moderate discharge events in meandering rivers, empirical data should be gathered extensively to study the relative contributions of moderate versus large flood events in the occurrence of river cutoffs. It should integrate the USGS hydrological data, aerial and satellite imagery and field data collection. First, flood frequency analysis should be conducted based on the hydrological data and discharge events should be categorized into small, medium (high frequency with moderate discharges below flood thresholds) and large (low frequency with high magnitude discharge exceeding bankfull discharge) events. The magnitude of flooding events then needs to be computed and associated with the river sections where cutoffs have occurred. Secondly, the occurrence time of cutoffs should be correlated with recorded discharge events using aerial and satellite imagery. The temporal correlation analysis between cutoff occurrence time and discharge magnitude helps determine the direct cause of cutoff occurrences, whether they are aligned with medium flooding events, instantly changed or slowly weakened by larger events. In this case, a lag analysis should be conducted to quantify the relationships between flood magnitude and cutoff occurrences (Black et al., 2021; Talei & Chua, 2012). Three scenarios are proposed: 1) if the cutoff occurs instantly or within a short period (e.g., days) without any large events occurring recently, this suggests that the cutoff could be driven by the medium event constantly occurring in the river. This moderate discharge has enough erosive power to trigger the cutoff occurrence without the additional larger events; 2) if the lag time between a large event and cutoff occurrence is long enough (e.g., months or years), there is a high possibility that the channel bank is initially weakened by the large event and then becomes more susceptible to subsequent medium discharges. In this scenario, the cutoff is caused by the synergistic effect of both medium and large events; 3) if the lag time is short (e.g., days) after a large event, the cutoff is more likely caused by the recent large event. However, the associations under these three scenarios are not conclusive enough, and the integration of field data collection is necessary to control variables and minimize variances in the study. Comparing the changes in soil erosion, sediment deposition and vegetation cover before and after the cutoff event, we can further confirm whether the occurrences of cutoffs are consistent with medium flooding events or residual effects after major events.

Other than that, a comparative analysis of cutoff density between rivers dominated by frequent medium floods and rare large events also helps understand the relationship between discharge and cutoff events. For instance, two groups of rivers should be classified: 1) rivers with medium discharges (e.g., 2-to-10-year recurrence intervals) occurring frequently and dominating the discharge regime; 2) rivers with large flooding events (e.g., >50-year recurrence intervals) occurring rarely but dominating the discharge regime. The number of cutoffs, river length, channel slope, sediment composition, land cover should be considered in the cutoff density calculation. Statistical analysis such as t-test and ANOVA test can be applied to assess the statistical differences between the two types of rivers. This result can reveal whether there is a relationship between cutoff density and flood regimes.

It is expected that the findings above could be very site-specific and event-driven, indicating that the primary cause of a cutoff can vary in different river bends, segments or channels; however, understanding whether the river is medium-event-dominated or large-event-dominated can guide effective strategies for floodplain management. For river cutoffs dominated by medium discharges, erosion prevention and channel restoration plans should be prioritized. Urban planners should focus on stabilizing and restoring natural river channels and avoiding any future increases in discharge frequency and magnitude. For river cutoffs dominated by rare and large flooding events, flooding protection structures and mitigation plans should be considered, such as levees, bridges and buffer zones.

2 Meandering Cutoff Simulations

The incorporation of cutoff simulations plays an important role in future studies since analyzing empirical datasets is not confident enough to conclude the direct cause of a cutoff event. And models can simulate different flood regimes, land cover conditions, and incorporate different variables (e.g., valley slope, soil erosion and channel sinuosity) to assess their relationships with cutoff occurrences (Hankin et al., 2020; Skhakhfa & Ouerdachi, 2016). Specifically, meandering river simulations like Hec-Ras modelling often heavily rely on certain parameters that require empirical validation and the analysis of the 12 rivers with 375 cutoffs in this research provides a detailed dataset for localized calibration and validation. This can significantly improve the accuracy of cutoff simulations (Hajek & Wolinsky, 2012; Peker et al., 2024). The meandering cutoff ratio criterion used in this study is a critical parameter that can be integrated into cutoff simulations to predict the probability of a cutoff formation. The value of CR_m acts as a threshold to distinguish between chute and neck cutoffs. For example, CR_m value can be incorporated into cellular automata models to simulate long-term landscape evolution, which determines when and where cutoffs occur in the model (Chen et al., 2023).

The findings on the relationship between the meandering cutoff ratio and land cover type validate the effectiveness of CR_m value, which can be taken into consideration when simulating the impacts of different land cover types on floodplains. Unvegetated areas with relatively higher CR_m value should be assigned with lower erosion resistance, whereas higher erosion resistance should be assigned with land cover types like forests, croplands and woody wetlands. Similarly, the findings on the tendency between cutoff types and land cover types also substantially increase the simulation performance of meandering evolution and cutoff formation. Chute cutoffs should be assigned a higher possibility of occurrence for unvegetated areas. Conversely, croplands and woody wetlands should be input with a higher occurrence of neck cutoffs than chute cutoffs.

Despite the variations at different spatial scales, the strong clustering tendency in both chute and neck cutoffs found in this study should also be incorporated in meandering cutoff simulations. The initial formation of a cutoff can trigger a clustering of cutoffs. When simulating long-term meander evolution, the finding in this study that neck cutoffs tend to cluster consistently at all scales can be used to validate and improve model performance. On the other hand, when simulating specific interactions between hydrological processes and landform changes, the finding that chute cutoff clustering tends to be more event-driven can be used to evaluate the accuracy of the model under various flow conditions, particularly during extreme or high-flow events.

3 Implications in River Management

The results of Chapter 2 help improve our understanding of how meandering river cutoffs form and evolve and have the potential for real-world contributions. A major contribution is the demonstration and application of the cutoff ratio ($CR = ol/cl$), which improves our ability to predict the formation of chute and neck cutoffs. An adjustment of the cutoff ratio criterion is presented in the study, specifically targeting the studies of meandering rivers, $CR_m = cl/ol$. For the classification of chute and neck cutoffs, CR_m values generated and evaluated in the research can be used and considered in future urban planning projects. Among the 12 rivers, chute cutoffs are more prone to occur and develop if their CR_m values are greater than 0.3, whereas neck cutoffs tend to form with values higher than 0.1. However, variances often exist among these values. It should be acknowledged that these values are not spatially and permanently universal considering the floodplain erodibility and landscape heterogeneity. For example, given the impact of land cover, it is evident that a meandering river flowing through vegetated floodplains like forests tends to have higher erosion resistance, thereby leading to lower occurrences of cutoff formation (Camporeale et al., 2013; Ielpi et al., 2022; Perucca et al., 2007). CR_m values generated in this study require to be adjusted and consolidated for other study areas and applications.

Understanding and utilizing CR_m values generated in this study can help establish thresholds and assess potential risks during the construction of artificial cutoffs. The estimation and assessment of CR_m values bring about more precise directions and predictions for engineers and decision makers, for the purpose of either promoting or reducing the continuing river meandering. For instance, for the purpose of improving navigation and controlling flooding events, the CR_m values can be estimated to help determine and predict the location and magnitude of cutoff formation. This can help reduce unintended consequences like excessive erosion or disturbance to both human activities and natural habitats. This finding is not merely helpful for the construction of artificial barriers in rivers, but also quantify the impact of land cover on cutoff formation. In other words, it can provide concrete data and evidence in urban planning to help prevent or reduce the consequences of natural cutoffs. One significant implementation is the integration of CR_m values during the risk assessment process. With the estimation of CR_m values, it can help urban planners and policymakers to determine if the area is facing higher possibilities of cutoff formation. Then the subsequent strategies and mitigation plans can be initiated and implemented, such as land use change, river restoration and riparian buffer zones.

These efforts not merely help maintain natural habitats and conservation areas, but also protect infrastructure and human activities from the impacts of unregulated meandering river behavior.

Furthermore, the findings of spatial clustering analysis have significance for river flood management and prevention. Specifically, places where neck cutoff clustering is found at larger scales (≥ 500 kilometers) may necessitate long-term risk management measures for channel movement and cutoff clustering. In these situations, floodplain restoration, erosion control and levee construction could be recommended to lessen their long-term impact on meandering rivers (Harmar et al., 2005; Poesen & Hooke, 1997; Rey & Rusu, 2021). Comparatively, for more localized chute cutoff clustering, the implementation of flexible and soft management strategies is recommended since it significantly focuses on the present water flow conditions and geomorphic processes causing these cutoffs to form at a local scale. Utilizing structures like restored riparian habitats, buffer zones and retention basins in flood management can mitigate the intense short-term impact of clustering of chute cutoffs by lowering water levels and regulating sediment accumulation in the floodplain (Acheampong et al., 2023; Mouton et al., 2012; Scholz, 2007).

4 Climate Change Mitigation

As climate change keeps intensifying weather extremes, increasing the frequency and magnitude of flood events and altering the discharge regimes of rivers across the world (Dettinger, 2011; Kiss & Blanka, 2012; Kleinen & Petschel-Held, 2007). Our ability to predict how rivers will respond to these changes is urgent for both climate adaptation strategies and flood risk management. The findings presented in this thesis emphasize the role of hydrological conditions in triggering meander cutoffs. Most cutoffs in the 12 rivers are likely to be caused by higher-frequency but lower-magnitude discharge. As climate change continues to progressively affect river systems, the impact of higher-frequency but lower-magnitude discharges on river cutoff formation cannot be ignored. High-flow events caused by weather extremes can indeed trigger the occurrence of cutoffs; however, the gradually increasing or climate change-induced discharge may also accelerate hydrological processes and cutoff formation in a long-term run. Instead of focusing on the extreme events, it is important to acknowledge and study the long-term impact of climate change on cutoff formations in meandering river systems. To improve flood resilience in urban areas, both short-term and long-term evolution of meandering rivers should be considered in the risk assessment and urban planning. While managing the cutoff formation and implementing its corresponding flood control infrastructures like dams and levees, it is essentially important to consider their long-term accountability and reliability (Bonacci et al., 1992; Chaudhuri, 2003; Słowik et al., 2018).

Furthermore, cutoff formations can affect floodplain sedimentation through maintaining carbon-rich environments and storing a large amounts of organic carbon (Barrera & Ielpi, 2024; Ritchie et al., 2007; Torres et al., 2017). Typically, floodplains act as significant carbon sinks in nature and the impact of cutoff formation in shaping floodplain morphology can help optimize carbon sequestration efforts. For example, the creation of oxbow lakes and other cutoff-related products can promote the accumulation of sediments and increase the amount of organic carbon stored in a floodplain. Under the influence of climate change, the formations of cutoffs should be emphasized considering its large carbon storage capacity in river systems (Cole et al., 2007; Torres et al., 2017). Therefore, the results and implications based on this research can be applied to floodplain restoration projects that aim to maximize carbon sequestration while maintaining natural river dynamics.

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