DISSERTATION

ISLANDS IN THE STREAM: SPATIAL AND TEMPORAL PATTERNS OF LOGJAM-INDUCED RIVER CORRIDOR DYNAMICS

Submitted by

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ABSTRACT

ISLANDS IN THE STREAM: SPATIAL AND TEMPORAL PATTERNS OF LOGJAM-INDUCED RIVER CORRIDOR DYNAMICS

Spatial and temporal variations in water and sediment fluxes moving within the river corridor drive changes in the three-dimensional geometry of channels and floodplains. In forested river corridors, pieces of large wood (> 10 cm diameter and 1 m length) and logjams (≥ 3 pieces of large wood) become an integral part of the interactions among water, sediment, and the resulting river corridor form and function. The net effect of logjams stored at least temporarily in the river corridor is to increase spatial heterogeneity, or patchiness, via processes such as channel avulsion and formation/abandonment of secondary channels, increased channel-floodplain connectivity, and greater instream aggradation.

The importance of spatial heterogeneity, logjams, and secondary channels/islands to river corridor function has been well documented, but a lack of existing quantitative underpinning creates knowledge gaps in the processes driving island formation and persistence, the role of wood in facilitating these processes, and the complex interactions between flow, sediment, and wood in dynamic river corridors. This dissertation

addresses some of the existing knowledge gaps around how logjams interact in a river corridor to create heterogeneity at different spatial and temporal scales by characterizing the patterns, processes, and interactions occurring in a naturally dynamic system. The topics explored here focus on research primarily conducted along the Swan River in the Northern Rocky Mountains of Montana with mention of sites in the Southern Rocky Mountains of Colorado. These locations represent some of the few remaining river corridors in the contiguous U.S. with natural flow, sediment, and wood regimes, but represent former widespread conditions.

In the work that follows, Chapter 2 explores the processes driving spatial patterns in bifurcations induced by logjams. I find that logjam-induced bifurcations exist as a continuum of different patterns and the position of a river segment along this continuum correlates with the ratio of erosive force to erosional resistance. Chapter 3 builds on this by investigating how accretionary and avulsive processes shape bifurcations over time, emphasizing a temporal progression of logjam-induced features using ^{14}C and tree ring data. I find that islands tend to grow through upstream migration – the presence of buried logs with contemporary trees growing on them indicates this process – and lateral accretion. Chapter 4 dives deeper into the interactions between process and form, demonstrating the relationship between channel dynamism, logjam presence, and spatial heterogeneity at larger temporal and spatial scales. I find that logjams and channel movement through time interact in a cascade of processes and feedbacks that foster increased spatial heterogeneity. Wood preferentially accumulates in more geomorphically heterogeneous portions of the river corridor that provide sites capable of trapping and retaining wood. Logjams can then drive greater total sinuosity and the formation of secondary channels that result in further wood trapping, greater heterogeneity of floodplain vegetation, and ideal habitat for beaver that further modify river corridor heterogeneity. I also find that bifurcations and spatial heterogeneity persist even after logjam is no longer present.

These results have implications for river management. If sections of the river corridor with more logjams and more beaver meadows display higher spatial heterogeneity, creating and protecting wood-rich heterogeneous retention zones within a river corridor is an important component to emphasize for river resilience. If physical effects persist even after a logjam is no longer present, than wood reintroduced to the river corridor as individual pieces or engineered logjams does not have to be anchored in place to facilitate formation of geomorphic heterogeneity within the river corridor. By dissecting the complexities of processes governing naturally dynamic river corridors, this work adds quantitative insight to the diverse functionality of heterogenous river systems in forested or historically forested regions and provides a launching point for future river management aimed at fostering river corridor function and resilience.

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I acknowledge that the lands this research was conducted on are the traditional and ancestral homelands lands of the Salish, Kootenai, and Flathead Tribal Nations and recognize, with respect, the Indigenous peoples as stewards of the land and waters that I worked on in this dissertation.

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DEDICATION

I dedicate this dissertation to my family, who have unwaveringly encouraged my wildest schemes and dreams. Specifically, my parents, who showed me the awe of exploring backyard forests and streams and taught me what it looks like to approach the world with compassion and curiosity. And to my sisters, who in keeping up with their imaginative games kayaking the backyard, floating leaf boats down creeks, and creating intricate networks of channels in the mud, allowed me to believe that playing in water could one day be a career. As it turns out, it can be.

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CHAPTER 1: INTRODUCTION

River channels can split and merge at various spatiotemporal timescales, creating and abandoning bifurcations as they migrate. Rivers have been depicted cartographically with bifurcating channels since at least the 16th century (e.g., Da Vinci's map of the Arno River, 1502 AD, The Royal Collection Trust) and knowledge of rivers bifurcating has long been passed down through oral histories (Evans, 2020; Koppes, 2022). Bifurcations divide the flow of water and sediment into secondary channels and are a key feature in anastomosing river corridors, a planform classification including at least two active parallel or sub-parallel channels with vegetated islands or interfluves between them (Schumm, 1968; Knighton and Nanson, 1993; Burge, 2006). I use the term river corridor rather than river, here, to encompass the connectivity between the active channel(s), hyporheic zone, floodplain, riparian zone, and river depositional landforms such as deltas and alluvial fans (Harvey and Gooseff, 2015).

The distinction between anastomosing river corridors and other channel planforms is, to some extent, arbitrary because natural channel planforms occur along continua such as those between anastomosing and braided, anastomosing and meandering, or braided and meandering. Different positions along these channel-planform continua can represent differences in either the underlying processes driving bifurcation or the balance between hydraulic erosive force and bank erosional resistance. The combination underlying every scenario of anastomosing is (i) limited lateral migration due to either bank stability and/or limited stream power, which prevents the channel(s) from being sufficiently laterally mobile to create a braided planform and (ii) sufficient discharge and stream power to, at least episodically, overtop the banks and erode persistent secondary channels into the floodplain (Smith and Smith, 1980; Harwood and Brown, 1993; Makaske, 2001).

Knighton and Nanson (1993) was one of the first studies to describe anastomosing river corridors as part of a continuum of bifurcating channel patterns defined in terms of a three-dimensional space where the axes are flow strength, bank erodibility and local sediment budget. More recently, Carling et al. (2014) advanced the characterization of bifurcations toward process-based rather than form-based, describing differences in bifurcations based on accretionary-bar flow splitting processes versus avulsive processes, with the former creating braided channels and the latter creating anastomosing channels. Process-drivers that often facilitate anastomosing include i) vegetation (e.g., Smith, 1976; Gradziński et al., 2003; Larsen, 2019); ii) sediment supply and bank cohesion (e.g., Rust, 1981; Smith, 1983; Gibling et al., 1998; Makaske, 1998); iii) tectonic uplift and basin subsidence (e.g., Rust et al., 1985; Smith, 1986); iv) increased flow magnitude (e.g., Smith and Smith, 1980; Knighton and Nanson, 1993); and v) channel obstructions such as large wood (e.g., Burge and Lapointe, 2005; Wohl, 2011; Collins et al., 2012), ice dams (e.g., King and Martini, 1984), and beaver dams (e.g., Woo and Waddington, 1990; Gurnell, 1998; Burchsted et al., 2010; Polvi and Wohl, 2012; Laurel and Wohl, 2019).

In the chapters that follow, large wood and logjams are the primary focus as process-drivers of bifurcations in anastomosing river corridors. Large wood is defined as pieces as downed wood $>$ 10 cm diameter and 1 m length and logjams as $\geq$ 3 large wood pieces in contact with each other (Gurnell et al., 2002). A single piece of large wood or a logjam can facilitate differences in bifurcations based on the dominant processes. Logjams can create locally lower shear stresses, which can cause sediment to accrete either downstream or upstream, creating alluvial patches elevated 1 to $>$ 4 m above the surrounding floodplain. Stable topographic patches are augmented by wood and wood jams that accumulate on, and protect from erosion, the upstream side of the patch (Collins et al., 2012). These stable patches can divert flow, split it into an anastomosing river pattern, and cause and mediate channel-switching avulsions. A logjam can force overbank flow, bank erosion, and lateral bifurcation via avulsion (Wohl, 2011; Wohl and Cadol, 2011; Collins et al., 2012). A logjam can also create lee deposition that is then stabilized by woody vegetation, forming a relatively short segment of split flow and a longitudinal bifurcation via accretionary-bar flow splitting processes (Gurnell and Bertoldi, 2020).

The broader ecologic, hydrologic, and geomorphic benefits that logjams, secondary channels, and islands can have within river corridors have been well documented. The net effect of logjams stored at least temporarily in the river corridor is to increase spatial heterogeneity, or patchiness, via processes such as channel avulsion and formation/abandonment of secondary channels (Jeffries et al., 2003; Wohl, 2011; Collins et al., 2012), increased channel-floodplain connectivity (Sear et al., 2010; Wohl, 2013), and greater instream aggradation (Brooks et al., 2003). Logjam-induced spatial heterogeneity enhances resilience to disturbance (Wohl et al., 2022, 2024). The lateral connectivity driven by wood-induced islands and avulsions fosters resilience during disturbances such as floods, drought, and wildfire (Benda et al., 2004). Higher floodplain water tables, deep pools, and lateral connectivity provide more stable base flows and drought refugia (Bêche et al., 2009; Boulton et al., 1998; Dixon, 2016; Puttock et al., 2017). Increased lateral connectivity facilitated by logjams and secondary channels helps to attenuate flood peaks and diffuse flood flows across the floodplain (Junk et al., 1989; Poff et al., 1997), making habitats persistent and more resistant to natural and anthropogenic disturbances (Amoros and Bornette, 2002; Henning et al., 2006; Jeffres et al., 2008). Multiple wood-rich channels laterally connected to the floodplain and vertically connected to the hyporheic zone support abundant and diverse habitats and species (Dolloff and Warren, 2003; Herdrich et al., 2018; Venarsky et al., 2018).

Frequent, minor channel adjustments and a high, reliable water table also create optimal settings for the germination and growth of aquatic and riparian vegetation (Braudrick et al., 2009; Nadler and Schumm, 1981; Tal and Paola, 2007). Wet woodlands on islands and floodplains supply and retain wood and widespread vegetation proximal to the channel (Fetherston et al., 1995; Gurnell et al., 2001; Montgomery and Abbe, 2006), supporting habitat and increased retention of organic matter and nutrients for other organisms (Bilby, 1981; Flores et al., 2011). Dense, diverse riparian vegetation provides abundant shade, which, together with an efficient hyporheic exchange, ameliorates water temperatures (Beechie et al., 2005; Montgomery et al., 1999).

Much of the work on this topic thus far has focused on channel planform as it relates to bar and island formation. Far fewer studies have focused on the lateral vs. longitudinal processes, the role of wood in facilitating these processes, and the complex interactions between flow, sediment, and wood in anastomosing river corridors. In the following chapters, I explore the interactions between logjams, bifurcations, and spatial heterogeneity, focusing on spatial and temporal patterns and the processes that create and maintain dynamic, anastomosing river corridors. In Chapter 2 (Marshall and Wohl, 2023), I build on the idea of a spatial continuum of bifurcation patterns and the process-based characterization of Carling et al. (2014) while suggesting that anastomosing rivers can have both avulsive and bar-splitting processes that form bifurcations. The process determining the type of bifurcation is based on the ratio of erosional force to erosional resistance, which governs a spatial continuum of logjam-induced bifurcation patterns. Chapter 3 (Marshall and Wohl, in review) expands this thinking to explore the temporal dimensions of accretion associated with avulsions and islands and introduces the concept of aggradation and erosion associated with wood levees. Chapters 2 and 3 focus on reach-scale interactions between flow, sediment, and wood along 10^1-10^2 m lengths of channel. In Chapter 4 (Marshall et al., 2024), I scale this work up to explore the interactions and feedbacks that exist between logjams and channel dynamics along a 32-km-length of the Swan River corridor over a decade and how those interactions govern spatial heterogeneity within the river corridor (Figure 1.1).

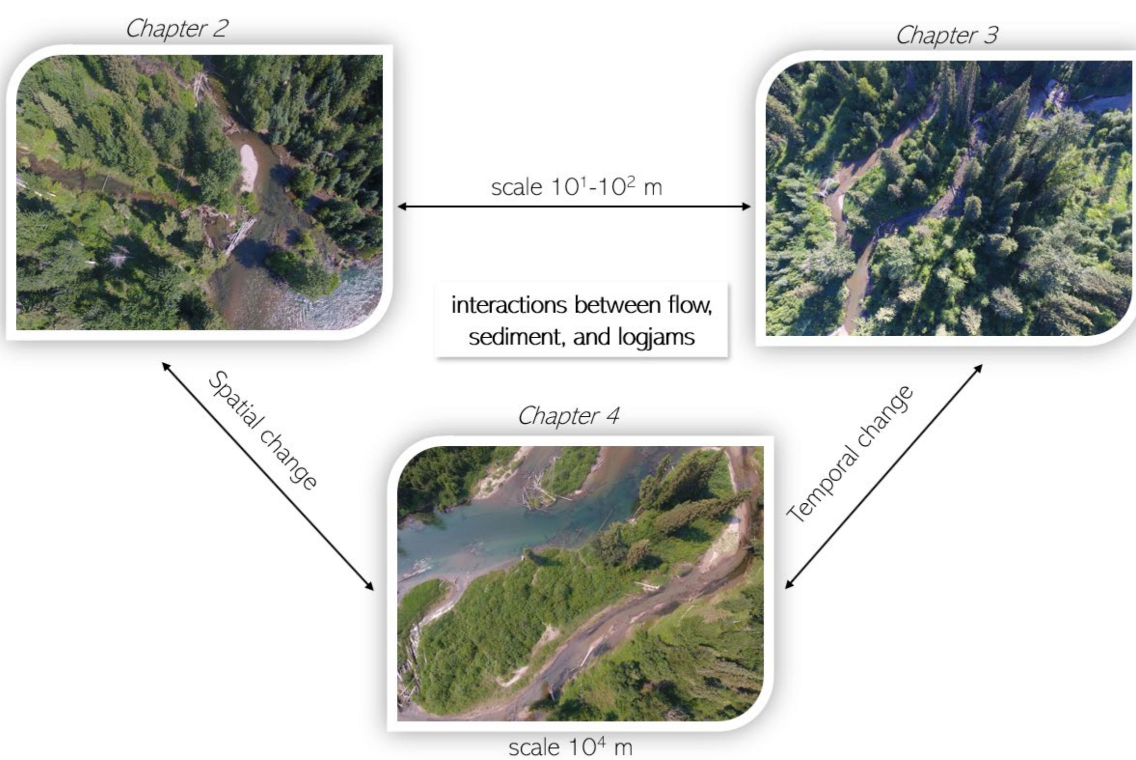

Figure 1.1. Overarching theme and conceptual links between dissertation chapters. Chapters 2 and 3 focus on reach-scale interactions between flow, sediment, and wood along 10^1-10^2 m lengths of channel. Chapters 2 and 4 explore spatial processes and patterns while Chapters 3 and 4 explore the temporal dimension of interactions within the river corridor. In Chapter 4, I scale this work up to explore the interactions and feedbacks that exist between logjams and channel dynamics along a 32-km-length of the Swan River corridor over a decade and how those interactions govern spatial heterogeneity within the river corridor.

Understanding the spatial and temporal dynamics of logjam-induced features is important to understanding the natural formation and persistence of river corridor morphology in forested regions. The topics explored here focus on research primarily conducted in the Northern Rocky Mountains of Montana with mention of sites in the Southern Rocky Mountains of Colorado. These locations represent some of the few remaining river corridors in the contiguous U.S. with natural flow (Poff et al., 1997), sediment (Wohl et al., 2015), and wood regimes (Wohl et al., 2019), but represent former widespread conditions. Historical descriptions of forested regions throughout the temperate latitudes suggest that orders of magnitude more wood were present in most forested river corridors prior to widespread deforestation and wood removal from the river corridor (Sedell and Froggatt, 1984; Montgomery and Bolton, 2003; Wohl, 2014). A legacy of human activities has simplified river corridors via landscape-scale changes that affect water, sediment, and wood delivery to, and movement within, the river corridor (Thoms, 2003; Graf, 2006; Knox et al., 2022), causing a fundamental shift in channel and floodplain process and form (Wohl, 2013). As process-based river restoration efforts that utilize wood become commonplace, understanding the spatial and temporal conditions that facilitate different types of logjam-induced features has increasingly important implications for the broader physical and biological processes in a river corridor.

By synthesizing and adding to direct observations of process and function in a wood-rich, heterogenous river corridor, this work holds the potential to influence management aimed at using wood to restore dynamic processes in altered river corridors as well as motivate future work continuing to tease apart the complex interactions between logjams, channel dynamism, and spatial heterogeneity.

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CHAPTER 2: THE CONTINUUM OF WOOD-INDUCED CHANNEL BIFURCATIONS

Summary

Accumulations of wood in rivers can alter three-dimensional connectivity and facilitate channel bifurcations. Bifurcations divide the flow of water and sediment into secondary channels and are a key component of anastomosing rivers. While past studies illustrate the basic scenarios in which bifurcations can occur in anastomosing rivers, understanding of the mechanisms of bifurcations remains limited. I evaluate wood-induced bifurcations across thirteen anastomosing reaches in nine different streams and rivers in the U.S. Rocky Mountains to address conditions that favor different bifurcation types. I hypothesize that (1) wood-induced bifurcations exist as a continuum of different patterns in anastomosing rivers and (2) the position of a river segment along this continuum correlates with the ratio of erosive force to erosional resistance (F/R). I use field data to quantify F/R and compare varying F/R to bifurcation types across sites. Results support these hypotheses and suggest that bifurcation types exist as a continuum based on F/R. At higher values of F/R, more channel avulsion is occurring and predominantly lateral bifurcations form. At lower values of F/R, banks are more resistant to erosive forces and wood-induced bifurcations are transitional or longitudinal with limited lateral extent. The relationship between F/R and bifurcation types is not

linear, but it is progressive. Given the geomorphic and ecological functions associated with large wood and wood-induced channel bifurcations, it becomes important to understand the conditions under which wood accumulations can facilitate different types of bifurcations and the processes involved in these bifurcations. This understanding can inform river corridor restoration designed to enhance the formation of secondary channels, increase lateral and vertical connectivity, and promote an anastomosing planform.

1. Introduction

River channels can split and merge at various spatiotemporal scales, creating and abandoning bifurcations as they migrate. Some of the earliest documentation of rivers depicts channels bifurcating (Carling et al., 2014, Figure 2.1, Figure 2.2) and an extensive literature characterizes bifurcations (e.g., Bolla Pittaluga et al., 2003, 2015; Kleinhans et al., 2013). Bifurcations divide the flow of water and sediment into secondary channels and are a key component of delta distributary networks, braided planform, and anastomosing planform (Schumm, 1968; Knighton and Nanson, 1993; Burge, 2006). I consider anastomosing rivers to include at least two active parallel or sub parallel channels where flow rejoins downstream and vegetated islands or interfluves (≥ secondary channel width) are present between secondary channels. This description distinguishes anastomosing systems from distributary networks and braided planforms. Past work has described processes facilitating an anastomosing planform and planform distinctions (Schumm, 1968; Smith, 1973; Smith and Smith, 1980; Rust, 1981; Nanson et al., 1986; Schumann, 1989; Knighton and Nanson, 1993; Schumm et al., 1996; Makaske, 1998, 2001; Burge, 2006; Carling et al., 2014), as well as the characteristics of anastomosing rivers across diverse settings (e.g., Schumm, 1968; Baker, 1978; Smith and Smith, 1980; Nanson et al., 1986; Schumann, 1989; Harwood and Brown, 1993; Wohl et al., 2022). While these studies illustrate the basic scenarios in which bifurcation can occur, understanding of some of the mechanisms of bifurcations in anastomosing systems remains limited. I briefly review the conditions facilitating the formation of anastomosing channels and the role of logjams in creating channel bifurcations.

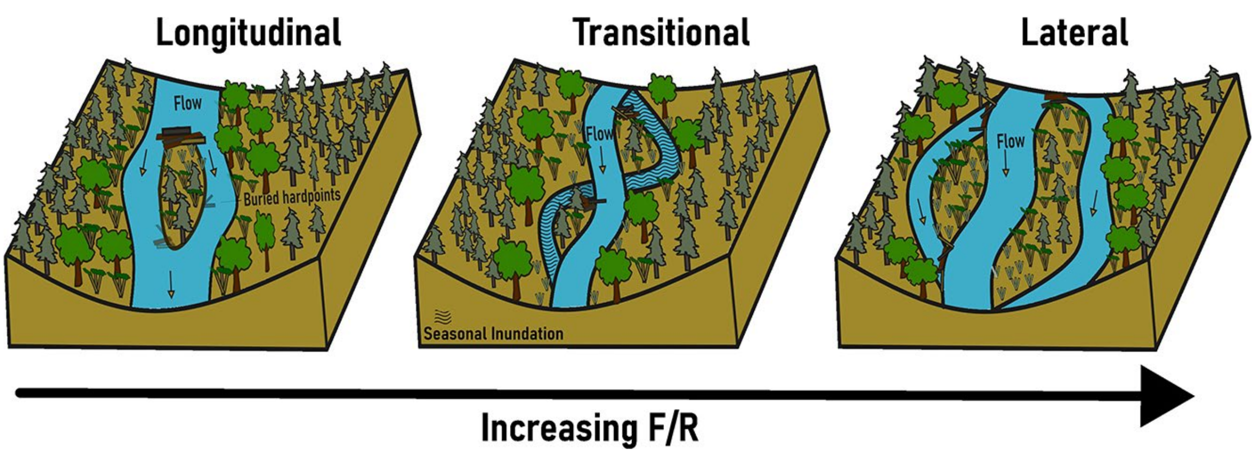

Figure 2.1. Conceptual illustration of jam-induced channel bifurcations. Lateral bifurcations (avulsive) form as a logjam forces overbank flow and bank erosion and the channel avulses laterally around the logjam. Longitudinal bifurcations (accretionary-bar splitting) form as a logjam creates lee deposition that is then stabilized by woody vegetation, forming a relatively short segment of split flow. Transitional bifurcations can

have lateral and/or longitudinal bifurcations and depend on seasonal persistence of flow in secondary channels. An arrow showing increasing F/R with lateral bifurcation formation illustrates hypothesis 2.

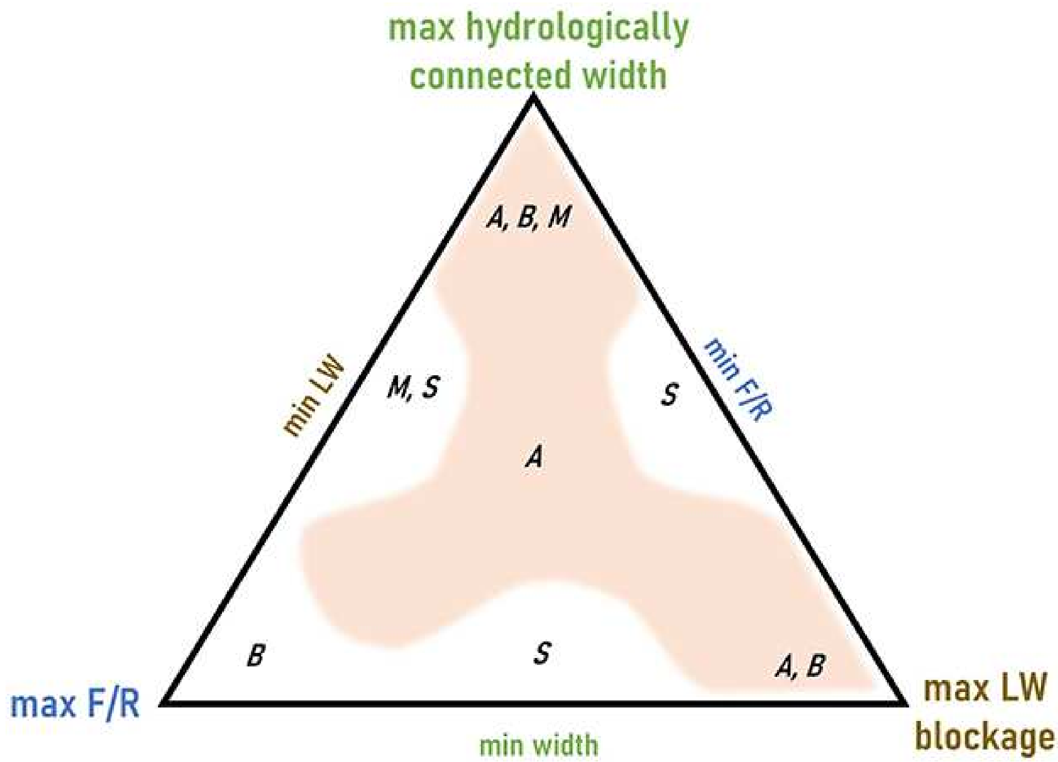

Figure 2.2. A ternary diagram illustrating how we conceptualize the interactions among three primary controls influencing wood-induced channel bifurcations. The maximum value of each of these controls occurs at a triangle vertex and the minimum at the mid-point of the opposite side of the triangle. Letters indicate channel planforms (A anastomosing, B braided, M meandering, S straight) and the shading indicates the range of conditions in which anastomosing channel planform can occur. Multiple letters separated by commas indicate that more than one channel planform is possible in that portion of the diagram.

1.1 Conditions Facilitating Anastomosing Planform

Anastomosing planforms have been attributed to diverse influences, including:

- Vegetation (e.g., Smith, 1976; Gradziński et al., 2003; Larsen, 2019)

- Sediment supply and bank cohesion (e.g., Rust, 1981; Smith, 1983; Gibling et al., 1998; Makaske, 1998)
- Tectonic uplift and basin subsidence (e.g., Rust et al., 1985; Smith, 1986)
- Increased flow magnitude (e.g., Smith and Smith, 1980; Knighton and Nanson, 1993)
- Channel obstructions such as large wood (e.g., Burge and Lapointe, 2005; Wohl, 2011; Collins et al., 2012), ice dams (e.g., King and Martini, 1984), and beaver dams (e.g., Woo and Waddington, 1990; Gurnell, 1998; Burchsted et al., 2010; Polvi and Wohl, 2012; Laurel and Wohl, 2019).

The combination underlying every scenario of anastomosing is (i) limited lateral migration due to either bank stability and/or limited stream power, which prevents the channel(s) from being sufficiently laterally mobile to create a braided planform and (ii) sufficient discharge and stream power to, at least episodically, overtop the banks and erode persistent secondary channels into the floodplain (Smith and Smith, 1980; Harwood and Brown, 1993; Makaske, 2001).

The distinction between anastomosing and other channel planforms is, to some extent, arbitrary because natural channel planforms occur along continua such as those between anastomosing and braided, anastomosing and meandering, or braided and meandering. Different positions along these channel-planform continua can represent differences in either the underlying processes driving bifurcation or the balance between hydraulic erosive force and erosional resistance. Carling et al. (2014), for example, described differences in bifurcations based on accretionary-bar flow splitting processes vs. avulsive processes. Accretionary alluvial islands can cause channel splitting as can avulsion across the floodplain (Carling et al., 2014).

A single piece of large wood or a logjam can facilitate differences in bifurcations based on accretionary-bar flow splitting or avulsive processes. A logjam can force overbank flow, bank erosion, and lateral bifurcation via avulsion (Wohl, 2011; Wohl and Cadol, 2011; Collins et al., 2012). A logjam can also create lee deposition that is then stabilized by woody vegetation, forming a relatively short segment of split flow and a longitudinal bifurcation via accretionary-bar flow splitting processes (Gurnell and Bertoldi, 2020) (Figure 2.1). Here, I build on this process-based understanding by examining the conditions under which logjams obstructing a channel can facilitate avulsive lateral channel bifurcations vs. accretionary-bar flow splitting longitudinal bifurcations.

1.2 Logjams and Channel Bifurcations

Wood accumulations can alter the three-dimensional connectivity of a river corridor. Here, connectivity refers to the degree to which matter (water, solutes, sediment, organic matter) and organisms can move among components of a landscape or ecosystem (Wohl, 2017). Accumulations of large wood can obstruct flow and facilitate channel bifurcations. I propose that the occurrence and characteristics of wood-induced bifurcations are influenced by (i) the hydrologically connected width, (ii) wood blockage, and (iii) the ratio of erosive force to erosional resistance (F/R) (Figure 2.2).

Hydrologically connected width is governed by valley-floor topography and the magnitude of overbank flow, which together limit the maximum possible lateral extent of channel bifurcations and whether there is sufficient space to form a multichannel (braided or anastomosing) planform. As suggested in Figure 2.2, a narrow valley floor will support only a single channel.

Wood blockage refers to the ratio of logjam frontal area to channel cross-sectional area. Even a logjam that does not span the entire channel can create sufficient blockage and enough hydraulic roughness to enhance overbank flow and initiate splays or avulsion channels (Brummer et al., 2006; Collins et al., 2012), although channel-spanning jams are more likely to deflect flow overbank and create backwater effects (Jeffries et al., 2003; Livers and Wohl, 2021). Even though multichannel planforms can occur in the absence of wood obstructions, they are more likely to occur where these obstructions are present (Collins et al., 2012).

F/R values can control whether overbank flow creates a new channel, as well as the spatial and longitudinal extent and cross-sectional area of secondary channels. Erosive forces exerted against the channel banks and floodplain surface, including shear stress, thermal erosion, and abrasion by ice, typically increase with discharge. Erosional resistance or bank erodibility results from the frictional properties of sediments, the effective normal stress of the bank, and effective cohesion (i.e., cohesion added from vegetation roots; Simon et al., 2000). Banks erode as individual grains detach from the bank or a mass failure occurs. Erosional resistance is commonly influenced by grain size distribution, stratigraphy, moisture level, vegetation (Järvelä, 2004; Pollen-Bankhead and Simon, 2010), large wood (Wohl, 2013), and topographic heterogeneity (Güneralp and Rhoads, 2011). The ratio of erosive force to erosional resistance, as originally conceptualized by Schumm (1985) based on gradient, sediment load, and bank composition, correlates with channel planform along a spectrum from a single, straight channel (low F/R) to a braided channel (high F/R).

Both dispersed pieces of large wood and logjams can have varying influences on erosive force and erosional resistance depending on the location, movement, and characteristics of the wood. Dispersed pieces of large wood within a channel can increase hydraulic roughness and thus reduce velocity and erosive force exerted against the banks (Manga and Kirchner, 2000; Brooks et al., 2003; Daniels and Rhoads, 2004). A jam can have the same effect and create a backwater that reduces bank erosion upstream (Triska, 1984; Le Lay et al., 2013). A jam or large wood piece can also deflect flow toward the bank, which promotes bar growth and lateral channel movement, and over the bank across the floodplain in a manner that promotes formation of secondary channels that branch from and then rejoin the main channel downstream (O'Connor et al., 2003; Collins et al., 2012; Martín-Vide et al., 2014). The movement of wood can increase erosional force as a jam moves in congested transport (Piegay, 1993) or the lack of movement can increase erosional resistance as jams remain stable for long periods of time, forming buried hard points (Collins et al., 2012).

1.3 Objective and Hypotheses

The primary objective of this work is to compare types of wood-induced channel bifurcations on multiple rivers and streams of differing size to address the conditions that favor one scenario over the other. I focus on systems where valley confinement, and thus hydrologically connected width, is not limited and where wood obstructions are abundant. I hypothesize that (1) wood-induced bifurcations exist as a continuum of different patterns in anastomosing rivers, as illustrated in Figures 2.1 and 2.2, and the position of a river segment along this continuum correlates with F/R.

2. Study area

I focus this study across nine rivers and streams of diverse size within the montane and mesic montane zone of the Rocky Mountains in Colorado and Montana, USA. I have thirteen study reaches across the nine study sites. Each river or stream reach has sufficient lateral space to create multiple channels (at least two) within the study areas.

2.1. Montana field sites

Study sites in Montana include Nyack Creek, the Swan River and two tributaries, Lost Creek and Goat Creek (Figure 2.3). I distinguish between upper and lower sites along the Swan River, Lost Creek, and Goat Creek. The Swan River (1,676 km2 drainage area) runs north along a valley bounded by the Mission Range to the west and the Swan Range to the east before draining into the Flathead River. Both Goat Creek (~94 km^2 drainage area) and Lost Creek (~85 km^2 drainage area) are within the Swan River Basin. Nyack Creek (~200 km^2 drainage area) flows west into the Middle Fork Flathead River before draining into the Flathead River.

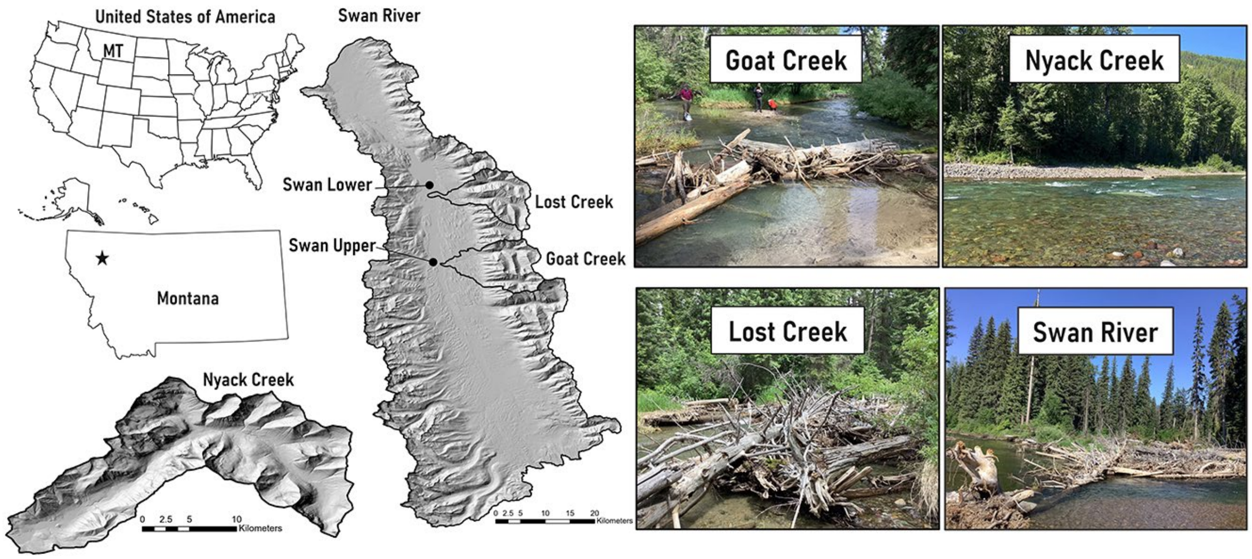

Figure 2.3. Montana field sites (Goat Creek, Lost Creek, Nyack Creek, Swan River). Note the different scale bars for the Nyack Creek and the Swan River watershed maps. Photos depict representative reach characteristics. I include two sites at Lost Creek, Goat Creek, and the Swan River in the results, but only show a photo of the upper reach for each site here.

The Swan basin receives ~750 mm of mean annual precipitation and the Nyack receives ~1500 mm of mean annual precipitation. Precipitation varies significantly with topography and rain shadow effect from the Rocky Mountains. Rainfall, snowmelt, and rain-on-snow precipitation can all produce peak flows, but the largest annual peak flow is typically associated with spring snowmelt (MacDonald and Hoffman, 1995). The hydrology of the region is dominated by the accumulation and melting of seasonal snowpack, with high flow occurring during the spring and low flow occurring during the late summer, autumn, and winter months.

The region is underlain by the Proterozoic-age Belt Supergroup, which mostly consists of weakly metamorphosed, fine-grained sedimentary rocks. The area is within the Intermountain Seismic Belt, a seismically active zone characterized by range-bounding normal faults (Hofmann and Hendrix, 2010). In addition to continuing uplift, topography in the region was shaped by Pleistocene glaciations. Lacustrine glacial lake deposits along with volcanic ash layers overlie rocky glacial till (Locke, 1995; Hofmann and Hendrix, 2010). Soils are thin, have poorly developed profiles (Antos and James, 1981), and are mostly gravelly loamy sand (USDA, 2022). Channels primarily have cobble- to boulder-bed substrate with pool-riffle sequences. Valley width along the Swan is ~1–2 km with an average channel gradient of 0.5%. Valley width along Nyack Creek averages 400–500 m with an average channel gradient of 0.2%.

Valley floors in the region are primarily covered with mesic montane conifer forests and wetlands, with some areas of subalpine forest. Shade-intolerant species include western larch (Larix occidentalis), western white pine (Pinus monticola), and Douglas-fir (Pseudotsuga menziesii). Climax, shade-tolerant species include grand fir (Abies grandis) and western redcedar (Thuja plicata) (Antos, 1977). Despite a history of patch timber harvest and stand-replacing fires in the upland portions of the valley (Antos and James, 1981; Parks et al., 2015), substantial portions of old-growth forest remain (Lesica, 1996) and the floodplain has experienced little development. The Swan River and Nyack Creek corridors have a high volume of downed wood within the channel and floodplain (Wohl et al., 2018).

2.2. Colorado field sites

Study sites in Colorado include a site along Little Beaver Creek (LBC), two sites along North Saint Vrain Creek (NSV), and one site along each of three NSV tributaries, Cony Creek, Ouzel Creek, and Hunters Creek (Figure 2.4). Cony Creek (~ 20 km^2 drainage area), Ouzel Creek (~15 km^2 drainage area), and Hunters Creek (~12 km^2 drainage area) are all within the NSV drainage. NSV (drainage area 345 km^2) and LBC (drainage area 40 km2) lie within the watershed of the South Platte River in the Colorado Front Range. The region receives ~550 mm of precipitation per year with variation based on elevation and has a mean annual temperature of 8.3°C (Barry, 1973). These sites are snowmelt dominated with a sustained seasonal peak, but summer convective storms can produce brief floods of higher magnitude (Jarrett, 1990).

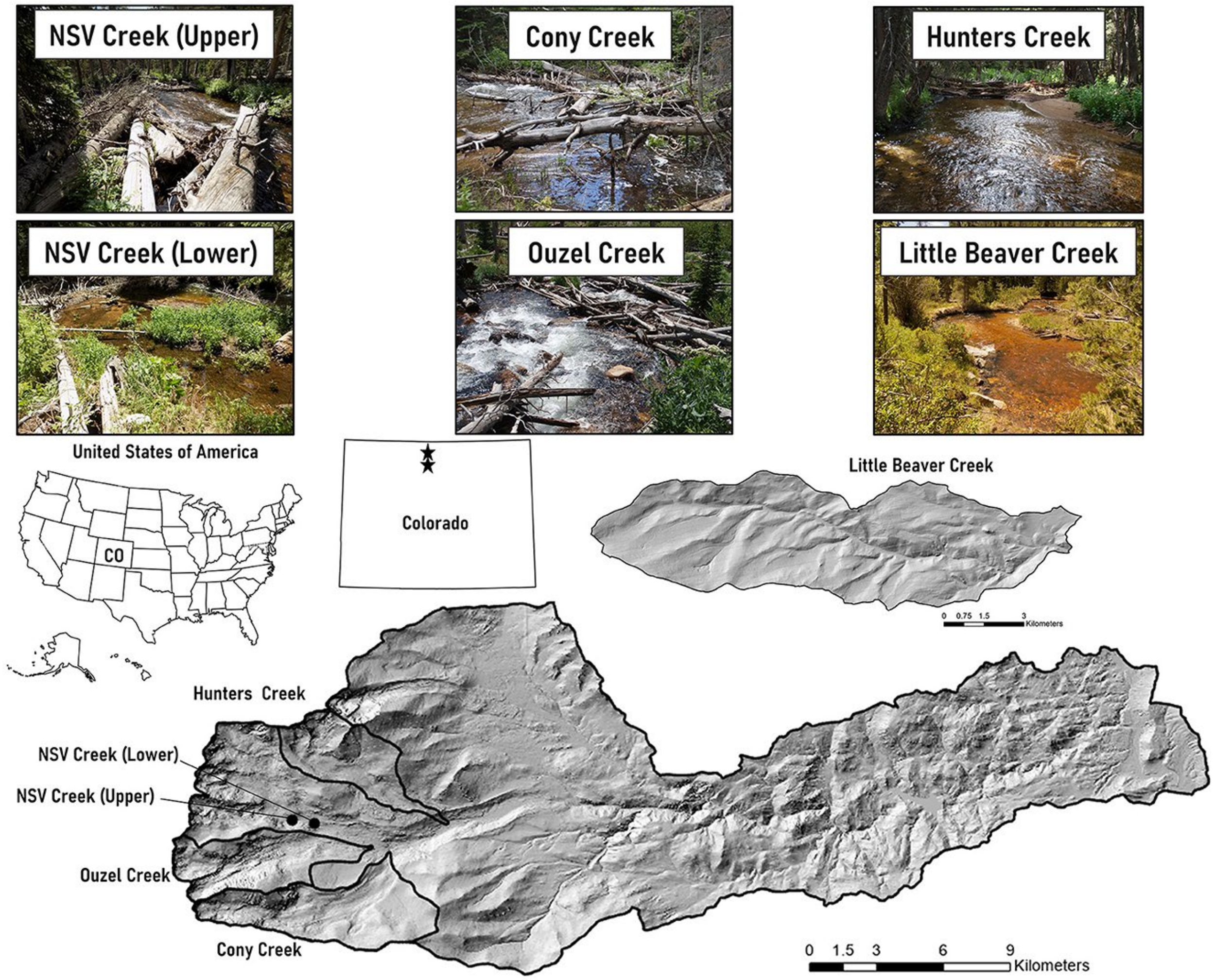

Figure 2.4. Colorado field sites (Cony Creek, Hunters Creek, Ouzel Creek, North Saint Vrain Creek, and Little Beaver Creek). Note different scale bars for Little Beaver Creek and the sites within the North Saint Vrain Creek watershed. Photos depict representative reach characteristics.

Front Range catchments are underlain by Precambrian Silver Plume granite (Braddock and Cole, 1990; Cole et al., 2010). Valley geometry is highly variable longitudinally (Wohl et al., 2017), largely as a result of variations in bedrock joint density (Ehlen and Wohl, 2002). Fracture patterns in the granite create downstream alternations between relatively steep, narrowly confined valley segments and lower-gradient, less confined segments at lengths of 101-102 m. Channel planforms typically alternates between step-pool channels with boulder substrate in the most confined sections to anastomosing channels with pool-riffle bedforms or wood-forced steps and pools, and a cobble substrate, in the wider valley segments. Average channel gradient varies from 6 (upper portion NSV site) to 2% (Cony Creek) and channel substrate averages 45–60 mm diameter clasts, except in logjam backwaters where sand and fine gravel are present. Lower gradient and less confined reaches have anastomosing planforms with abundant channel-spanning logjams (Wohl, 2011) or beaver dams (John and Klein, 2004; Polvi and Wohl, 2012).

The region has old-growth montane forest. Dominant species include ponderosa pine (Pinus ponderosa), Engelmann spruce (Picea engelmannii), Douglas-fir (Pseudotsuga menziesii), aspen (Populus tremuloides), and willows (Salix spp.). Large wood is recruited to channels primarily from bank erosion and individual tree fall and channel-spanning logjams are abundant in the channels (Jackson and Wohl, 2015). Both watersheds have experienced recent disturbances by fire, flooding, and mass movements that significantly altered the watersheds and river corridors (Sibold et al., 2006; Rathburn et al., 2017; Sutfin and Wohl, 2019; Wohl et al., 2022). Most recently, the 2020 Cameron Peak fire burned substantial portions of the LBC watershed. New anastomosing reaches were created in both burned and unburned portions of the watershed during post-fire flash floods.

3. Methods

At each study site, I characterized channel bifurcations and associated jams. I measured bank height, root depth/organic layer thickness, and coarse layer thickness, and collected one representative bank sample for organic layers and one for coarse layers to use in grain size analysis at locations where bifurcations occurred. Bank samples were sieved for grain size distribution. I measured the width of logjams relative to the width of the channel to calculate blockage ratios and used the most up-to-date Google Earth imagery at each site (spanning 2014–2022) to measure hydrologically connected width using the built-in measure tool (https://earth.google.com/web/).

I used field data to quantify metrics of F and R. I use stream power as the primary indicator of F, which is the product of discharge, channel gradient, and the specific weight of water. Stream power is a useful predictor of channel form and dynamics because it quantifies the amount of geomorphic work that can be done by a stream, such as moving sediment on the bed or in the banks of the river (i.e., erosion or sediment transport). More specifically, stream power is commonly used as a tool to investigate the lateral stability of river channels (e.g., Chang, 1979; Nanson and Croke, 1992; Makaske, 1998). I used USGS StreamStats (https://streamstats.usgs.gov/ss/) to determine average snowmelt peak flow as a discharge value at which we expect wood can move. I used field measurements and LiDAR data to extract reach-scale channel gradient for each study site. I used the bank stability and toe erosion model (BSTEM; https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/bstem/) from the National Sedimentation Laboratory to provide comparative estimates of R (Simon et al., 2011). BSTEM integrates grain size, bank height and angle, sediment layer thicknesses, and vegetation data and is a commonly used tool for modeling streambank erosion and failure (Simon et al., 2000, 2011; Curran and Hession, 2013; Rinaldi and Nardi, 2013; Klavon et al., 2017). I use F/R to determine how much force relative to resistance is acting at each site and to compare the relative ratios across sites. I did not attempt to calculate a dimensionally correct ratio with respect to units. Rather, I use this ratio as an indicator of potential excess energy available for bank and floodplain erosion associated with channel bifurcations.

I manually measured total sinuosity and the ratio of channel migration width to average channel width as river corridor geometric variables using the built-in measure tool in Google Earth (https://earth.google.com/web/). Measurements were averaged across 500-m reaches at study sites. Total sinuosity is the ratio of total channel length of all active channels/valley length (Hong and Davies, 1979; Egozi and Ashmore, 2008).

Channel migration width is measured as the meander belt or total width between the outermost active channel edges in a multi-channel system. The ratio of this value to main channel bankfull width provides a dimensionless indicator of the lateral extent of active channel bifurcations. I used both total sinuosity and channel migration width/channel width as metrics for the degree to which a river has bifurcated. The larger the value of either metric, the more the river approaches the lateral bifurcation endmember in Figure 2.1; smaller values indicate the longitudinal bifurcation endmember.

Given the small dataset, I ran both parametric and non-parametric statistical analyses to assess the relationship between F/R and bifurcations. I used RStudio to perform the statistical analyses (R Core Team, 2022). I ran a simple linear regression and calculated the Pearson correlation coefficient (r) from the multiple R-squared. I calculated the Spearman rank correlation coefficient (ρ) as a non-parametric measure of the relationship between F/R and bifurcations. Given the repetition in values for some F/R ratios, I also calculated the Kendall rank correlation coefficient (τ) to ensure there is no impact from ties in the analyses (Hollander et al., 2014). All correlation coefficients were calculated using the cor.test() function in base R. I conducted the same analyses looking at the correlation between F/R and total sinuosity and F/R and channel migration width/channel width. The Pearson, Spearman, and Kendall correlation coefficients all measure the strength of the relationship between two variables (F/R and total sinuosity and F/R and channel migration width/channel width) for parametric (Pearson) or non-parametric (Spearman and Kendall) datasets. I used an alpha (probability of rejecting the null hypothesis when the null hypothesis is true) of 0.05 in all statistical analyses.

4. Results

Results support both hypotheses that (1) wood-induced bifurcations exist as a continuum of different patterns in anastomosing rivers and (2) the position of a river segment along this continuum correlates with F/R. The full dataset is included as Supplementary Information to Chapter 2. I plot F/R with both total sinuosity and channel migration width/channel width as proxies for the types of bifurcations. The results for both suggest that bifurcation types exist as a continuum based on the ratio of F/R. I report only the Pearson Correlation Coefficients given the agreement between parametric and non-parametric correlation coefficients, but Spearman and Kendall correlation coefficients are included as Supplementary Table S2. Pearson correlation coefficients suggest a positive relationship between F/R and bifurcations ($r = 0.837$ for total sinuosity and $r = 0.829$ for channel migration width/channel width). At higher values of F/R, more channel avulsion is occurring and lateral bifurcations form (Figure 2.5, Figure 2.6). At lower values of F/R, jam bifurcations are transitional or longitudinal but are not lateral (Figure 2.5, Figure 2.6). The relationship between F/R and bifurcation type is not linear, but it is progressive.

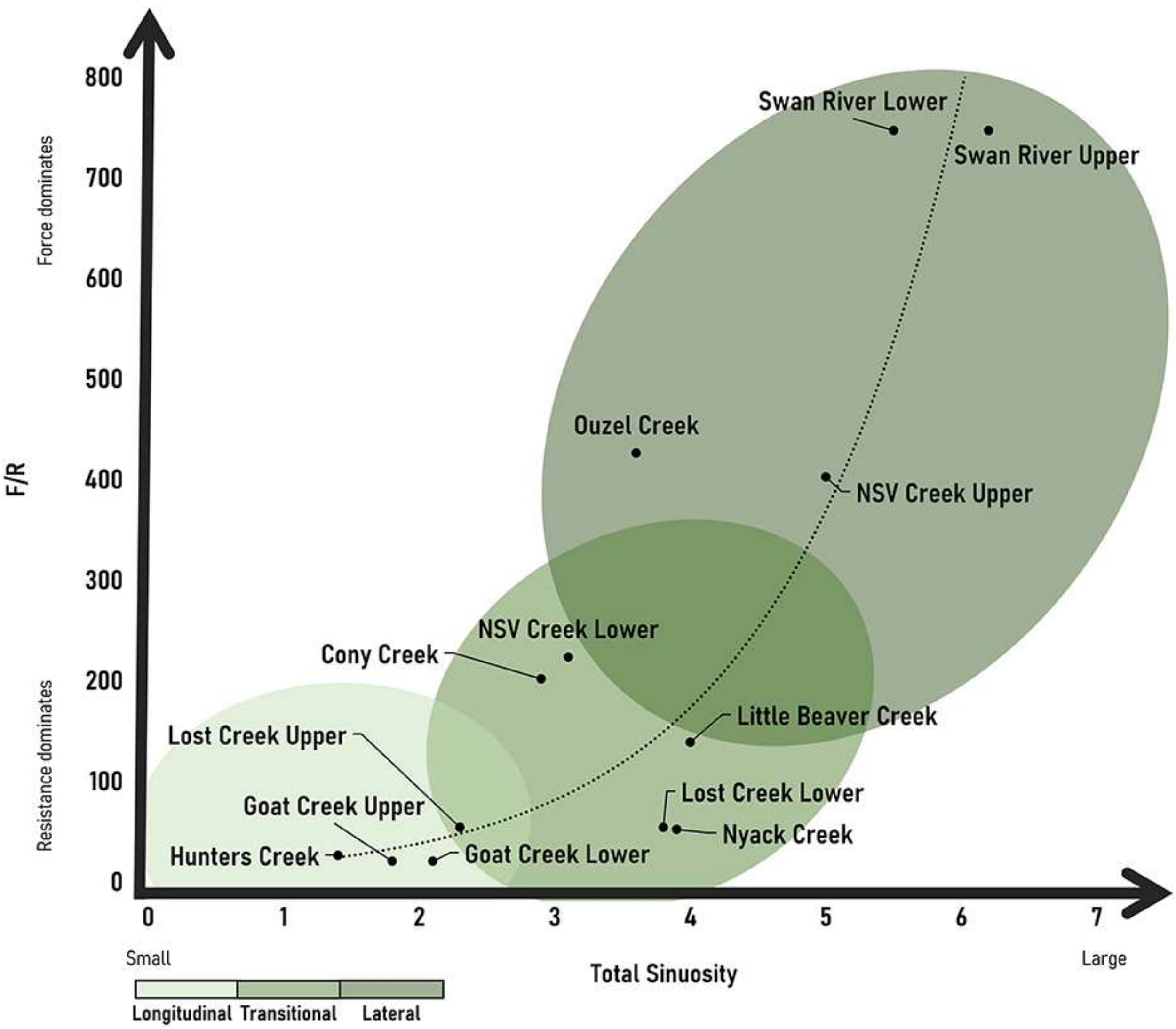

Figure 2.5. Observed continuum of channel bifurcations based on total sinuosity and F/R with an exponential line of best fit.

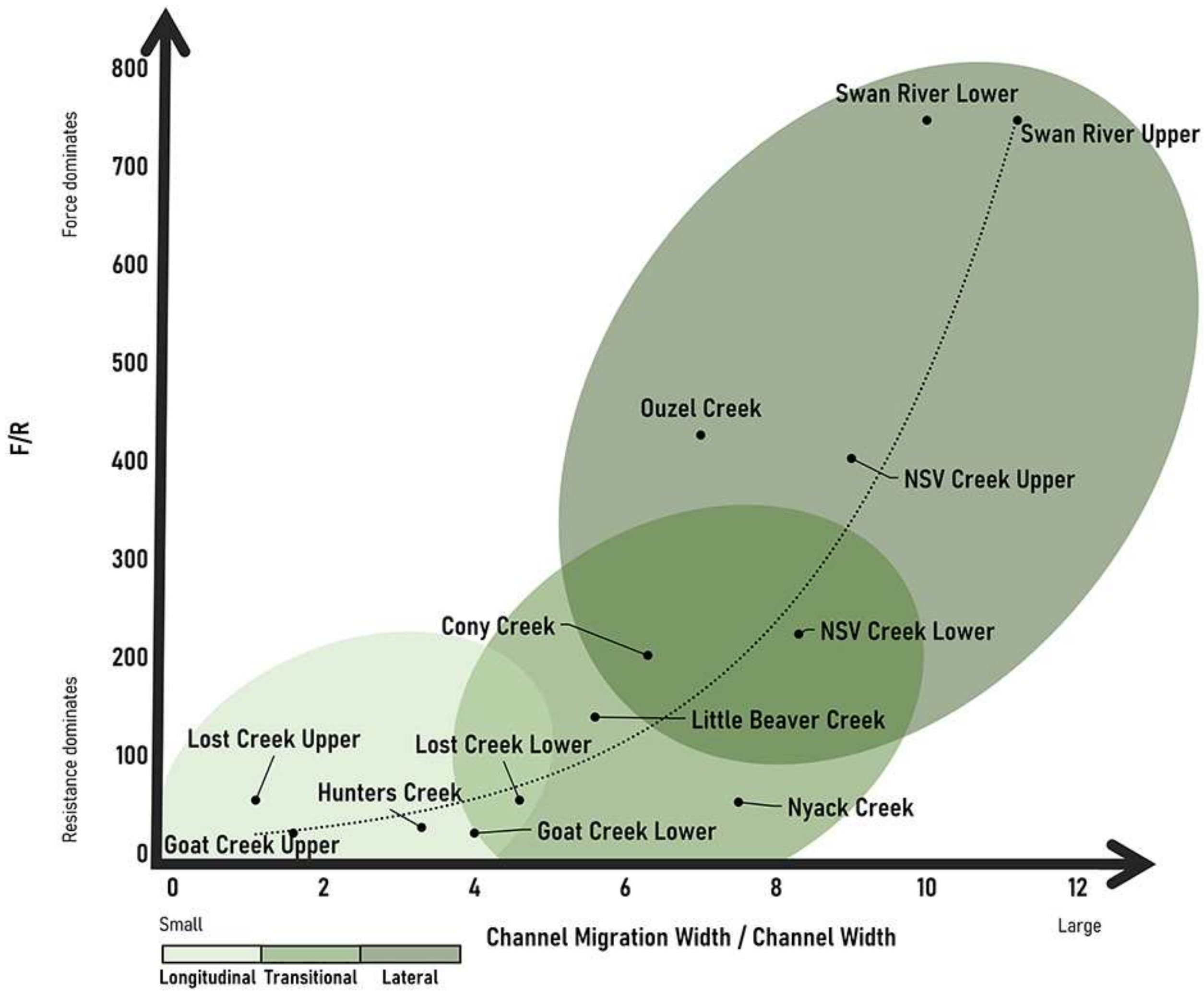

Figure 2.6. Observed continuum of channel bifurcations based on channel migration width/channel width and F/R with an exponential line of best fit.

5. Discussion

Results suggest that bifurcation types exist as a continuum based on F/R. I observe a relationship between bifurcation type and F/R, where at higher values of F/R, more channel avulsion is occurring and lateral bifurcations with an increasing number of secondary channels and relative lateral extent form. I see the highest F/R and number of lateral bifurcations at the Swan River sites. Not surprisingly, this site has the highest stream power, and we assume the highest transport capacity for wood. Visual observations in the field suggest that wood is regularly reworked within the Swan. I observed newly forming anastomosing reaches along the Swan where wood accumulations appear to have been transported and deposited during high flows, causing new bifurcations to form as flow avulsed laterally around logjams. The Swan also has a smaller root depth relative to the coarse layer of sediment, which contributes to more erodible banks relative to other sites. I see the lowest F/R and number of bifurcations along the upper portions of Goat Creek and Lost Creek as well as Hunters Creek. At each of these sites, conifers (>2 m in height) had established on the longitudinal bifurcations and buried pieces of wood were observed along the length of the bifurcation, suggesting the persistence and presence of older logjams. The transition from longitudinal to lateral bifurcations is progressive as F/R increases. This likely reflects a combination of increasing stream power and decreased root depth relative to the coarse layer in the banks, causing less erosional resistance. In other words, a combination of the flow having more erosive power and the banks being less stable as the root depth relative to the total bank height changes drives a transition from longitudinal to lateral bifurcations.

5.1. Significance of wood-induced bifurcations

Understanding the conditions that facilitate different types of wood-induced bifurcations has important implications for the broader physical and biological processes in a river corridor. Wood-induced channel bifurcations support beneficial hydrologic, geomorphic, and ecologic function. In-channel logjams split flow and trap sediment, creating multiple channels and islands that dissipate energy during high flows (Brummer et al., 2006; Wohl, 2011; Collins et al., 2012). The ratio of wood blockage in a channel and F/R can influence the degree to which longitudinal and vertical connectivity is increased and lateral connectivity is decreased. Wood-induced bifurcations promote connectivity in the lateral (Baxter et al., 2005; Kondolf et al., 2006; Wohl, 2013) and vertical (Hester and Doyle, 2008; Sawyer et al., 2011; Marttila et al., 2018; Wilhelmsen et al., 2021) dimensions of a river corridor. Multiple, wood-rich channels that are laterally connected to the floodplain and vertically connected to the hyporheic zone support abundant and diverse habitat and species (Dolloff and Warren, 2003; Herdrich et al., 2018; Venarsky et al., 2018). The connectivity driven by wood-induced bifurcations provides refugia and resilience during disturbances such as flood, drought, and wildfire (Benda et al., 2004). For example, high water table, deep pools, and lateral connectivity provide drought refugia and more stable base flows (Boulton et al., 1998; Bêche et al., 2009; Dixon, 2016; Puttock et al., 2017). Increased lateral connectivity facilitated by logjams and secondary channels helps to attenuate flood peaks and diffuse flood flows across the floodplain (Junk et al., 1989; Poff et al., 1997), making habitats persistent and more resistant to natural and anthropogenic disturbances (Amoros and Bornette, 2002; Henning et al., 2006; Jeffres et al., 2008).

Hydrologic connectivity and interactions with wood are accompanied by hydraulic effects. Wood obstructions can divert and concentrate flow, creating local areas of high velocity and shear stress separated by wood-sheltered areas where velocities and shear stresses are drastically reduced (Gurnell, 2013; Matheson et al., 2017). Wood-induced bifurcations maximize hydraulic heterogeneity through partitioning of flow between branches that widen the range of in-channel depths and velocities (Gordon et al., 1992). Logjams reduce flow velocity and create pools (Beechie and Sibley, 1997; Montgomery and Buffington, 1997; Abbe and Montgomery, 2003) and bifurcations create multiple, marginal zones of slower flow. Both attributes promote bed heterogeneity and maximize morphological features in the channel and on the floodplain (Montgomery et al., 1996; Buffington and Montgomery, 1999), providing high capacity to store sediment and cycle nutrients (Parker et al., 2017). Frequent, small channel adjustments and a high, reliable water table also create optimal settings for germination and growth of aquatic and riparian vegetation (Nadler and Schumm, 1981; Tal and Paola, 2007; Braudrick et al., 2009). Wet woodlands on islands and floodplains supply and retain wood and widespread vegetation proximal to the channel (Fetherston et al., 1995; Gurnell et al., 2001; Montgomery and Abbe, 2006), supporting habitat and increased retention of organic matter and nutrients for other organisms (Bilby, 1981; Flores et al., 2011). Dense, diverse riparian vegetation provides abundant shade which, together with efficient hyporheic exchange, ameliorates water temperatures (Montgomery et al., 1999; Beechie et al., 2005).

5.2. Continuing work

The results summarized here suggest additional questions with respect to wood-induced channel bifurcations. These include potential thresholds of wood blockage, persistence of wood accumulations, and erosive mechanisms. First, is there a threshold size of wood accumulation or wood volume relative to channel dimensions that is necessary to drive bifurcations? Second, how long must wood accumulations persist relative to recurrence of peak flows to create persistent bifurcations? I was not able to directly observe interactions between potentially transient wood accumulations and channel bifurcations. I suspect, based on inference and multi-year field observations of some sites, that one large peak flow is sufficient to form a new bifurcation, even if the peak flow removes the wood accumulation that initiated the process of bifurcation. However, this inference has not been quantitatively tested. Third, what specific erosional mechanisms create channel bifurcations? Wood accumulations can cause preferential local bank erosion that could develop into a longitudinal bifurcation, for example. My observations also indicate that diffuse overbank flow across the floodplain can concentrate into secondary channels over multiple seasons of peak flow. I have also observed overbank flow that returns to the channel downstream, creating a floodplain knickpoint at the point of re-entry to the channel during flows below bankfull stage. This knickpoint could presumably erode headward and help to stabilize a secondary channel.

Additional work is also needed across diverse settings to understand whether wood is a key driver of bifurcations in rivers with different hydrologic, wood, and sediment regimes. My study focuses on snowmelt-dominated rivers with floodplains that are highly erodible (relatively uncohesive upper sediment layers and shallow-rooted conifers) except where willows grow in relatively dense stands. Additional work looking at the effects of flashier peak flow in rainfall-dominated rivers, highly cohesive silts and clays in floodplain alluvium, or different vegetation communities with greater hydraulic roughness and root resistance, would all provide valuable insight into understanding bifurcations across diverse settings.

6. Conclusion

Results suggest that bifurcation types exist as a positive continuum based on the ratio of F/R. Longitudinal and lateral bifurcations occur at either end of the continuum, with transitional bifurcation types between. At higher values of F/R, more channel avulsion is occurring and lateral bifurcations form across a broader portion of the floodplain. At lower values of F/R, banks are more resistant to erosive forces and wood-induced bifurcations are transitional or longitudinal with a much lower lateral extent. More work considering thresholds of drivers forming new bifurcations across diverse settings will provide further insight into understanding of the mechanisms behind bifurcations. As the need for resilient and more connected river systems increases in the face of accelerated environmental change, understanding the conditions under which wood accumulations can facilitate different types of bifurcations and the processes involved in these bifurcations is both significant and timely to river corridor science and management.

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CHAPTER 3: WOOD-INDUCED DEPOSITION AND EROSION IN THE RIVER CORRIDOR

Summary

Large wood causes and responds to deposition and erosion within a river corridor. I focus on the anastomosing, gravel-bed Swan River and two meandering, gravel-bed tributaries in northwestern Montana, USA to explore the temporal dimensions of deposition and erosion associated with channel avulsions and island formation and to introduce the concept of wood levees. Channel avulsion represents isolation of part of the existing floodplain and formation of an anastomosing channel planform, with wood-induced deposition at the point of channel bifurcation. Islands form at a wood jam that migrates upstream with time as sediment accumulates in the lee of the jam. The island creates only a local interruption of the single-channel planform. I use tree-ring and ^{14}C dating to constrain wood-induced island ages. I interpret the three wood-induced forms of deposition and erosion that I describe here as reflecting a temporal continuum. Wood levees have primarily non-woody vegetation and may be transient relative to the other features. Tributary islands appear to persist from a decade to over a century. Tree ages of 100-200 years at the floodplain avulsion site and the characteristics of the secondary channels suggests that these wood-induced avulsion features can persist for more than a century. Understanding the temporal dynamics of wood-induced features and spatial

variation in erosion and deposition provides insight into the dynamics and spatial heterogeneity of natural river corridors, with implications for river restoration.

1. Introduction

1.1 Previous work on large wood and channel dynamics

The potential for individual wood pieces and accumulations of large and small wood and sediment (hereafter, wood jams) to induce sediment storage in channels and floodplains within river corridors has been recognized for decades (e.g., Keller and Swanson, 1979; Keller and Tally, 1979). Processes of sediment erosion and deposition influence the morphology of a river channel and floodplain, as well as the spatial distribution and residence time of sediment. Large wood pieces ($\geq$ 10 cm diameter and 1 m length) and wood jams ($\geq$ 3 large wood pieces) both cause and respond to sediment deposition and erosion. Large wood causes deposition by obstructing flow, increasing hydraulic roughness, and creating zones of flow separation with lower velocity and sediment transport capacity (Wohl and Scott, 2017). Large wood causes erosion by concentrating and directing flow toward the channel bed, banks, or overbank areas (Webb and Erskine, 2005; Grabowski et al., 2019). Large wood in transport also responds to the river corridor morphology created through deposition and erosion: wood is preferentially trapped and stored on bars and in secondary channels, for example (Wyżga & Zawiejska, 2005; Scott and Wohl, 2018).

The details of the volume and grain-size distribution of sediment stored in association with wood in the river corridor vary across geomorphic settings. Wohl and Scott (2017), for example, distinguished channel-spanning wood jam steps and backwater sediment wedges (e.g., Short et al., 2015) in steep channels from more widespread channel aggradation associated with wood-induced increases in bed hydraulic roughness (e.g., Brooks et al., 2003). Other studies have documented wood rafts and associated floodplain sedimentation in large, low-gradient rivers (e.g., Triska, 1984; Boivin et al., 2015). These interactions between large wood and sediment can be broken down to include six basic forms of wood-induced deposition in river corridors, which can be paired with wood-induced erosion in river corridors (Figure 3.1.).

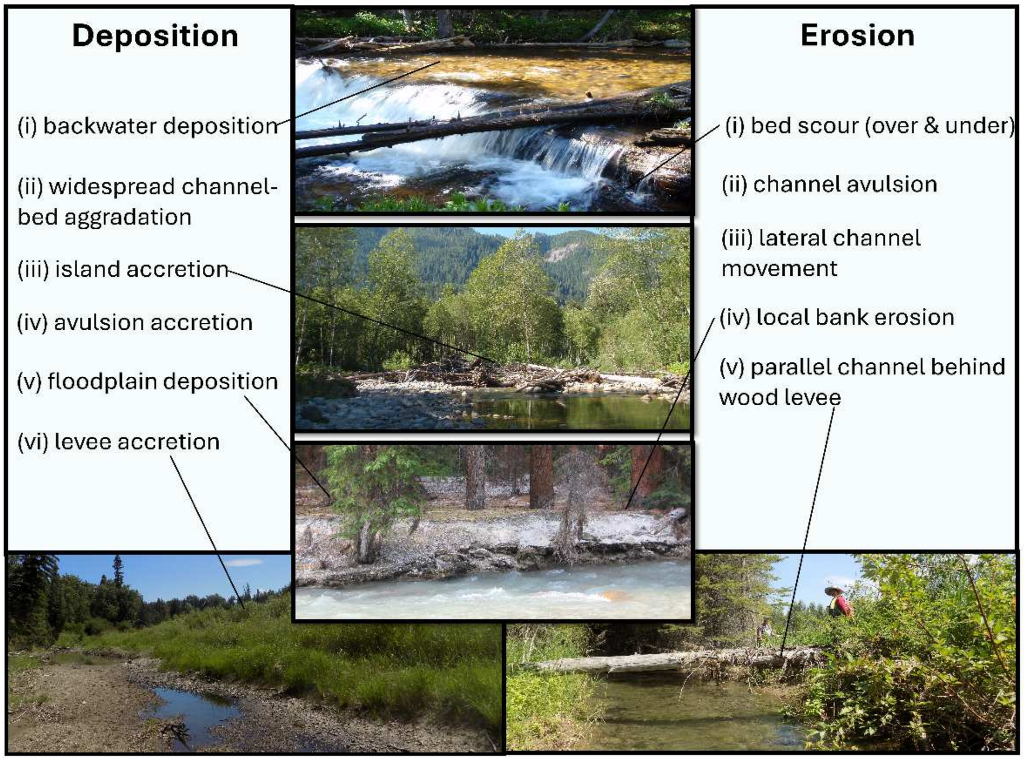

Figure 3.1. Basic forms of wood-induced aggradation and erosion in the river corridor.

Wood-induced deposition can occur: (i) in a backwater upstream from a wood jam (Mao et al., 2008; Welling et al., 2021); (ii) across and along a channel in which dispersed wood pieces increase bed roughness (Brooks et al., 2003); (iii) as bar deposition downstream from a wood jam, which can lead to island accretion as vegetation colonizes the bar and traps additional large wood at the upstream end of the island (e.g., Abbe and Montgomery, 1996; Gurnell et al., 2005); (iv) as accretion at the upstream end of a portion of the floodplain where the channel bifurcates as a result of wood-induced channel avulsion; (v) as localized or widespread floodplain deposition where large wood obstructs flow in the channel (Jeffries et al., 2003; Oswald and Wohl, 2008); and (vi) as levee accretion where relatively long, narrow wood accumulations form at the channel-floodplain boundary (Figure 3.1.). At any of these locations, the amount and grain-size distribution of sediment stored depends on factors such as the degree to which transport capacity is reduced by greater roughness and obstruction of flow, the persistence of the large wood, and the amount of sediment in transport within the river corridor.

Wood-induced erosion can occur where: (i) flow is concentrated over, around, or under large wood, creating localized bed scour (Webb and Erskine, 2005; Ravazzolo et al., 2015); (ii) wood jams promote sufficient overbank flow to create channel avulsion on the floodplain (Sear et al., 2010); (iii) flow around large wood is sufficient to enhance channel lateral migration (Brummer et al., 2006); (iv) flow around large wood creates localized bank erosion (Phillips, 2012); and (v) secondary channels parallel to the main channel form on the floodplain side of a wood levee (Figure 3.1.). The magnitude of erosion reflects the degree to which flow is deflected by wood, the erosional forces exerted against channel and floodplain boundaries, and the erosional resistance of those boundaries.

Many of these types of wood-induced deposition and erosion have been extensively described in existing studies, except for wood levees. Existing studies examining wood-induced bar and island formation come from gravel-bed, lowland rivers of the northwestern United States (Maser & Sedell, 1994; Abbe & Montgomery, 2003; O'Connor et al., 2003; Naiman et al., 2010; Collins et al., 2012), sand-bed, lowland rivers of the interior western United States (Osterkamp, 1998), the gravel-bed, braided Tagliamento River in Italy (e.g., Edwards et al., 1999; Kollmann et al., 1999; Gurnell et al., 2001; Zanoni et al., 2008; Bertoldi et al., 2009; Gurnell & Petts, 2006; Moggridge & Gurnell, 2009; Gurnell et al., 2019; Gurnell et al., 2020), and gravel-bed rivers in the Polish Carpathians (e.g., Wyżga & Zawiejska 2005; Wyżga & Zawiejska, 2010; Mikuś et al., 2013; Mikuś et al., 2019). Much of the work published thus far is descriptions of the relationship between bar/island development and wood jams, including conceptual models. For example, over 17 years, Gurnell et al. (2019) documented bar/island development on the Tagliamento River in Italy. Kollmann et al. (1999) found that succession from bar to established island takes approximately 20 years in the same system. Zanoni et al. (2008) looked at the age/turnover of islands based on air photos of the Tagliamento River and found that most islands persisted for less than 24 years. Mikuś et al. (2013) used tree-ring dating to estimate the time of island inception on Czarny Dunajec, Poland, and observed trees aged approximately 45 years or younger. Mikuś et al. (2019) observed island development over about a decade in response to floods and passive restoration in the Raba River of Poland. In the U.S. Pacific

Northwest, Naiman et al. (2010) developed a conceptual diagram with a general timeline for rates of island development of approximately 70 years.

1.2 Channel avulsion versus island formation

I build on existing work by adding insight to current gaps in our understanding of temporal processes and features associated with wood-induced deposition and erosion, focusing on accretion associated with channel avulsion and island formation, and deposition and erosion associated with wood levees. I differentiate accretion associated with channel avulsion from accretion associated with island formation as follows. Wood jams accumulating at the upstream side of floodplain trees along the margin of an active channel can facilitate overbank flow that leads to the formation of a secondary channel separated from the mainstem by a portion of intact, forested floodplain that is much wider than the active channel. Repetition of this process creates an anastomosing channel planform (Collins et al., 2012). The wood jam can persist after the channel avulsion, and its presence enhances sediment deposition and trapping of additional wood upstream, creating a site on which woody vegetation can germinate. This is what I describe as avulsion accretion.

In contrast, islands in our study area form in smaller channels (e.g., tributaries or anabranches) where channel-spanning wood jams divert flow toward the banks and create a channel split that extends a relatively short (roughly 2-4 times the bankfull channel width) distance downstream before the channels merge again. In this scenario, the channel retains the straight or meandering planform that characterizes it upstream and downstream from the site of island formation. The wood jam can continue to accumulate wood at the upstream side, growing upstream with time, while woody vegetation germinates on the protected downstream end of the jam. This is what I refer to as island accretion. The relatively narrow island that results is constructed as a result of the presence of the wood jam, whereas an avulsion represents the isolation of a part of the existing floodplain, but with local deposition upstream from the wood jam that facilitated the avulsion (Figure 3.2.).

The key distinction is that an island can occur in a straight, meandering, braided, or anastomosing channel, but the wood-induced avulsion I am describing here creates an anastomosing channel planform in which portions of floodplain with mature forest are much wider than the secondary, anastomosing channels formed between them.

1.3 Objectives of this study

Our objective here is to introduce and briefly describe a new form of wood-induced feature (wood levees and associated backchannels) and explore the temporal dimensions of wood-induced island and avulsion deposition and erosion. I build on the work of

Marshall and Wohl (2023), identifying a continuum of spatial patterns in wood-induced accretionary and avulsive bifurcations along the Swan River of northwestern Montana, USA, and its tributaries. Marshall & Wohl (2023) found that the ratio of erosive force to erosional resistance present at each site was important in dictating accretionary vs. avulsive processes and the subsequent pattern of wood-induced bifurcations that occur. Here, I consider whether a temporal continuum exists between wood-induced accretionary and avulsive features. I constrain tributary island persistence (via ^{14}C dates) and document rates of vegetation establishment (via tree rings) for islands as I examine what causes island persistence vs. avulsions through time.

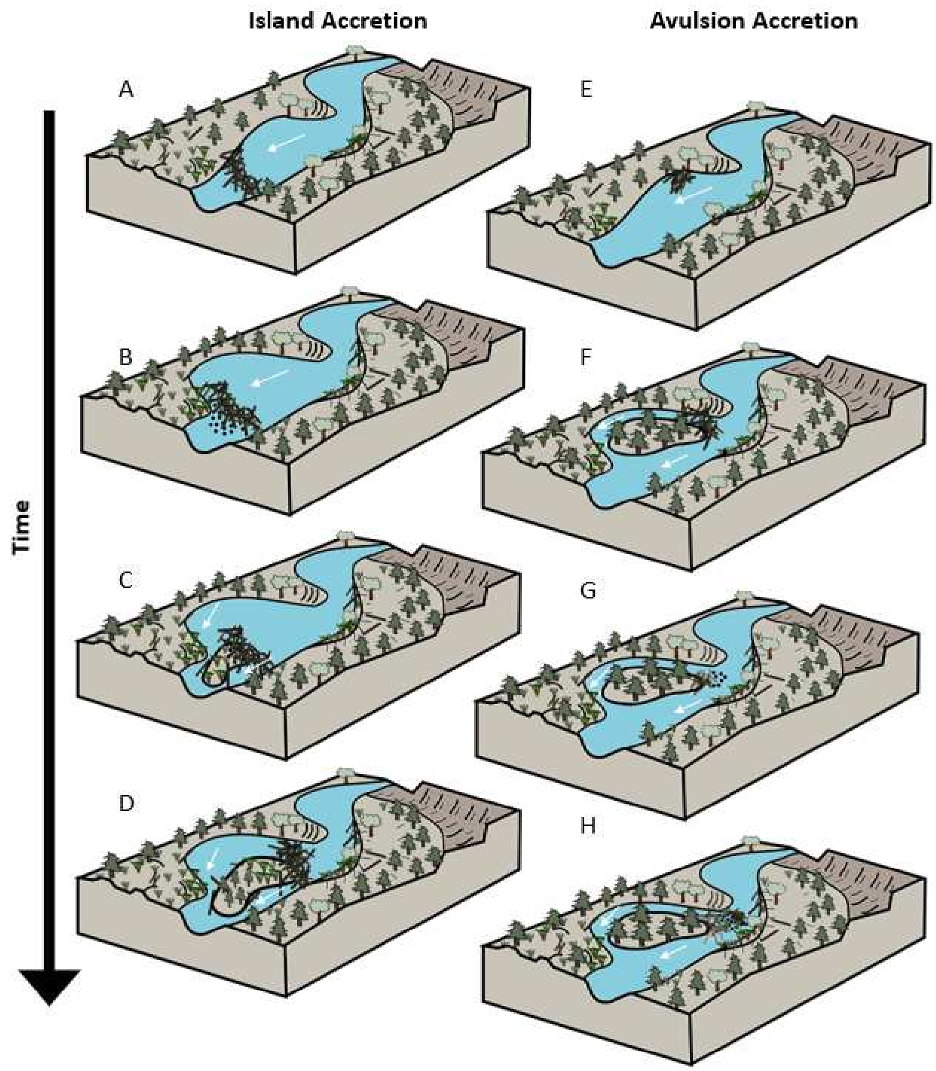

Figure 3.2. (A-D) Conceptual model of island growth upstream with time. Arrows within the block diagram indicate flow direction. Initial wood deposition (A) creates a low-velocity zone in the lee of the jam in which sediment is deposited and on which plants can germinate (B). The first obstacle wood meets in transport downstream, however, is the upstream face of the jam. As the jam grows upstream, downstream portions of the jam/island could be covered in sediment and vegetation (C). Consequently, I expect ages to be progressively older downstream on an island (D). (E-H) Conceptual model of avulsion accretion with time. Initial wood deposition along the channel margin (E) facilitates overbank flow, creating a much narrower secondary channel than the channel from which it splits (F). The newly isolated portion of the floodplain can accumulate additional wood at the upstream end, growing upstream with time as described for islands (G-H).

1.4 Significance of large wood dynamics in river corridors

Understanding the spatial and temporal dynamics of wood-induced features is important to understanding the formation and persistence of river corridor morphology in natural channels. Both wood jams and islands/secondary channels increase spatial heterogeneity in a channel, which promotes resilience to disturbances such as floods, drought, and wildfire (Wohl et al., 2022, 2023). The lateral connectivity between active channel(s) and floodplain driven by wood-induced islands and avulsions provides ecological refugia and resilience during disturbances (Benda et al., 2004). Higher water tables, deep pools, and lateral connectivity provide drought refugia and more stable base flows (Bêche et al., 2009; Boulton et al., 1998; Dixon, 2016; Puttock et al., 2017). Increased lateral connectivity facilitated by wood jams and secondary channels helps to attenuate flood peaks and diffuse flood flows across the floodplain (Junk et al., 1989; Poff et al., 1997), making habitats persistent and more resistant to natural and anthropogenic disturbances (Amoros and Bornette, 2002; Henning et al., 2006; Jeffres et al., 2008). Multiple wood-rich channels laterally connected to the floodplain and vertically connected to the hyporheic zone support abundant and diverse habitats and species (Dolloff and Warren, 2003; Herdrich et al., 2018; Venarsky et al., 2018). Frequent, minor channel adjustments and a high, reliable water table also create optimal settings for the germination and growth of aquatic and riparian vegetation

(Braudrick et al., 2009; Nadler and Schumm, 1981; Tal and Paola, 2007). Wet woodlands on islands and floodplains supply and retain wood and widespread vegetation proximal to the channel (Fetherston et al., 1995; Gurnell et al., 2001; Montgomery and Abbe, 2006), supporting habitat and increased retention of organic matter and nutrients for other organisms (Bilby, 1981; Flores et al., 2011). Dense, diverse riparian vegetation provides abundant shade, which, together with an efficient hyporheic exchange, ameliorates water temperatures (Beechie et al., 2005; Montgomery et al., 1999). As efforts to restore natural processes are emphasized in river restoration, understanding the spatial and temporal conditions that facilitate different types of wood-induced features has important implications for the broader physical and biological processes in a river corridor.

2. Study Area

I focus on the Swan River (1,676 km^2 drainage area) in northwestern Montana, USA, and two of its tributaries, Goat Creek (~94 km^2 drainage area) and Lost Creek (~85 km^2 drainage area). I selected five wood-induced tributary island study sites along Goat and Lost Creeks based on existing locations delineated by Marshall and Wohl (2023) (Figure 3.3.). Our study area is uncommon as a contemporary river corridor in the contiguous US due to its natural flow (Poff et al., 1997), sediment (Wohl et al., 2015), and wood (Wohl et al., 2019) regimes. However, the Swan likely represents formerly widespread conditions across forested river corridors in the temperate latitudes.

The Swan catchment receives ~750 mm of mean annual precipitation. The most significant annual peak flow is associated with spring snowmelt, but rainfall and rain-on-snow precipitation can also produce peak flows (MacDonald & Hoffman, 1995). The region was shaped by Pleistocene glaciation and is underlain by the Proterozoic-age Belt Supergroup, which mainly consists of weakly metamorphosed, fine-grained sedimentary rocks. Valley width throughout the catchment is ~1-2 km with an average channel gradient of 0.5%. The Swan River has an anastomosing planform and Goat and Lost Creeks have meandering planforms. Channels primarily have cobble to boulder bed substrate with pool-riffle sequences. Along Goat Creek and Lost Creek, banks heights average around 0.5 m and along the Swan River, bank heights average around 1 m. Soils have poorly developed profiles (Antos and Habeck, 1981), and are mostly gravelly loamy sand (SI Figure 2). While we observed longitudinally discontinuous clay units ~1 m thick exposed along cutbanks in Goat Creek and Lost Creek Channel width averages 5 to 15 m in Lost and Goat Creeks and 20 to 40 m in the Swan River.

Valley floors in the region are primarily covered with mesic montane conifer forests and wetlands, with some areas of subalpine forest. Shade-intolerant, early successional species include western larch (*Larix occidentalis*), western white pine (*Pinus* *monticola*), and Douglas-fir (*Pseudotsuga menziesii*). Climax, shade-tolerant species include grand fir (*Abies grandis*) and western redcedar (*Thuja plicata)* (Antos and Habeck, 1981). Despite a history of patch timber harvest and stand-replacing fires in the upland portions of the valley (Antos and Habeck, 1981), substantial portions of old-growth forest remain (Lesica, 1996), and the floodplain has experienced little development. The Swan River has a high volume of downed wood within the channel and floodplain (Wohl et al., 2018) and is a highly dynamic and spatially heterogeneous river corridor (Marshall et al., 2024). Sections of the river with greater presence and persistence of large wood exhibit more channel movement laterally on both a seasonal and decadal time scales as well as a greater number of secondary channels and spatial heterogeneity (Marshall et al., 2024)

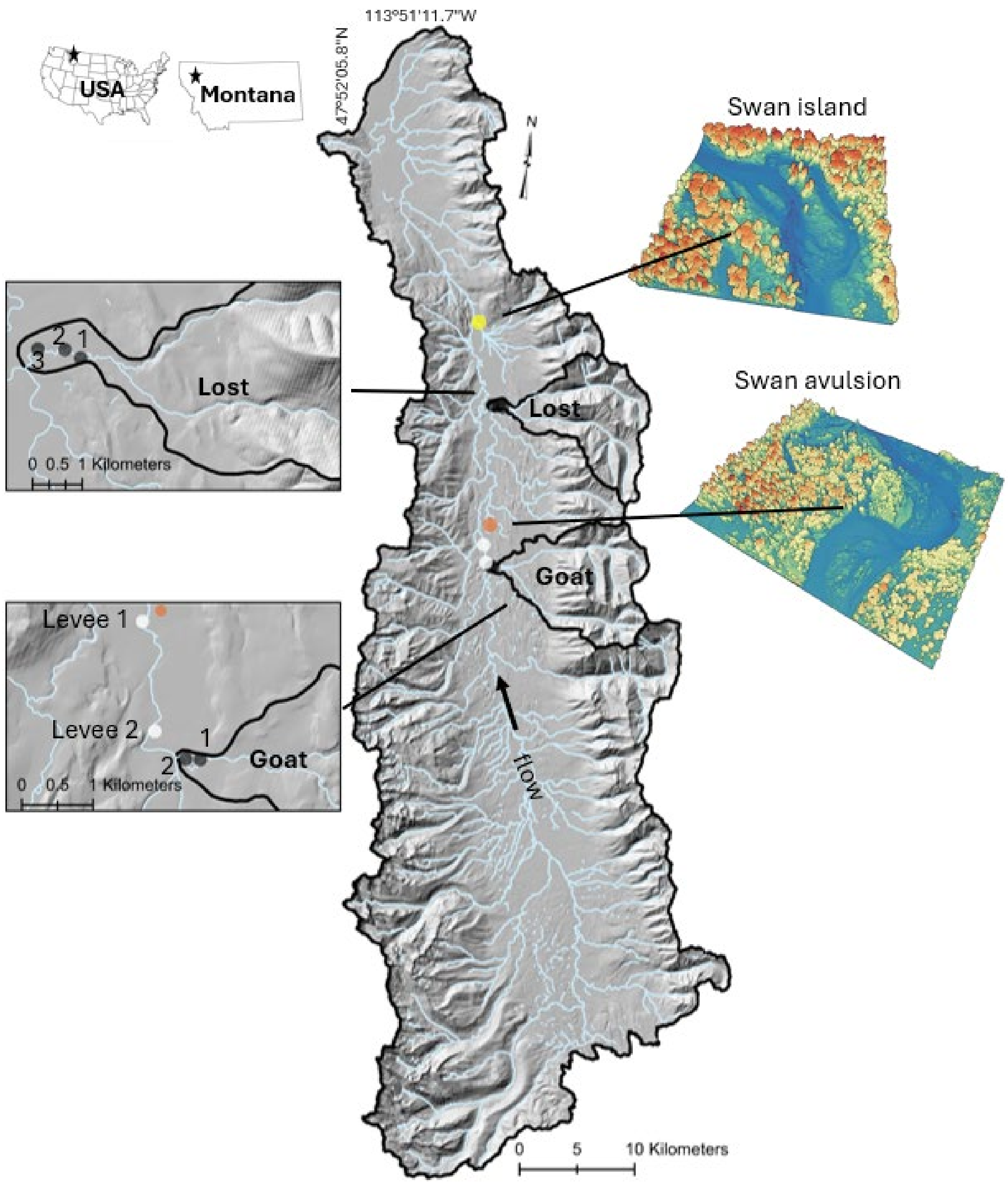

Figure 3.3. Lost Creek and Goat Creek in the Swan River catchment of Montana, USA. The portion of each of the three catchments included in this study is outlined in black in the central part of the figure. Black dots represent tributary island sites, white dots represent wood levee sites, the yellow dot represents the Swan River island site, and the red dot represents the Swan River avulsion site. There are three island study sites on Lost Creek (Lost 1, Lost 2, Lost 3) and two on Goat Creek (Goat 1, Goat 2), depicted in the inset maps on the left side of the figure. The Swan River avulsion and island accretion are shown as insets on the right side of the figure.

3. Methods

3.1 Characterizing wood-induced features

I mapped a subset of wood deposits with (i) accretion associated with avulsions and islands and (ii) deposition and erosion associated with wood levees in the field using a handheld GPS (Garmin eTrex with $\pm$ 3 m horizontal resolution). Data were collected along the Swan River, Goat Creek, and Lost Creek (Figure 3). Locations were overlain onto 1 m resolution lidar collected for the study area (Figure 3; Marshall, 2023).

At Goat Creek and Lost Creek, I characterized all contemporary wood jams with island accretion or the potential to form wood-induced accretionary islands. I identified five wood-induced accretionary island sites along Goat and Lost Creeks with tree diameters >10 cm. At each site, I collected sediment samples from the island and adjacent floodplain to compare the grain size distribution of islands relative to adjacent floodplain surfaces. I qualitatively described vegetation characteristics of primary vegetation types (e.g., grasses, deciduous trees, coniferous trees). I used tree-ring and ^{14}C dating to temporally constrain wood-induced island ages at the five sites along Goat and Lost Creek. Tree-core ages represent a minimum estimate for island surface age because of a delay of at least a few years between wood/sediment deposition and germination of woody vegetation. ^{14}C ages represent a maximum estimate because the age represents the time of tree death, and dead trees can remain standing for several years to more than a decade before falling and being repeatedly deposited and mobilized along a river corridor. I made field observations of vegetation and sediment characteristics as well as dimensional measurements at wood levee and avulsion accretion locations but did not use tree-ring and ^{14}C dating to further constrain ages of those wood-induced features.

3.2 Dendrochronology data collection and processing

I visually identified the oldest living trees at each island site based on size. I only cored trees that were ≥ 10 cm in diameter. Cores were taken roughly 1.2 m above the ground using a Haglof increment borer. Cores were mounted and sanded using progressively finer grits of sandpaper, and rings were counted under a dissecting microscope to estimate tree age. The tree species that were cored differed by island site but were likely green alder (*Alnus viridis*), paper birch (*Betula papyrifera*), Engelmann spruce (*Picea engelmannii*), and grand fir (*Abies grandis*). I further constrained tree-ring age estimates using diameter-breast-height (DBH)-age relation curves for individual species (Burns, 1990 for alder and birch; Veblen, 1986 for Engelmann spruce; and Puritch & Talmon-De L-Armee, 1971 for grand fir). Tree growth rates vary by location; thus, DBH age estimates are approximate.

3.3 ^{14}C data collection and processing

Samples for ^{14}C analysis were collected from the outer 5 cm of wood pieces (tree trunks) in jams or buried wood from upstream, middle, and downstream locations at each island site. Samples were dried and sent to the Yale Analytical and Stable Isotope Center for processing. A subsample was selected from each bag of samples. Sample preparation involved grinding the subsample to powder with a mortar and pestle. The standard Acid Base Acid sample treatment for wood follows: Inorganic carbon is dissolved in a 1.5 M HCl acid treatment and rinsed. Base treatment with 0.5 M NaOH removes base-soluble organic acids. A final acid treatment removes residual base and inorganic carbon potentially absorbed into solution before neutralization and drying. Once dry, samples are weighed into tin capsules and introduced to the Mini Carbon Dating System (MICADAS) using an Elemental Analyzer connected to a Gas Interface System. The MICADAS uses Bats version 4.30 to produce the final data. Results are provided in F14C (Table S4). The IntCal20 curve was used in OxCal 4.4 to obtain calibrated ages. Where F14C values were less than 1, a pre-bomb calibration curve was used, where F14C values were >1, a post-bomb NH3 curve was used, where F14C values were right around 1, both calibration curves were used (Figure S1).

4. Results

4.1 Island accretion

Tributary island ages based on tree rings and ^{14}C dates are provided in Tables S4 and S5. Figure 3.4. summarizes minimum island ages derived from tree rings and ^{14}C dating. Ages derived from tree cores ranged from 16 to 90 years old, and ages derived from ^{14}C dating ranged from 38 to over 150 years old (Figure 3.4). The ^{14}C ages summarized in Figure 4 are a simplification of age range variability using the average year within the highest probability age range for each ^{14}C sample (Table S4) and are not intended as absolute ages. Older samples (before 1950) have a much greater range of variability given that the atmospheric line was relatively flat between 1700 and 1950, which decreases our ability to do high-precision measurements during that time. The full range of variability in ^{14}C ages is included as Table S4 and Figure S1. I observed no significant difference between grain size samples at each island site relative to the adjacent floodplain (Figure S2).

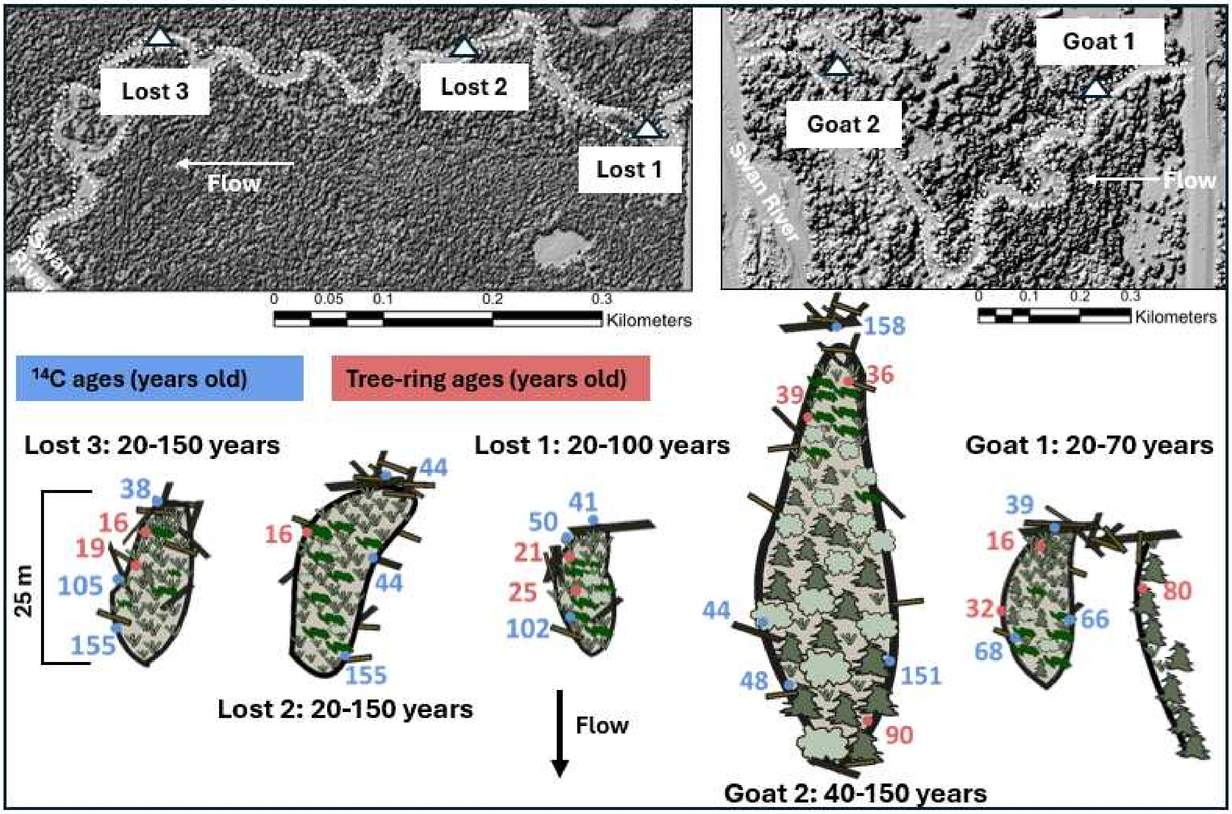

Figure 3.4. Tree-ring and ^{14}C-derived island ages along Goat and Lost Creek (tributary islands). The upper portion of Figure 4 depicts the locations of each tributary island within Lost or Goat Creek. The lower portion of Figure 4 illustrates each island's bird's eye schematic, scaled relative to the other islands. A scale is provided along the side of Lost 3 for reference. The black numbers indicate minimum estimated island age in years for each location, shown here for simplicity in visualization. Refer to SI Table 2 for errors associated with radiocarbon ages as well as a more robust range of island ages based on variability in the data. Blue points and numbers represent ^{14}C ages and locations. Red points and numbers represent tree-ring ages and locations. All numbers are reported in years. The Goat 1 inset drawing includes the edge of another, more prominent feature that likely represents a floodplain isolated by channel avulsion.

I also observed a site that appears to be transitional between avulsion and island accretion along the mainstem Swan River (Figure 3.3.). Although I did not obtain tree-ring or ^{14}C ages for this site, I observed an upstream progression of apparently younger vegetation and significant wood accumulation, similar to those on the tributary islands

(Figure 5). Specifically, this site has (i) a contemporary wood jam at the upstream end of the feature, (ii) an older wood jam (based on buried wood and decay state) among herbaceous vegetation and shrubby willows at the midpoint, and (iii) mature conifers (about 20-25 m tall) at the downstream end. This feature's special characteristics resemble those of an island, but I do not know whether there was once a channel-spanning or marginal wood jam here. The dimensions of the secondary channel on one side of the feature (~15 m wide) are quite small relative to the mainstem (~40 m wide) and relative to the length of the feature (~210 m), which is more similar to an avulsion (Figure 3.5.). Also, the mature conifers at the downstream side of the feature are similar in height (and probably age) to the adjacent floodplain forest. This site may be transitional between an island and an avulsion.

Figure 3.5. Accretion along the mainstem Swan River, downstream of Goat Creek confluence (Figure 3 for location within the catchment). This feature may be transitional between an island, as described for the tributaries, and an avulsion on the Swan River. The ground view is on the left, first-return hillshade from lidar is at the center, and the drone photograph is on the right. The pink box denotes the location of

the accretionary feature, and the star indicates the contemporary wood jam. Arrows indicate flow direction.

4.2 Avulsion accretion

Numerous sites of channel avulsion along the Swan River during the past 20 years appear in aerial imagery. I examined one site of wood-induced avulsion with recently formed accretion in the field (Figure 3.6.). I first observed this site during the summer of 2022, when relatively high flows had inundated much of the left-bank floodplain. The overbank flow was initially poorly organized but was steered into distinct secondary channels by floodplain topography, living vegetation, significant wood accumulations, and pre-existing secondary channels. By summer 2023, well-established secondary channels contained all flow outside the mainstem. Sand and finer sediment had vertically accreted to > 20 cm depth in portions of the floodplain inundated during 2022.

Figure 3.6. An avulsion on the Swan River downstream of Goat Creek (Figure 3 for location within catchment). The first return hillshade from lidar is on the left, ground view of floodplain vertical accretion during 2022 peak flows is at the center, and the

drone photograph is on the right. The pink box denotes the location of the avulsion. Arrows indicate flow direction.

4.3 Wood levees

During our field data collection, I observed linear depositional wood features with associated erosional backchannels, which I call wood levees (Figure 3.7.). The two wood levees occurred on the Swan River mainstem, adjacent to the Goat Creek confluence at avulsion sites. Each wood levee was a linear accumulation of large wood parallel to the flow direction, 1-2 m in vertical thickness and 3-5 m wide. The levees are now partly covered with sand-sized and finer sediment, herbaceous vegetation, and grasses. A small secondary channel parallels each levee on the floodplain side. Although their size makes wood levees difficult to distinguish in satellite imagery, review of historical imagery suggests that these wood levees have been present for less than a decade.

Figure 3.7. Ground view (left and right) and hillshade view (center) of wood levees observed on the mainstem of the Swan River, delineated here by pink lines. (A) shows levee 2 on a secondary channel of the Swan River, and (B) shows levee 1 on the main channel (refer to Figure 3 for location within the river corridor). Both sites have a backchannel running parallel to the wood levee. White arrows indicate flow direction.

5. Discussion

5.1 Chronology of tributary island accretion

Island ages derived from tree-core and ^{14}C data suggest a temporal range of island formation and persistence from multiple decades to over a century, which is comparable to island ages documented for the Tagliamento (Zanoni et al., 2008) and Czarny Dunajec (Mikuś et al., 2013) Rivers. Lost 1 is a relatively small island with only deciduous trees. These trees tend to be multi-stemmed alder and birch, and the tree cores obtained from the largest stem represent a minimum age for that portion of the island (~20 years) while the radiocarbon ages (~40-100 years) represent the maximum age for that portion of the island. Lost 2 also has primarily herbaceous vegetation and relatively young deciduous trees. However, it has well-decayed buried wood with the oldest age at the downstream end, as I expect if the island is aggrading upstream with time. Lost 3 has primarily deciduous and young conifer trees and ages generally increase downstream. The Lost Creek islands have a clear sequence in the ^{14}C and tree ring samples from ~20-40 years upstream to ~100-150 years downstream, suggesting that the islands have persisted for approximately a century. However, none of the Lost Creek islands host mature trees.

Goat 1 has deciduous and coniferous trees with ages suggesting upstream island formation with time. I interpret the older tree core (80 years) taken at a parallel island as indicating a portion of the floodplain isolated by avulsion (Figure 3.4.). Goat 2 was the largest island I examined and includes deciduous and mature coniferous trees. The tree ring ages at Goat 2 suggest island accretion upstream with time. The oldest ^{14}C sample for Goat 2 was taken at the contemporary wood jam upstream, suggesting older pieces of large wood were likely re-mobilized upstream and more recently deposited at the upstream end of the island. The two younger ^{14}C samples (44 and 48 years) on the river right side of the island might represent more recent pieces of wood that have been transported and re-deposited from upstream. Taken together with the tree ages, these suggest later lateral/downstream addition of wood. Wood jams are not complete wood traps, so wood is likely transported beyond them and could well accrete to the sides of the island or, potentially, the downstream end with time. Similarly, sediment and plant propagules might accrete to the sides with time, leading to younger tree ages than in the center.

Our conceptual model based on field observations and island age data suggests that islands grow upstream with time, exhibited by a clear chronosequence in both tree ring and ^{14}C ages. Initial wood deposition creates a low-velocity zone in the lee of the jam in which sediment is deposited and on which plants can germinate (Figure 2b). The first obstacle wood meets in transport downstream, however, is the upstream face of the jam. As the jam grows upstream, downstream portions of the jam/island could be covered in sediment and vegetation (Figure 2c). Consequently, I expect ages to be progressively older downstream on an island (Figure 2d). The anomalously old tree-core age from Goat Creek site 1 (80 years) may reflect portions of the floodplain that became an island via channel erosion rather than island accretion.

In the context of island accretion, similar ^{14}C ages for wood pieces in the active wood jam at the upstream end of the island and buried wood pieces in the downstream portion were sometimes obtained. The buried pieces, however, were consistently far more decayed than pieces in the active wood jam and likely contributed to soil formation and nutrient availability on the island. Existing literature (e.g., Harmon et al., 1986; Merten et al., 2013) points to an understanding that wood pieces in rivers typically decay faster than those on the forest floor because they are being abraded and broken apart. However, our observations suggest that burial in the river corridor may be important in accelerating decay.

In summary, the patterns of tree and radiocarbon ages generally support the model of upstream accretion of islands with time. However, the multi-decadal differences between tree ages and radiocarbon ages at each island reflect the difficulty in constraining the time of island formation and the persistence of islands.

5.2 Where does wood-induced accretion occur?

I characterized all wood jams along Goat Creek and Lost Creek with accretionary islands hosting trees large enough to core (our five tributary study sites) as well as wood jams with the potential to form accretionary islands in the future (an additional 3 jams on Goat Creek and 14 on Lost Creek). I observed multiple channel-spanning wood jams with accretionary deposits hosting trees too small to core (<10 cm diameter). I also observed channel-spanning wood jams without accretionary islands that appeared newly formed (i.e., bark still on the wood pieces). I did not observe any islands without a wood jam at the upstream head. In other words, channel-spanning wood jams appear necessary for islands to form in the study area. However, either not all channel-spanning wood jams create islands, or – more likely – there is some minimum time over which a wood jam persists before an island forms. I observed relatively uniform spacing of wood jams on Goat and Lost Creek with a wood jam per 100-150 m length of channel. Pools and riffles were more closely spaced, although wood jams created bed scour and occurred in association with pools.

I have observed hundreds of channel-spanning wood jams in the mountain streams of the Colorado Front Range in the U.S. (Wohl and Scamardo, 2021; Wohl and Iskin, 2022), but almost none of these create the accretionary islands that I observed in the Swan River corridor. I attribute the difference to the low suspended sediment concentrations, relative to the Swan, on steep, boulder-bed rivers in the Colorado Front Range. I have observed aggradation of the channel-bed upstream from channel-spanning wood jams in the Colorado Front Range. However, this sediment accumulates primarily within the active channel below the annual high-flow stage and does not provide good germination and growth sites for woody vegetation.

Our field observations in the Swan River corridor indicate that accretionary islands are less likely to occur on the mainstem than on the tributaries. The ratio of erosive force to erosional resistance influences whether avulsion or island formation occurs in response to the presence of a wood jam (Marshall and Wohl, 2023). Channel-marginal wood jams and avulsion are abundant along the mainstem Swan and may reflect a self-enhancing feedback in which wood jams initiate avulsions that increase spatial heterogeneity and facilitate the formation of additional wood jams (Marshall et al., 2024). These interactions develop most fully where floodplain width permits the development of an anastomosing planform (Wohl, 2011) and where the supply and mobility of large wood are sufficient to create numerous large wood jams relative to average channel dimensions. I did not observe evidence of substantial bank erosion and channel widening without island formation. Similar interactions have been described for rivers of the Puget Lowlands in the northwestern U.S. in the floodplain large-wood cycle hypothesis of Collins et al. (2012) and small mountain streams of the Colorado Front Range (Livers et al., 2018).

5.3 The temporal continuum of wood-induced accretion

I interpret the three wood-induced forms of deposition that I describe here as reflecting a temporal continuum of accretion (Figure 3.9.). Wood levees have primarily non-woody living vegetation and may be more transient features than forested islands or secondary channels created by avulsion. However, while wood levees persist, they influence near-channel floodplain topography and channel bank erosional resistance in a manner that can limit overbank flow by increasing bank height and erosional resistance at the wood levee but concentrate overbank flow immediately upstream and downstream from the levee. I have observed unvegetated linear deposits of wood along the top of a channel bank outside bends and in relatively straight channel segments (and without the backchannels present along the Swan) on boreal rivers in Alaska and Canada. These features can occur when a wood raft forms in a channel, completely blocking the channel over a length several times the average channel width. Wood rafts can form via the gradual accumulation of wood at a persistent blockage or via mass transport during wood floods (Kramer et al., 2017). The rivers along which I noted wood levees have abundant supply and relatively high transport capacity for large wood because of wood abundance in relation to flow width and depth. Although I introduce wood levees here, future work is needed to provide spatial and temporal constraints.

Islands appear to persist for more than a decade to a century. At the Lost Creek islands, I see the most unambiguous indication of island accretion and upstream growth with time, as exhibited by tree and radiocarbon ages (Figure 3.4). The Goat Creek islands suggest that wood may also accrete laterally to the downstream portion of islands. The similar sequence of mature conifers downstream and younger woody deciduous trees upstream at the Swan Island site suggests a similar temporal sequence.

However, our work lacked a robust dataset of tree cores due to a lack of mature trees on many of our island sites. Additional cores would provide further insight into some challenges associated with interpreting results from a small sample size.

What happens to islands as they continue to age? Observations at the Lost 2 site suggest that one of the channels beside an island may become blocked with large wood and living vegetation, allowing that channel and the adjoining island to become part of the floodplain through lateral accretion (Figure 3.8.). I observed a large, mostly inactive relict channel between the left side channel around Lost 2 and the floodplain, which suggests this scenario. The relict channel still had some surface hydrologic connectivity with Lost Creek via backflooding at the downstream end of the relict channel. The upstream end of the relict channel, although still discernible as a linear surface depression, was elevated above the stage of normal peak flow and was covered with woody vegetation. Between the relict channel and the contemporary active channel, there was a higher, forested floodplain that presumably was once an island. The conifers growing on this former island's surface are comparable in size and apparent stand age to the adjacent floodplain forest, suggesting that the former island has been abandoned for over a century.

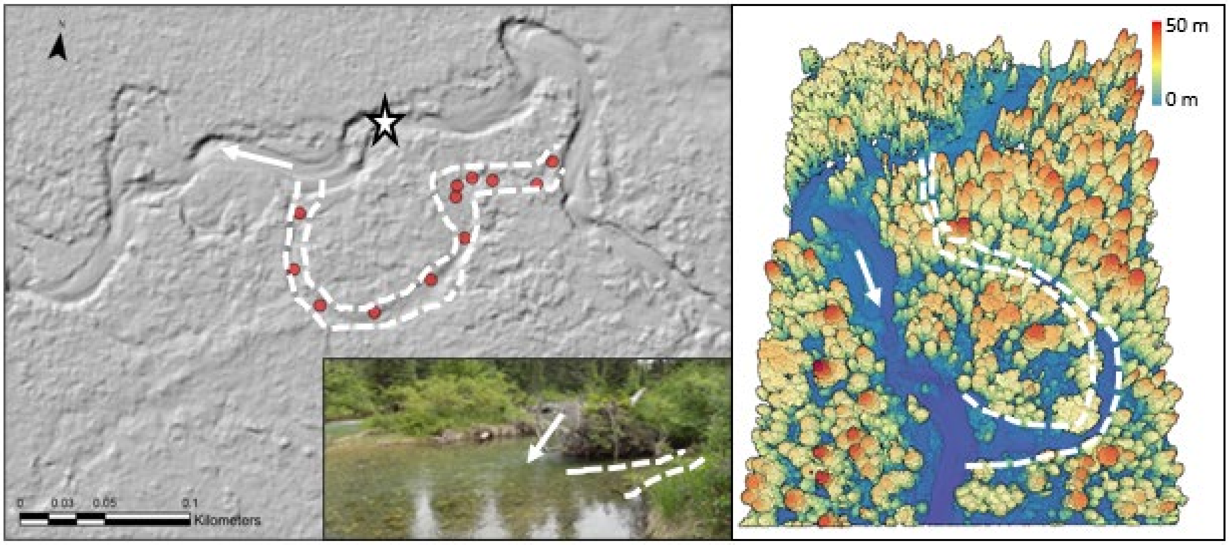

Figure 3.8. An inactive relict channel is present between the left side channel of Lost 2 (white star) and the floodplain. Red points indicate GPS points tracing the channel, arrows indicate flow direction, and dashed lines indicate approximate channel outline. The inset photo shows the outlet of the relict channel downstream of Lost 2.

The size of trees at the floodplain avulsion site suggests a stand age of 100-200 years on the portion of floodplain between anabranches. This indicates a minimum age for the floodplain at that site. Localized bank erosion and in-channel or overbank deposition along secondary channels at the avulsion site can locally alter the age of the floodplain alluvium. However, the bulk of the floodplain that the secondary channel has isolated will either remain stable or experience overbank deposition that is likely to be thin relative to the total alluvial thickness of the floodplain: at the Swan avulsion site, I observed > 20 cm of deposition overlying 1-2 m of floodplain alluvium. The secondary channels at the avulsion appear to be able to persist for many decades to centuries. I observed secondary channels with varying degrees of surface hydrologic connectivity with the mainstem, including relict, ephemeral secondary channels filled with large wood, and partly disconnected secondary channels dammed by beaver and converted to lentic environments.

The wood jam at the point of bifurcation between the mainstem and the avulsion (Figure 3.8.) may continue to accumulate large wood and sediment and undergo the type of upstream deposition that I describe for islands, but this is likely to be limited in spatial area relative to the size of the newly isolated floodplain. This is a primary difference between an avulsion and an island. All the vegetated surfaces of an island result from wood-induced flow separation. In contrast, most of the vegetated surface between the main and secondary channels in an avulsion is floodplain forest, and only a small proportion of the vegetated surface at the bifurcation point of an avulsion results from wood-induced flow separation.

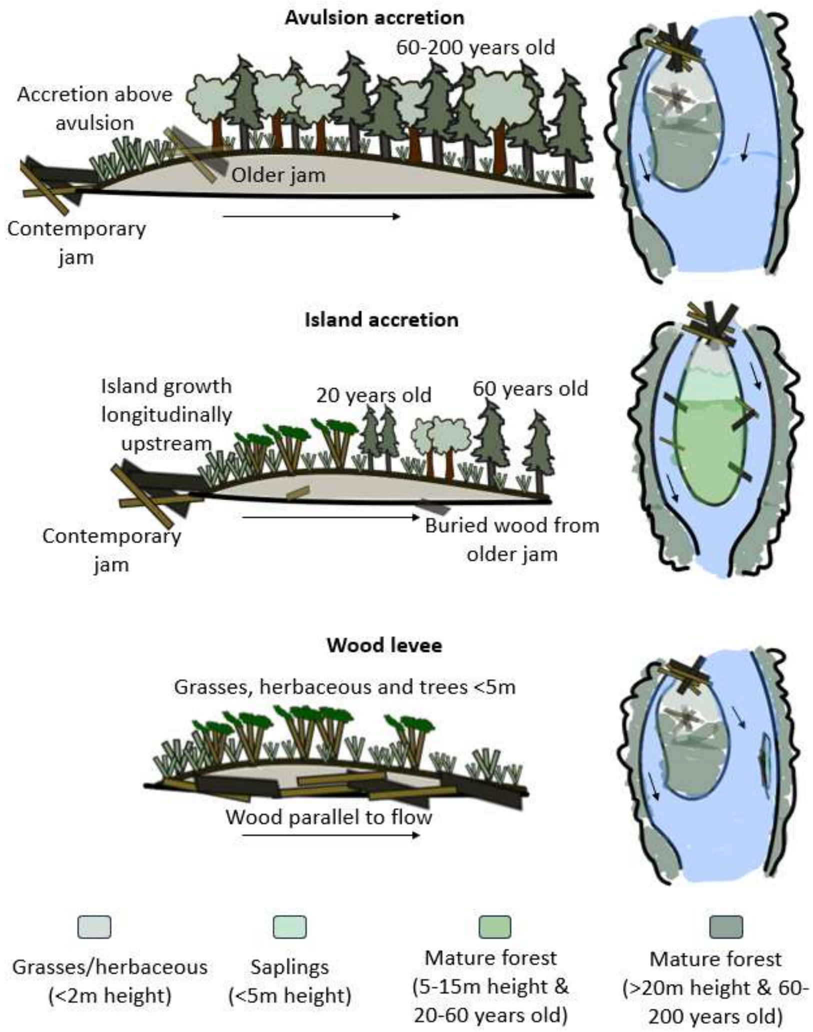

Figure 3.9. Wood-induced island and avulsion accretion, and wood levee erosion and aggradation (side views at left, planform views at right). Arrows indicate flow direction in plan view and side view illustrations.

6. Conclusions

The combination of bank height, bank erosional resistance, and wood jams all influence where deposition and erosion can occur (e.g. Brummer et al., 2006; Sear et al., 2010; Marshall and Wohl, 2023). Overbank flow and bank erosion then influence where wood-induced features such as wood levees, avulsion and secondary channels, or islands and split flow can form. Vegetation established on any of the wood features I examined

– wood levees, channel-marginal jams at avulsions, or channel-spanning jams at islands – helps stabilize the feature and create persistent areas of flow separation, erosion, and deposition. However, the absence of contemporary wood jams at the bifurcation point of some past channel avulsions on the Swan and the continued presence of the secondary channels suggests that relatively transient wood jams may still create persistent secondary channels. In contrast, I did not observe any islands without wood jams on the tributaries, perhaps because the island blocks such a substantial portion of the channel width that, even if the original channel-spanning wood jam is somehow removed, the island will quickly trap and store new wood.

Our results show the complexities in constraining island persistence with tree-ring and ^{14}C ages. Islands may grow through upstream migration – the presence of buried wood pieces with contemporary trees growing on them indicates this process – and lateral accretion. I recommend using both tree-ring and ^{14}C ages, wherever feasible, to bracket the age range of depositional features. I had limited sites and samples within each site, which added challenges in interpreting results. I recommend increasing samples at a given site to constrain results further. In a forested river corridor where high-resolution imagery is limited due to canopy cover and tributary size, this method can help provide a temporal understanding of how and why islands in the stream form and persist.

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CHAPTER 4: INTERACTIONS OF LOGJAMS, CHANNEL DYNAMICS, AND GEOMORPHIC HETEROGENEITY WITHIN A RIVER CORRIDOR

Summary

Natural rivers are inherently dynamic. Spatial and temporal variations in water, sediment, and wood fluxes both cause and respond to an increase in geomorphic heterogeneity within the river corridor. I analyze 16 two-kilometer river corridor segments of the Swan River in Montana, USA to examine relationships between logjams (distribution density, count, and persistence), channel dynamism (total sinuosity and average channel migration), and geomorphic heterogeneity (patch density) in the river corridor. I hypothesize that i) more dynamic river segments correlate with a greater presence, persistence, and distribution of logjams; ii) higher annual peak discharges correspond with greater channel dynamism and logjam presence and distribution; and iii) greater logjam distribution densities and channel dynamism are predictive of more spatially heterogeneous sections of the river corridor. My results suggest that, first, decadal-scale channel dynamism, as reflected in total sinuosity, corresponds to greater numbers of logjams and greater persistence of logjams through time. Second, higher peak discharges correspond to greater presence and distribution of logjams, but not to greater channel dynamism. Third, greater geomorphic heterogeneity in the river corridor, as reflected in the spatial distribution of landscape patch density, is explained

by greater logjam distribution density, total sinuosity, and proportions of beaver meadows. The results presented here reflect the complex interactions of water, sediment, and wood in river corridors; the difficulties of interpreting causal relationships among these variables through time; and the importance of spatial and temporal analyses of past and present river processes to understand future river conditions.

1. Introduction

The dynamic nature of a river corridor through space and time is reflected in its geomorphic heterogeneity. I refer to a river corridor, here, as the active channel(s), floodplain, riparian zone, and underlying hyporheic zone to incorporate the interactions of water, sediment, and wood between different portions of a valley bottom (Hynes, 1975; Harvey and Gooseff, 2015). Geomorphic heterogeneity within the river corridor represents the spatial and temporal variability of geomorphic units, or patches, that have been created and reworked by a particular set of processes, namely fluxes of water, sediment, and large wood (Wheaton et al., 2015; Wohl et al., 2019; Fryirs and Brierley, 2022; Scott et al., 2022). Relationships between river corridor process and form determine the type, spatial distribution, and formation and maintenance of geomorphic units (Fryirs and Brierley, 2022) (Figure 4.1). I distinguish between spatial and temporal components of geomorphic heterogeneity, with spatial heterogeneity referring to patch characteristics at a specific point in time and temporal heterogeneity capturing changes in patches over time at a defined spatial scale.

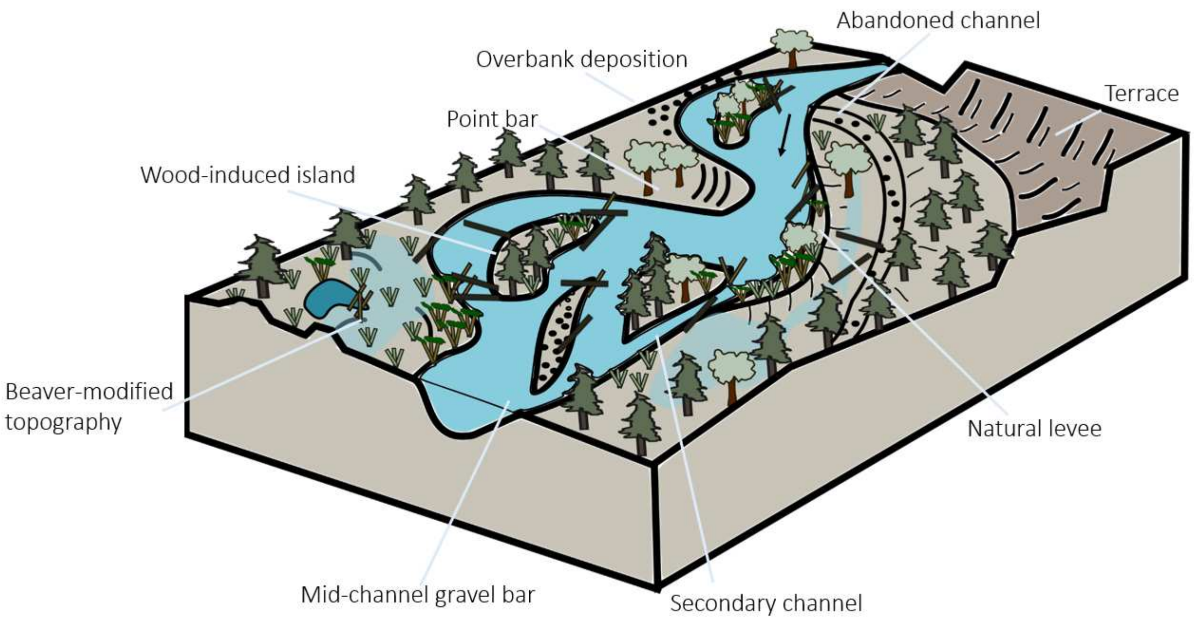

Figure 4.1. Block diagram of geomorphic units within a dynamic river corridor where logjams are both causing and responding to geomorphic heterogeneity across space and time. Black arrows represent flow direction.

Individual pieces of large wood ($\geq$10-cm in diameter, $\geq$1-m in length) and logjams ($\geq$ 3 pieces of large wood) both influence and respond to geomorphic heterogeneity within the river corridor and it is typically difficult to differentiate cause and effect. Fundamentally, large wood increases hydraulic roughness, obstructs flow, and alters erosional force (Piégay, 1993) and substrate erosional resistance (Collins et al., 2012) in the channel and floodplain. The net effect of large wood stored at least temporarily in the river corridor is to increase spatial heterogeneity via processes such as:

- bar and secondary channel formation (Montgomery & Abbe, 2006; Collins *et al.*, 2012; Polvi and Wohl, 2013; Marshall & Wohl, 2023)
- meander geometry and rate/direction of meander migration (Hickin, 1984; Piégay, 1993; Abbe & Montgomery, 1996; Gurnell *et al.*, 2002; Daniels & Rhoads, 2004)
- topographic and substrate heterogeneity within the channel (e.g., scour exposing coarse sediment at the upstream flow divergence around the wood; fine sediment deposition in zones of slower flow created by the wood) (Gurnell *et al.*, 2005)
- instream aggradation (Brooks et al., 2003)
- channel avulsion and formation/abandonment of secondary channels (Jeffries *et al.*, 2003; Wohl, 2011; Collins *et al.*, 2012; Wohl & Iskin, 2022; Marshall & Wohl, 2023)
- floodplain roughness (Wohl, 2013, 2020)
- channel-floodplain connectivity (Sear et al., 2010; Wohl, 2013; Keys *et al.*, 2018)
- lateral and vertical accretion of floodplains (Sear *et al.*, 2010; Wohl, 2013)

Logjams can also respond to river corridor geomorphic heterogeneity. Spatially heterogeneous river corridors are more likely to recruit and retain wood relative to transport-dominated homogeneous river corridors (Wyżga and Zawiejska, 2005; Collins *et al.*, 2012; Scott and Wohl, 2018). Spatial heterogeneity can strongly influence river corridor functions such as, diverse hydrologic pathways and residence times (Helton *et al.*, 2014); nutrient stocks and biogeochemical reactions (Appling and Heffernan, 2014); organic carbon storage (Lininger *et al.*, 2018); hydrologic and other forms of connectivity (Ward and Stanford, 1995); habitat creation and maintenance (Stanford *et al.*, 2005); and biodiversity (Bellmore *et al.*, 2013). Consequently, river management increasingly emphasizes understanding, protecting, and restoring river corridor heterogeneity (Poff *et al.*, 2007; Peipoch *et al.*, 2015; Klaver, 2018).

Historical descriptions of forested regions throughout the temperate latitudes indicate that orders of magnitude more wood were present in most forested river corridors prior to widespread deforestation and wood removal from the river corridor (Sedell and Froggatt, 1984; Montgomery and Bolton, 2003; Wohl, 2014). The legacy of human activities has simplified river corridors via landscape-scale changes that affect water, sediment, and wood delivery to, and movement within, the river corridor (Thoms, 2003; Graf, 2006; Knox *et al.,* 2022). Removal of wood from the river corridor has caused a fundamental shift in channel and floodplain process and form (Figure 4.2;

Wohl 2013). With this loss in geomorphic heterogeneity comes a loss of river corridor function via disruption of lateral, longitudinal, and vertical connectivity between aquatic, wetland, and terrestrial ecosystems (Tockner *et al.,* 2010; Kuiper *et al.*, 2014; DeBoer *et al.*, 2020). Failure to adequately consider the historical effects of wood in river corridors, along with loss of these effects, distorts understanding of contemporary river process and form.

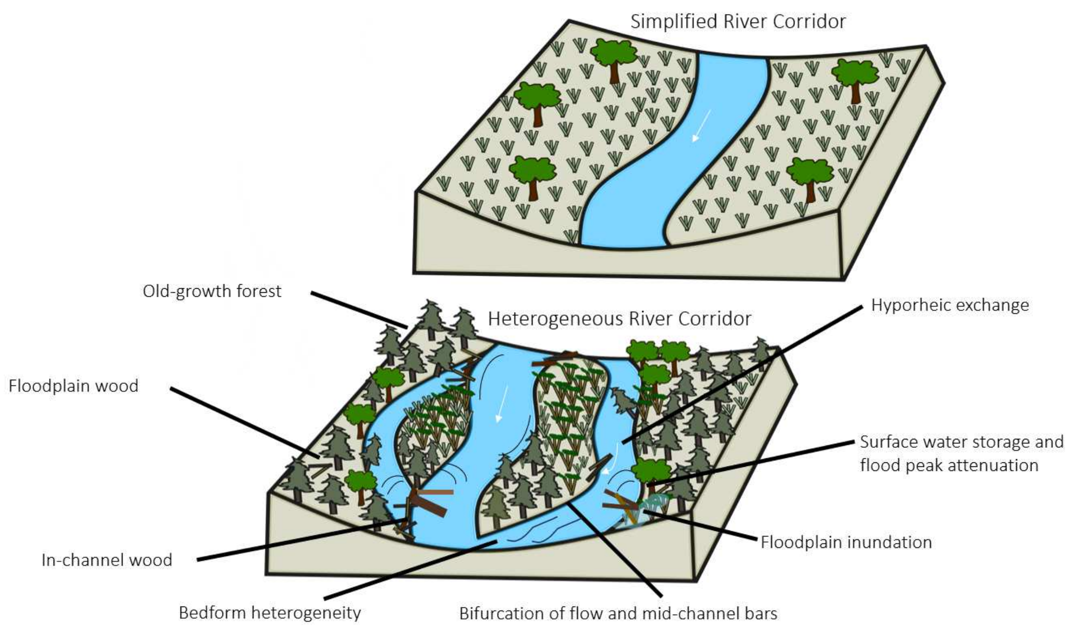

Figure 4.2. Illustrative example of a simplified river corridor where logjams have been historically removed (top) and a forested heterogeneous river corridor where logjams are present (bottom). White arrows indicate flow.

Despite a growing awareness in the value of complex and heterogeneous river corridors and increasing efforts to restore river corridor heterogeneity (Peipoch *et al.*, 2015; Wohl, 2021), there remains considerable uncertainty as to exactly how natural channels change, as well as the role of wood and geomorphic heterogeneity in this channel dynamism. River science still lacks quantitative underpinning as to how function can most effectively be restored in river corridors that have lost substantial geomorphic heterogeneity. Through an evaluation of the interactions between logjams, channel dynamism, and geomorphic heterogeneity, here, I attempt to peel back layers in time and tease apart spatial details to investigate how form and process interact in a natural river corridor.

The objective of this study is to examine relations between logjams, channel movement, and spatial heterogeneity. My data covers a range of spatial and temporal resolutions, which limits the ability to conduct a single, integrated analysis of the multiple variables that I examine. Consequently, I test three hypotheses that each focus on a limited number of variables. I hypothesize that i) more dynamic sections of the river corridor will correlate with a greater presence, persistence, and distribution of logjams; ii) higher peak annual discharges will correspond with greater channel dynamism and logjam presence and distribution; and iii) persistent values of geomorphic heterogeneity, as reflected in the spatial distribution of landscape patch density, can be explained by the distribution of logjams and total sinuosity in the river corridor. The rationales underlying my hypotheses is that: i) logjams promote channel migration, bifurcation, and avulsion, leading to a more dynamic channel through time; ii) higher peak discharge equates to greater erosional force and transport capacity, which promotes channel change and redistribution of individual wood pieces into logjams within heterogeneous portions of the river corridor; and iii) logjams alter flow and sediment deposition patterns, creating and maintaining more spatially heterogeneous sections of the river corridor.

In the subsequent sections, I use field measurements and remotely sensed data to statistically explore the relationships between logjam presence, distribution, and persistence, channel movement through time, spatial heterogeneity, annual peak discharge, and the proportion of beaver meadows within a river corridor. Although previous work has presented compelling conceptualizations of these interactions (e.g., Collins *et al.*, 2012), I use the wood-rich Swan River in Montana, USA to investigate the details of these interactions across a decadal scale and contribute to a deeper understanding of the processes shaping natural dynamic river corridors.

2. Study Area

The Swan River, located in northwestern Montana, USA, is conducive to evaluating the association between logjams, geomorphic heterogeneity, and channel dynamism due to its natural flow, sediment, and wood regimes. The selection of the Swan River as my study area is underpinned by its limited development and substantial portions of old-growth forest within the river corridor (Lesica, 1996). Although portions of the hillslopes have experienced patch timber harvest and stand-replacing wildfire, the floodplain of the Swan River remains largely undeveloped. This can be observed as little-to-no change of land use category via the National Land Cover Database (NLCD) Land Cover Change Index (Wickham *et al.*, 2021). The Swan also has a high volume of downed wood within the river corridor (Wohl *et al.*, 2018) and high geomorphic heterogeneity as reflected in landscape ecology metrics (Iskin and Wohl, 2023a). The natural wood regime of the Swan is relatively unique among rivers in the contiguous USA but is representative of historically widespread conditions in forested river corridors (Wohl, 2019).

To facilitate data collection, I selected a 32-km straight-line study reach based on river access, variations in geomorphic planform, and human alterations to the river corridor. For the purposes of analyses, I segmented the reach into 2-km sub-reaches (Figure 4.3). Physical and vegetation characteristics of the Swan River are included in Table 4.1.

Table 4.1. Study area characteristics for the Swan River catchment

Drainage area (km^2)	1,676	USGS, 2023
Mean basin annual precipitation (mm)	750	PRISM, 2022
Mean basin slope (%)	0.5	USGS, 2023

Channel planform	Longitudinal alternations between meandering, braided, and anastomosing	Wohl et al., 2018
Flow regime	Snowmelt-dominated	MacDonald & Hoffman, 1995
Channel substrate	Cobble- to boulder-bed	Field observations
Confinement	Unconfined	Field observations
Valley-floor width (km)	1-2	Field observations
Underlying lithology	Proterozoic-age Belt Supergroup	Hofmann & Hendrix, 2010
Soil type	Gravelly loamy sand	USDA, 2023
Dominant vegetation	Mesic montane conifer forests and wetlands, with some areas of subalpine forest	Antos, 1977

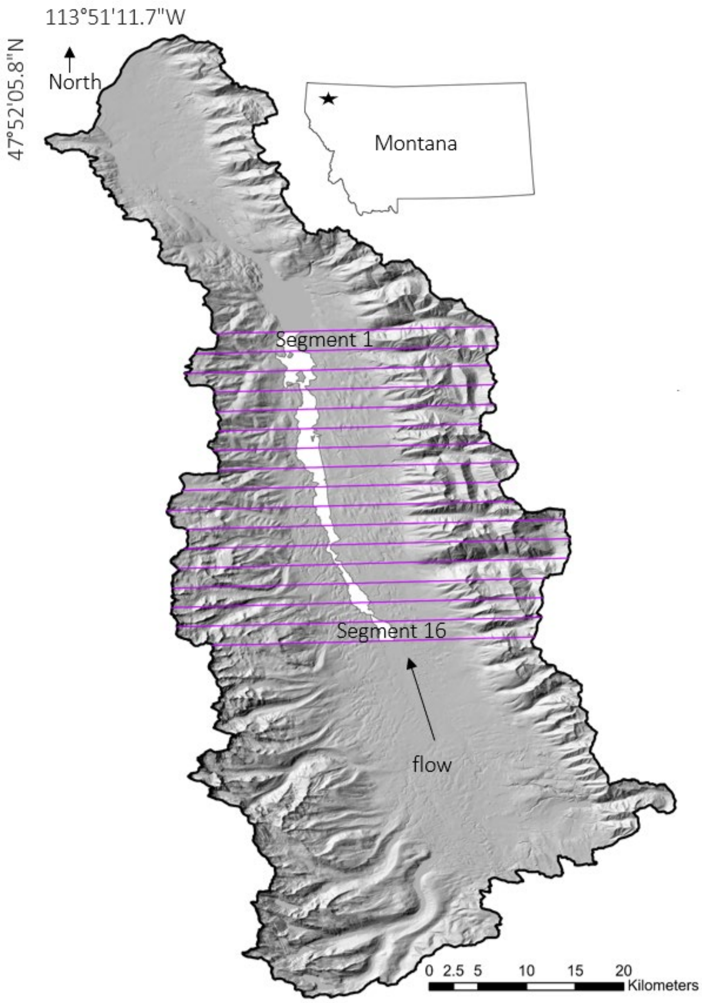

Figure 4.3. Study area within the Swan River catchment in northwestern Montana, USA. Perpendicular lines represent the 32-km reach extent, segmented at 2-km intervals to provide spatial context in data analysis. The white shaded area represents the floodplain extent of the Swan River through the study area.

3. Methods

I employed a combination of field and remote sensing methods to evaluate associations between logjams, geomorphic heterogeneity, and channel dynamism in the Swan River corridor. All field data collected and used in this study were collected in 2022. The temporal resolution of remotely sensed data varied based on the availability of sufficiently high-resolution imagery (10-m or better) (see Table 4.2. for collection dates). For analyses where higher spatial resolution was needed, the temporal range was limited. I made deliberate decisions, described in the following sections, regarding the trade-offs between spatial and temporal resolution for each variable based on the importance of these factors in testing my hypotheses.

To provide spatial context for the measurements of logjams, geomorphic heterogeneity, and channel dynamism along my 32-km study reach, I segmented the study reach at uniform 2-km intervals prior to data collection (Rowland et al., 2016). A total of 16 2-km segments were delineated along the 32-km study reach (Figure 4.3). The downstream-most 8 segments were selected based on the naturalness of the river corridor and the presence of abundant logjams in the active channel(s). I focused on these segments for ground-based measurements. I subsequently expanded analyses to include an additional 8 upstream segments. These segments were included because of anecdotal evidence of bank stabilization and large wood removal from the active channel. I included these sites to provide a greater range of values within some of the variables analyzed and thus potentially increase the power of my statistical analyses.

3.1. Logjams and beaver modifications

I conducted aerial logjam surveys using available high resolution satellite imagery between 2013 and 2022 (four years of available imagery: 2013, 2016, 2020, 2022). I mapped all logjams within the active channel that could be detected via the aerial imagery. I recorded the number of logjams per 2-km segment for each available imagery year as a minimum logjam count and divided the count by floodplain area for each segment to get a logjam distribution density. I also noted the occurrence of persistent logjams that were continually present in the Google Earth imagery, in what I refer to as "sticky sites" (Wohl and Iskin, 2022). GPS coordinates of logjams were collected in the field during August 2022 to verify imagery identification.

I also manually identified active and remnant beaver meadows using our 2022 satellite imagery. Similar to large wood, American beaver (*Castor canadensis*) both respond to spatial heterogeneity in the river corridor and create spatial heterogeneity through their ecosystem modifications. Beaver-modified portions of the river corridor were identified based on presence of standing water in ponds with a visible berm; wetland vegetation including rushes, sedges, and willow carrs that appear a different color than adjacent floodplain areas in imagery; and detectable active or relict beaver dams. Several of the sites identified in imagery were also visited in the field to verify identification.

3.2. Channel dynamism and annual peak discharge

Channel dynamism was quantified using metrics of active channel migration and total sinuosity over time. To measure active channel migration, I developed a semi-automated approach to map surface water extent and planimetric centerline movement, which are commonly used to understand morphological evolution in rivers (Boothroyd *et al.*, 2021). I followed existing methodologies using base flow conditions as a conservative delineation of planimetric change (O'Connor *et al.*, 2003), given my goal of looking at relative channel change over time to understand which segments of my study area were the most dynamic.

Surface water extent was delineated for 2013, 2016, 2020, and 2022 to keep the timestep consistent with my wood surveys. Imagery collected for the National Agriculture Imagery Program (NAIP) was used when available (2013 and 2016) (Maxwell et al., 2017). For 2020 and 2022, cloud-free multispectral composite images were created in Google Earth Engine (GEE) (Gorelick *et al.*, 2017) from Sentinel-2 imagery from average baseflow months (August-October). Surface water was classified using the normalized difference water index (NDWI) (Gao, 1996) for NAIP imagery, and modified normalized difference water index (MNDWI) (Xu 2006) for Sentinel-2 imagery (Tobón-Marín and Cañón Barriga, 2020). A unique threshold was empirically determined for each year to optimize the identification of the river surface while minimizing false-positive water identification, resulting in binary water and non-water masks for each year. Gaps and voids in the Sentinel-2 derived water masks (from shadow-covered areas, thin river segments, or mixed pixels along the river edge) were filled by sequentially buffering the water areas outwards by 30-m (three pixels) and then inwards by 15-m. Similarly, gaps and voids in NAIP-derived water masks were filled using a sequential 20-m outwards then inwards buffer. The resulting binary water masks were imported into ArcGIS Pro and vectorized. Manual adjustments were made to remove any remaining misclassified areas and join disconnected segments.

I delineated centerlines of my channel masks in using the ArcGIS Pro Polygon to Centerline tool. When multiple channels were present, the dominant channel branch was chosen for the channel centerline (O'Connor *et al.*, 2003; Wieting *et al.*, 2023). Consequently, my analysis represents a minimum value of centerline channel migration during each time step because it does not include secondary channel movements. The Feature to Polygon tool was used to create a polygon between two centerlines and extract area differences between the two centerlines at each segment (Wieting *et al.*, 2023). Areas between the centerlines for each segment were divided by reach length to get a normalized reach average channel migration rate.

I measured total sinuosity in each 2-km segment for 2013, 2016, 2020, 2022 using satellite imagery and the built-in Measure tool in Google Earth. I measured total sinuosity as the ratio of total channel length of all active channels/valley length (Egozi and Ashmore, 2008; Hong and Davies, 1979).

I obtained annual peak discharge from the nearest US Geological Survey gauge (12370000, Swan River near Bigfork, MT). The gauge is located below Swan Lake, a natural lake, into which my study reach of the Swan River flows. Consequently, the gauge records reflect relative inter-annual fluctuations in peak discharge, but not actual discharge at the study site. I used annual peak discharge for the same time intervals used for analyzing channel position. I included annual peak discharge in statistical analyses because this value varies between years and could explain differences in channel migration and logjam abundance between years.

3.3. Geomorphic heterogeneity

I modified the workflow developed by Iskin and Wohl (2023a,b) to quantify geomorphic heterogeneity for the Swan River corridor. I performed an unsupervised remote sensing classification on a stack of data containing a 2022 Sentinel-2 imagery mosaic prepared in GEE, and normalized difference vegetation index (NDVI) and normalized difference moisture index (NDMI) rasters calculated from the Sentinel-2 mosaic in ArcGIS Pro (Figure 4.4). The Sentinel-2 mosaic was prepared for the approximate growing season in Montana, USA, (June 1 to October 31) based on annual phenology activity curves (2018-2022) of the existence of leaves or needles on flowering plants (US National Phenology Network, 2023). Unlike Iskin and Wohl (2023a), I did not include a digital elevation model (DEM) in the classification data stack, as there is only a 10-m resolution model available for the entire 32-km reach (USGS, 2021) and including it seemed to reduce the quality of the classification. The unsupervised classification was completed on the floodplain extent of the Swan. The floodplain is a modified version of the boundary from Iskin and Wohl (2023a) delineated manually in ArcGIS Pro using the 10-m U.S. Geological Survey 3D Elevation Program (3DEP) DEM, a hillshade prepared from the DEM, Sentinel-2 imagery, and ArcGIS Pro Imagery basemap as visual references.

Although the classification is unsupervised, the classes were intended to represent distinct types of habitats within the river corridor that blend geomorphic features and vegetation communities as observed in the field, including, but not limited to active channels, secondary channels, accretionary bars, backswamps, natural levees, old-growth forest, wetlands, and beaver meadows (Figure 4.1). Specific habitat types can be differentiated from the unsupervised classes when paired with field data (Iskin & Wohl, 2024). The *ISO Cluster Unsupervised Classification* ArcGIS Pro tool was used to perform the classification (Figure 4.4). Inputs to the tool were a maximum of 10 classes, a minimum class size of 20 pixels (tool default), and a sample interval of 10 pixels (tool default). The entire reach was classified once, and then clipped into individual 2-km segments. The classified Swan raster was brought into R (R Core Team, 2023) for statistical analysis of heterogeneity metrics. Data were visualized using the *tidyverse* and *terra* packages (Wickham *et al.*, 2019; Hijmans, 2023).

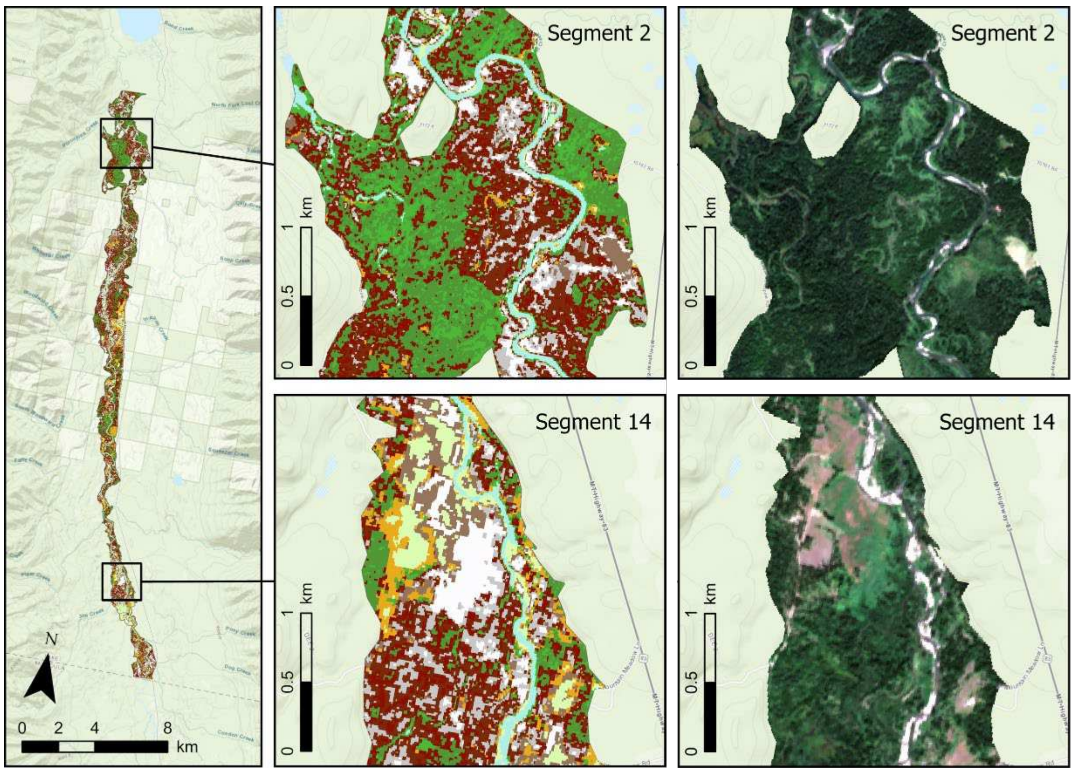

Figure 4.4. Unsupervised classification of the Swan River floodplain with detail insets of Segment 2 (top) and Segment 14 (bottom), including Sentinel-2 imagery mosaic. Colors here do not represent specific geomorphic units, but rather simply differentiate the pixels between the 10 classes that were identified by the classification tool.

Spatial heterogeneity of the river corridor can be described as the patchiness of the floodplain (Beechie et al., 2006; Ward et al., 1999). Patches are discrete spatial units that differ from adjacent units. I calculated patch density as my primary metric of spatial heterogeneity for each of the 16 segments, where I interpret greater patch density as indicating greater spatial heterogeneity. Patch density is a measure of how broken up a landscape is, and a higher density indicates a landscape with more individual patches (Hesselbarth *et al.*, 2019). I calculated three additional heterogeneity metrics for the Swan River used also in Iskin and Wohl (2023a): aggregation index (aggregation), interspersion and juxtaposition index (interspersion), and Shannon's evenness index (evenness). Aggregation measures class clumping across a landscape and low values of aggregation indicate that few pixels are adjacent to pixels of the same class (He *et al.*, 2000; Hesselbarth *et al.*, 2019). Interspersion measures the intermixing of class types at a patch level, or how spatially mixed patches of different classes are (McGarigal and Marks, 1995; Hesselbarth *et al.*, 2019). Evenness is a measure of diversity and distribution of classes across a landscape (Hesselbarth *et al.*, 2019). All heterogeneity metrics were calculated using the *landscapemetrics* package (Hesselbarth *et al.*, 2019) using the eight-neighbor rule (the Queen's case). For clarity, I only report results and interpretation of patch density as a metric of spatial heterogeneity. Analysis and interpretation of aggregation, interspersion, and evenness as additional heterogeneity metrics are included as Supplementary Information to Chapter 4.

3.4. Statistical analyses

Statistical analyses were conducted in R (R Core Team, 2023). The data I collected span different time intervals (Table 4.2), and I conduct my statistical analyses to match the temporal and spatial scales of data I have for each of my hypotheses. I used an alpha (probability of rejecting the null hypothesis when the null hypothesis is true) of 0.05 in all statistical analyses.

I started with spatial and temporal exploratory analyses examining whether there was significant variation in the medians of river corridor variables between timesteps or between segments using a Kruskal-Wallis Rank Sum test (Kruskal and Wallis, 1952).

To address hypotheses *i* and *ii*, I calculated both Pearson (*r)* and Kendall (τ) correlation coefficients. Given my small sample, I report both *r* and τ values. All correlation coefficients were calculated using the *cor.test()* function in base R. To further test the impact of channel dynamism on logjam variables across study segments, I developed linear mixed-effects models. To account for the lack of independence in samples from the same river corridor, segment was treated as a random effect to account for the multiple surveys over time in the same segment and adjacent proximity to other segments. I developed two models with logjam distribution density and count as fixed effect response variables and total sinuosity, average channel migration, and peak annual discharge as fixed effect predictor variables. The best mixed-effect model for each response variable was chosen based on Akaike's Information Criteria, adjusted for small sample sizes (AICc; Burnham & Anderson, 2002). Mixed-effects models were developed using the lme4 package in R (Bates et al., 2015).

To address hypothesis *iii,* I developed mixed-effect models with logjam variables, channel dynamism variables, proportion of beaver meadows, and peak annual discharge as predictor variables and heterogeneity metrics as response variables, all treated as fixed effects. Once again, I accounted for a lack of independence in data from the same river corridor in my mixed-effect models by creating a random variable with the same value for all observations given that I did not have a grouping variable for heterogeneity data. I only used data from 2022 when addressing hypothesis *iii* to keep a consistent timestep across all variables. I used AICc to select the model that best predicted each heterogeneity metric.

Table 4.2. Data used in analyses

Variable	Time interval or time span	Number of data points (n)	Source data
Logjam distribution density*	2013, 2016, 2020, 2022	64 (16 segments for each year)	Google Earth satellite imagery, field verification
Logjam count*	2013, 2016, 2020, 2022	64 (16 segments for each year)	Google Earth satellite imagery, field verification
Logjam sticky sites (logjam persistence)*	Integrated based on 2013-2022	16	Google Earth satellite imagery

Beaver meadows	Integrated based on 2013-2022	16	Google Earth satellite imagery
Active channel migration*	2013, 2016, 2020, 2022	64 (16 segments for each year)	NAIP and Sentinel-2 imagery
Total sinuosity*	2013, 2016, 2020, 2022	64 (16 segments for each year)	NAIP and Sentinel-2 imagery
Annual peak discharge	2013, 2016, 2020, 2022	4 (one for each year of interest)	USGS gauge record
Spatial heterogeneity	2022	16	Sentinel-2 imagery, US National Phenology Network, USGS 10-m 3DEP DEM

*For simplicity, logjam distribution density, logjam count, and logjam sticky sites (persistence) are referred to in the text as logjam variables when referring to all three

**For simplicity, total sinuosity and average channel migration are referred to in the text as channel dynamism variables when referring to both.

4. Results

I first conducted an exploratory analysis of logjam and channel dynamism variables through time. I found no consistent differences in median values between channel migration (p=0.52), total sinuosity (p=0.94), logjam distribution density (p=0.12), or logjam count (p=0.26) between years (Figure S1). I did not include beaver meadows, logjam sticky sites, or heterogeneity metrics in my exploratory analysis of time because the data values for these variables are integrated over time rather than collected annually and thus do not have the variability through time.

I also conducted an exploratory spatial analysis of logjam and channel dynamism variables across segments. I found significant variation in median values for river corridor variables between segments ($p<0.0001$ for total sinuosity, channel migration, logjam distribution density, and logjam count) (Supplementary Figure S4). I could not do this type of exploratory analysis for variables that only had one data value per segment (logjam sticky sites, proportion of beaver meadows, discharge, and landscape heterogeneity metrics; Table 4.2). I acknowledge that individual pieces of large wood can be persistent over many years, but do not attempt to determine residence time of individual wood pieces in this study. In this dynamic river corridor, individual pieces can be buried or exhumed and remobilized from burial in a single high-flow season. In the results below, I focus on how logjam and channel migration variables change by segment rather than by year and treat segment as a random effect in modeling efforts to account for the multiple surveys over time in the same segment and adjacent proximity to other segments.

Hypothesis i: more dynamic sections of the river corridor will have a greater presence, persistence, and distribution of logjams

I examined correlations between logjam metrics and channel dynamism metrics (Figure 4.5). My data showed a significant positive correlation between total sinuosity and logjam count (r=0.63, τ =0.45, $p<0.01$) (Figure 4.5B), a significant positive correlation between total sinuosity and logjam persistence (r=0.69, τ =0.47, p<0.01) (Figure 4.5C), and a weak positive correlation between total sinuosity and logjam distribution density (r=0.14, τ =0.12, p=0.1) (Figure 4.5A). In other words, an increased number of channels corresponds with a strong increase in the presence and persistence of logjams and a weak increase in the distribution of logjams. If greater total sinuosity is interpreted as an indicator of a more dynamic river corridor over timespans of multiple years to decades, these results support my hypothesis. I observed a weak but significant positive correlation between channel migration and logjam count (r=0.18, τ = 0.21, p=0.01) (Figure 4.5F), a weak but insignificant positive correlation between channel migration and logjam sticky sites (r=0.11, τ= 0.09, p=0.6) (Figure 5G), and no correlation between channel migration and logjam distribution density (r=-0.07, τ= 0.03, p=0.7) (Figure 4.5E). I reiterate that my analysis of channel migration considered only the mainstem centerline channel movement and thus missed the type of channel dynamism that results in creation and abandonment of secondary channels.

I include beaver meadow presence here as a fourth variable given that beaver activity involves redistribution of wood within the river corridor. The presence of beaver meadows was weakly correlated with total sinuosity (r=0.25, τ = 0.18, p=0.3) and was not correlated with average channel migration (r=-0.06, τ = -0.009, p=0.9) (Figure 4.5D and Figure 4.5H).

I identified 86 logjam sticky sites that persisted throughout the imagery between 2013-2022. Of the 86 sticky sites, only five sites were not in a complex planform segment (i.e., less than 6% in a single-thread, meandering reach). Complex planform is defined here as having two or more channels present, meaning it has multiple channels in a braided or anastomosing planform rather than a single meandering channel. This further supports hypothesis *i* by indicating that logjams are more likely to form and persist in portions of the river corridor in which channel movements create and maintain greater total sinuosity.

I additionally statistically modeled whether logjam variables and peak discharge are predictors of channel dynamism using mixed-effect models. That is, as the presence, persistence, and distribution of logjams increase in a river corridor or as peak annual discharge increases, should I expect to see more channel movement? I included segment as a random effect in my mixed effect models and found that the 16 segments are a strong indicator of random variation in the models, making it important to leave segment as a random effect in my models. Model selection indicated that changes in total sinuosity are best predicted by changes in logjam distribution density and logjam count. Changes in average channel migration are best predicted by changes in logjam distribution density (Table 4.3). As the distribution density of logjams increases in the

Swan River corridor, so does total sinuosity and average channel migration. An increase in logjam count also typically results in an increase in total sinuosity.

Table 4.3. Summary of model selection for the mixed-effect models with total sinuosity or average channel migration as response variables and logjam distribution density, count, persistence, and flow as fixed effects and segment as a random effect, starting with the null model (segment + no fixed effects) and fixed effect terms that caused the largest reduction in the AICc value.

Model	AIC_c	ΔAIC_c
Total Sinuosity		
Segment+ Logjam Distribution Density + Logjam Count	34.3	0
Segment+ Flow + Logjam Distribution Density + Logjam Count	46.9	12.55
Segment + No Fixed Effects (Null Model)	57.8	23.51
Average Channel Migration		
Segment + Logjam Distribution Density	271.5	0
Segment + No Fixed Effects (Null Model)	271.7	0.23

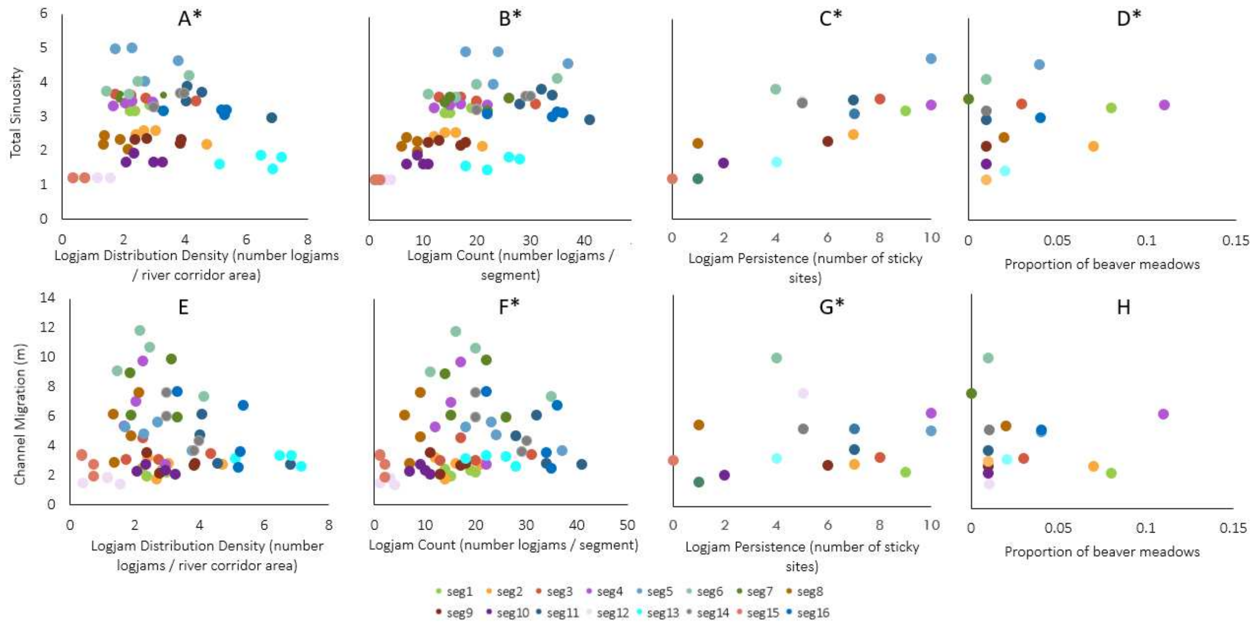

Figure 4.5. Relationship between logjam variables and channel dynamism variables. A-C depict the relationship between total sinuosity and logjam variables. D-F depict the relationship between average channel migration and logjam variables. Note, plot C and F (sticky sites) have fewer data available compared to the other plots because they have an integrated timestep (i.e., logjam sticky sites was measured across 2013-2022, whereas wood distribution density and wood count were measured in 2013, 2016, 2020, and 2022). An asterisk at the top of a plot indicates where there is any correlation between variables, including weak correlations.

Hypothesis ii: years with higher peak discharge correspond with greater channel dynamism and presence of logjams

I tested the correlations between peak discharge and channel dynamism and logjam variables (Figure 4.6). Higher annual peak discharges were weakly but significantly correlated with greater logjam distribution densities (r=.16, τ =0.19, p=0.05) and weakly but not significantly correlated with a greater number of logjams (r=0.14, τ =0.14, p=0.1) (Figure 4.6A and Figure 4.6C). In the field, I observed further evidence of a correlation between peak discharge and logjam variables. Following a high peak discharge in 2022, for example, both median logjam counts, and logjam distribution density increased by over 50% compared to the two prior years in the Swan River corridor. For comparison, peak discharge in 2022 was a 13-year flow recurrence interval, peak discharge in 2020 and 2014 was a 5-year flow recurrence interval, and peak discharge in 2016 was a 1-year flow recurrence interval.

I did not observe any significant correlation between annual peak discharge and channel migration (r=-0.09, τ =-0.07, p=0.4) or between peak annual discharge and total sinuosity (r=-0.04, τ =-0.04, p=0.7) (Figure 4.6B and Figure 4.6D). In my mixed-effect models, I see that changes in peak discharge play a role in predicting changes in total sinuosity, but the relative role of logjam variables is more important in predicting channel dynamism (Table 4.3). In other words, the number of channels and how much the primary channel centerline shifts did not always increase significantly following high discharge, while the distribution density and number of logjams did increase somewhat following high discharge. I did not test the correlation between logjam persistence and discharge because the sticky site data are integrated over multiple years (2013-2022) and therefore cannot be associated with unique peak annual discharge values.

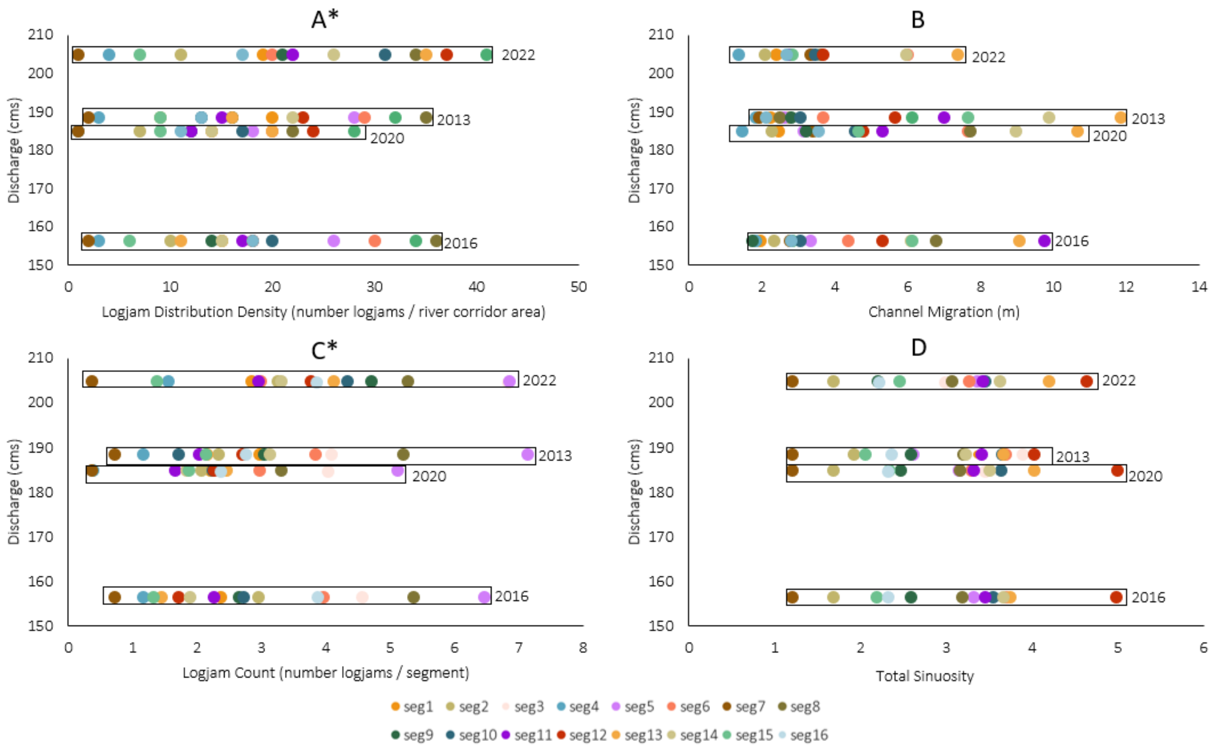

Figure 4.6. Relationship between peak discharge and channel dynamism (B and D) and logjam variables (A and C). Note, comparison by segments for any given peak annual discharge is not applicable here given the use of a constant discharge rather than point-discharge measurements. Asterisks at top of each plot indicate where there is any correlation between variables, including weak correlations.

Hypothesis iii: persistent values of geomorphic heterogeneity, as reflected in the spatial distribution of landscape patch density, is explained by greater logjams and channel dynamism in the river corridor

In partial support of hypothesis *iii*, I found that logjam distribution density and total sinuosity are predictors of spatial heterogeneity, although the proportion of beaver meadows plays an important role as well. Much of the variation in my mixed-effect models was explained by the effect of spatial similarities in the data and I included a random effect in all models to account for this.

Patch density varied across the segments within my study area (Table S1), indicating that some segments were more fragmented than others within the river corridor. Model selection indicates that logjam distribution density, total sinuosity and beaver meadows all play a role in predicting spatial heterogeneity. (Table 4.4). Logjam distribution density, beaver meadows, and total sinuosity, combined with the random effect, explained 39% of the variation in patch density (conditional R^2=0.39).

Table 4.4. Mixed-effect model selection for best predictor variables of spatial heterogeneity, as indicated by patch density.

Model	AIC_c	ΔAIC_c
Random Effect+ Beaver Meadow + Logjam Distribution Density + Total Sinuosity	178.7	0
Random Effect+ Beaver Meadow + Logjam Distribution Density	182.9	4.23
Random Effect+ Beaver Meadow + Total Sinuosity	183.4	4.73
Random Effect + No Fixed Effects (Null Model)	200.9	22.16

In summary, my results indicate moderate support for hypothesis *i* that more dynamic sections of the river corridor correlate with increased presence, persistence, and distribution of logjams, based on positive correlations with total sinuosity but not channel migration. The analyses partially support hypothesis *ii* in that higher peak discharge correlates with greater logjam presence and distribution but not to greater channel dynamism. The results also partly support hypothesis *iii* that logjam distribution density and total sinuosity as well as the proportion of beaver meadows best explains spatial heterogeneity, as described by patch density.

5. Discussion

My results reflect both the complex interactions of water, sediment, and large wood in river corridors and the difficulties of interpreting causal relations among these variables through time. I distill the interactions of logjams, channel dynamism, and spatial heterogeneity into a conceptual model (Figure 4.7). My results suggest that these variables interact in a cascade of processes and feedbacks in which (i) high flows recruit and mobilize wood in the river corridor, (ii) the presence, distribution, and persistence of logjams aid in the formation and movement of channels, as reflected by total sinuosity, and (iii) the persistent effects caused by higher total sinuosity, logjam distribution densities, and beaver meadows help to explain spatial heterogeneity within the river corridor. The interactions between these variables all exist with self-enhancing feedback loops. Individual pieces of wood and logjams, for example, act as a trapping mechanism for more logjams and, as logjams divert flow to form new secondary channels, those secondary channels in return act as further trapping mechanisms for new logjams. The self-enhancing feedback loop of channel processes in the Swan River corridor consistently acts to facilitate spatial heterogeneity (Figure 4.7).

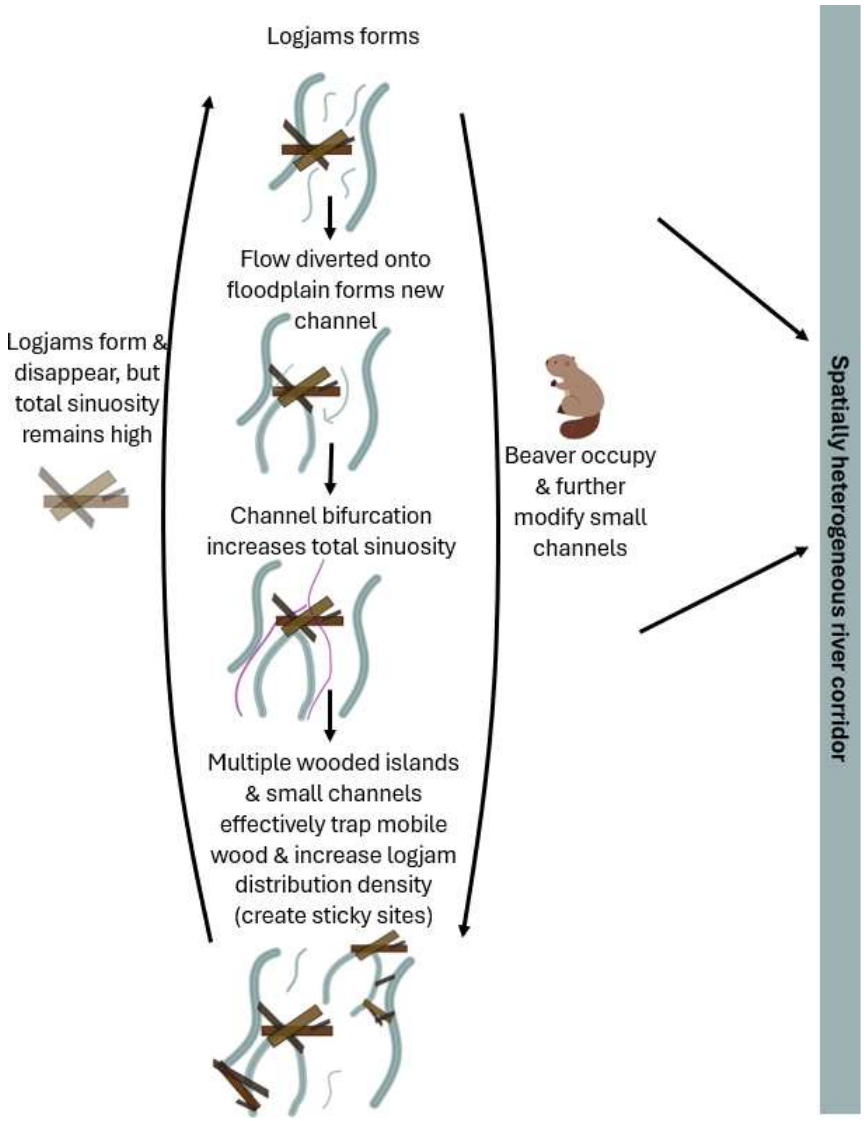

Figure 4.7. Schematic illustration of the river corridor interactions that I infer for the Swan River study site. Arrows indicate feedback between processes.

Significant differences exist among segments of the Swan River corridor with respect to channel dynamism and logjams. As mentioned in the methods, I initially selected the downstream-most 8 segments of the study area based on the naturalness of the river corridor and the presence of abundant logjams in the active channel(s). I subsequently expanded analyses to include an additional 8 upstream segments. These segments were included because of anecdotal evidence of bank stabilization and large wood removal from the active channel. I included these sites to provide a greater range of values within some of the variables analyzed. I expected significant differences in the variables I analyzed between the upper 8 and lower 8 segments, but instead I found variation throughout the 16 segments. Although I added an additional 8 segments upstream of the initial site selection to include segments that might include variation in river corridor variables due to human impacts, I was not able to distinguish with enough certainty which reaches were impacted and are unable to report those findings in the results. I interpret the lower values of logjam distribution density in the upstream segments of the study area to reflect greater human alterations of the river corridor, including deforestation, roads and bridges, and dispersed housing and other infrastructure, and at least some wood removal from the active channel (pers. comm. with Swan River valley residents, Aug. 2023). In this context, it is worth noting that segment 15, which has the greatest degree of human alteration based on qualitative field and remote sensing observations, also has the lowest values of total sinuosity and logjam distribution density. I interpret lower logjam distribution density in the most downstream segment as reflecting lower transport capacity and erosional force as the river approaches Swan Lake in the downstream-most reach. Figure 4.8 captures the variation in channel dynamism variables by segment. The differences I observed among segments facilitate the statistical analyses that indicate three key findings.

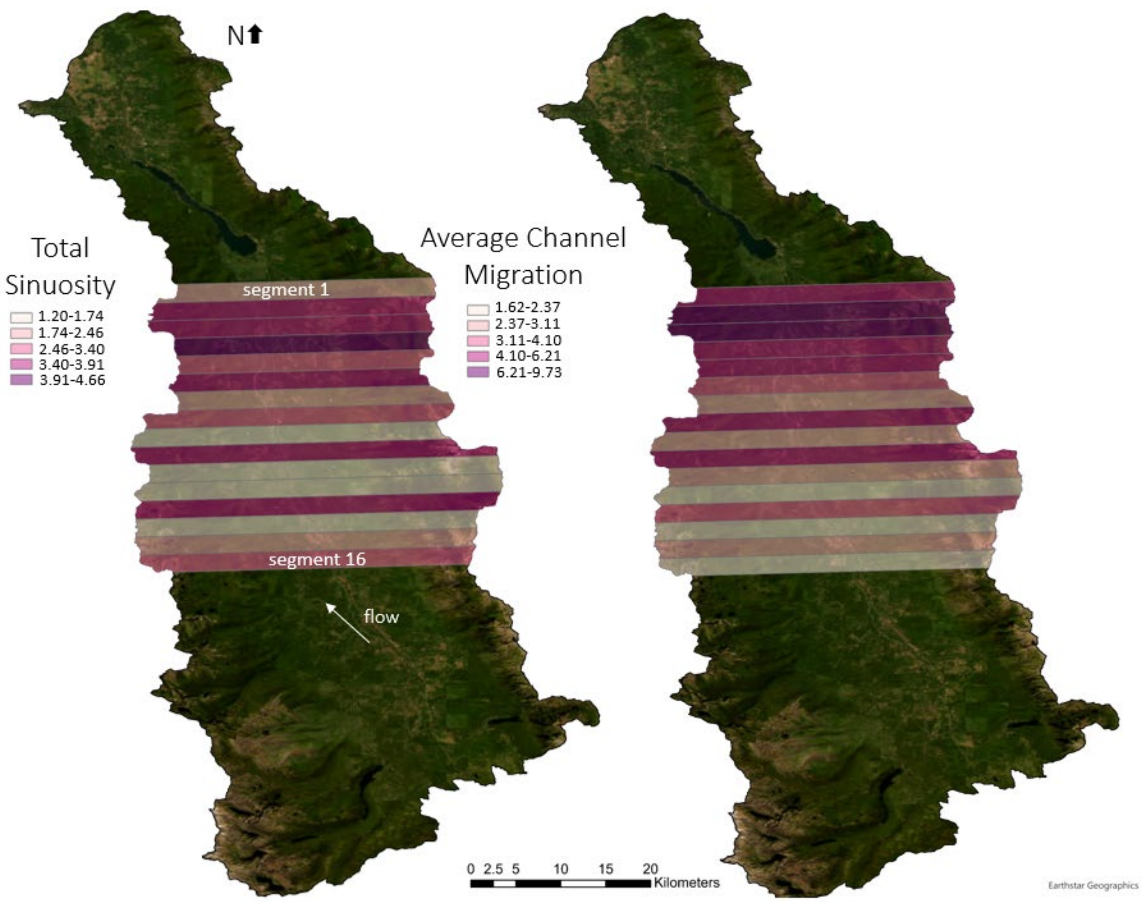

Figure 4.8. Total sinuosity and average channel migration values for each segment, averaged across years. Darker shades of pink correspond with greater values of total sinuosity or average channel migration and are conceptualized as more dynamic segments of the river corridor. Lighter shades of pink correspond with low total sinuosity or average channel migration and are conceptualized as less dynamic segments of the river corridor. Note, color gradient for the same segment can vary by total sinuosity and average channel migration. As mentioned in the text, the metric of total sinuosity includes secondary channels while the metric of average channel migration only includes the main channel centerline migration.

5.1. Channel dynamism and logjams

My first key finding is that decadal-scale channel dynamism, as reflected in total sinuosity, corresponds to greater presence, distribution, and persistence of logjams in the river corridor. This finding is supported by previous work (e.g., Wohl and Iskin, 2022). Greater total sinuosity equates to longer flow paths that are likely to provide areas of low-transport capacity such as small secondary channels, bars, and channel bends that can preferentially trap and retain wood.

5.2. Effects of peak discharge

Second, as peak discharges increase, logjam presence and distribution density increase. I observed a weak positive correlation between higher peak discharges and greater values of logjam presence and distribution density, based on correlation coefficients and a lack of correlation between peak discharge and channel dynamism, as reflected in mainstem channel migration rates and values of total sinuosity. Qualitative field observations following high discharge in summer 2022 further support the relationship between increased peak discharge and increased logjam presence and distribution and I infer that there is a positive correlation between logjam quantity and peak discharge based on these observations in addition to the correlation coefficients. Higher peak discharges are more likely to mobilize individual wood pieces recruited to the river corridor through tree fall via bank erosion, individual tree mortality, and other processes. These mobile wood pieces can be incorporated into logjams in heterogeneous portions of the river corridor where existing logjams or vegetated channel bars and banks trap and retain mobile wood pieces.

The most interesting aspect of the second key finding is the lack of correlation between peak discharge and either mainstem channel migration rates or total sinuosity. Although flow with sufficient erosional force is necessary to drive channel migration or avulsion, my field observations during the unusually high peak flows of the 2022 runoff season suggest that it is the combination of flow obstructions in the form of logjams and high flow that is particularly effective in driving channel dynamism. I observed a newly inundated portion of the floodplain forest in July 2022 (Figure 4.9). A large logjam formed at the head of a forested island had deflected flow onto a portion of the floodplain that already had small secondary channels. The entire floodplain was inundated, however, and when I returned to the site in July 2023, I found new secondary channels as well as enlargement of the secondary channels that were present prior to 2022. I only observed this type of secondary channel formation in association with logjams that deflected flow onto the floodplain.

Figure 4.9. Field observations following ~12-year recurrence interval flood in summer 2022. A) flow redirected from the main channel by a logjam onto the floodplain and moving as non-channelized flow (4m channel spanning logjam for scale). B) new logjams transported onto the floodplain during peak discharge and pinned against existing floodplain forest (1m measuring tape for scale). C) more established channels at the same location in summer 2023 (4m channel spanning logjam for scale). D) logjam that previously spanned the channel and burst during 2022 flows, redirecting water onto the floodplain (2.5m person for scale).

5.3. Geomorphic heterogeneity

Third, persistent values of geomorphic heterogeneity, as reflected in patch density values, relate to logjam distribution density, the proportion of beaver meadows, and the degree of total sinuosity (Table 4.4). To interpret the third key finding, I compared patch density values calculated by Iskin and Wohl (2023a) for natural river corridors across the United States to my values for the Swan River (Figure 4.10). When comparing the lower 8 segments of the Swan River to other locations in the U.S., the Swan had higher spatial heterogeneity, as indicated by patch density, across segments, relative to other natural river corridors across the United States (Figure 4.10). When comparing the full sixteen segments of the Swan River to other locations in the U.S., I see a lower patch density. I infer that the differences in heterogeneity between the 8 and 16 segments is due to inclusion of human-modified segments and a decrease in floodplain area and density of patches. However, I opted to keep all 16 segments in my statistical analysis to both increase statistical power and because I did not find statistically significant differences between median heterogeneity values when comparing the upper and lower segments on the Swan River.

These details of patchiness in the Swan River corridor presumably reflect the formation of new logjams and secondary channels through time, as well as the subsequent modification of secondary channels by beaver and by additional logjams that can reduce discharge through these channels. The Swan was one of the few river corridors listed in Figure 4.10 which combined regular movements of wood, channel bifurcations, and channel avulsions along the main channel and beaver activity and gradual channel infilling along secondary channels. These multiple biogeomorphic processes likely create numerous geomorphic units within the Swan River corridor and keep these units dispersed, rather than clumped, in space.

Logjam distribution density, total sinuosity, and proportion of beaver meadows were the strongest predictors of patch density, so it seems reasonable that the abundant logjams, beaver activity, and secondary channels of the Swan River corridor correspond to greater patchiness. This relationship likely reflects the persistent influence and interactions that beaver, logjams, and the presence of secondary channels have on heterogeneity even after the wood has been re-distributed or beaver no longer actively occupy an area. These results also agree with the results from Iskin and Wohl (2023a) that total sinuosity, large wood volume, and channel planform (including beaver-modified planforms) influence floodplain heterogeneity.

Low correlations overall between my river corridor variables and patch density could be due to comparing heterogeneity between segments of the same river, which are not independent of each other, as well as the limited number of data points. Although I account for these effects in my statistical analyses, the results highlight the fact that it is difficult to isolate individual river corridor characteristics from each other (such as logjams variables, flow, and channel migration variables), because they commonly have dependent effects and are likely governed by thresholds that have yet to be identified. The interpretations of results in this study reflect the interactions among diverse processes (high peak flows, formation of logjams, formation of secondary channels, modifications of the river corridor by beavers) that together create and maintain a river corridor in which diverse individual patches distributed across the landscape foster spatial heterogeneity and the associated heterogeneity of habitat, biota, and floodplain functions such as nutrient dynamics (Appling et al., 2014) and flow paths (Helton et al., 2014).

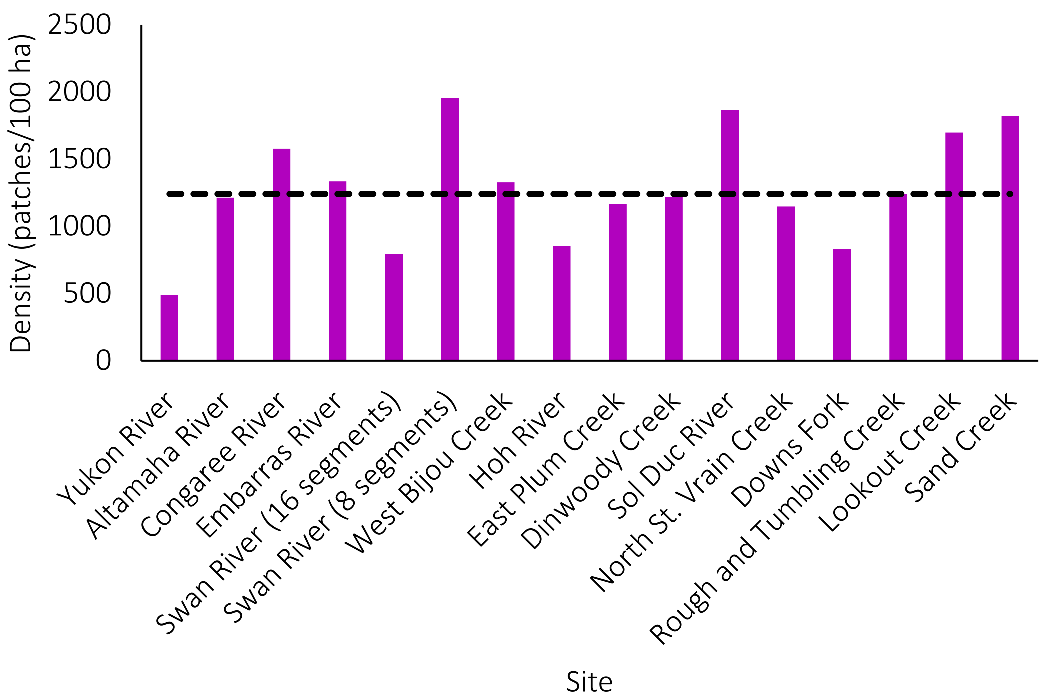

Figure 4.10. Comparison of Swan River corridor patch density to 14 other rivers in the United States from Iskin and Wohl (2023a). Sites differ in relative channel mobility, flashiness of flood peaks, and biome to provide insights into the fluvial and ecological processes that create and maintain spatial heterogeneity in natural river corridors. All non-Swan sites and the "Swan River (8 segments)" depict values calculated in Iskin and Wohl (2023a). "Swan River (16 segments)" depicts patch density values calculated for the 16 segments used in this study. The dashed line represents the median value across all sites.

5.4. Implications for river management

My findings have practical implications for river management. Natural rivers are inherently dynamic. Spatial and temporal variations in water and sediment fluxes moving down the river corridor drive changes in the three-dimensional geometry of channels and floodplains. In forested river corridors, large wood becomes an integral part of the interactions among water, sediment, and river corridor form. Wood preferentially accumulates in more geomorphically heterogeneous portions of the river corridor that provide sites capable of trapping and retaining wood. Logjams can then drive greater total sinuosity and the formation of secondary channels that result in further wood trapping, greater heterogeneity of floodplain vegetation, and ideal habitat for beaver that further modify river corridor heterogeneity. A lack of logjams results in demonstrably simpler and more homogeneous river corridors (Collins et al., 2002).

Although the correlation between logjams and total sinuosity illustrated in Figure 4.5 does not unequivocally indicate cause and effect, the distribution of data suggests total sinuosity is more conservative through time and does not change substantially even if wood presence and distribution nearly double. In previous work, I have observed scenarios in which a logjam present for only one runoff season deflected flow onto the floodplain and created secondary channels that persisted for years, even if the logjam broke up during the original or subsequent peak flows (Wohl and Iskin, 2022). I also observed this scenario in 2022 during high flows at the Swan River where the floodplain was inundated, as described previously. This suggests that wood reintroduced to the river corridor as individual pieces or engineered logjams does not have to be anchored in place to facilitate formation of geomorphic heterogeneity within the river corridor. However, the work of Collins et al. (2002) indicates that removal of most or all the large wood from the active channel(s) eventually results in a simplified river channel with a single active channel and more homogeneous floodplain. The proportion of wood that can be removed without causing this shift to an alternate state of a simplified river corridor remains an open question and relates directly to the issue of restoring large wood sources and storage in river catchments.

Figure 4.5 also suggests the difficulty of predicting a threshold value of logjam distribution density that will increase total sinuosity: some of the highest and lowest values of wood distribution density are associated with low values of total sinuosity. This may reflect the temporal disparity between logjam distribution density measured at four-time intervals over nine years for logjams that can form and disappear during a single high-flow year versus the more slowly changing values of total sinuosity.

Both spatial and temporal analyses of past and present river processes are necessary to understand future river conditions (Grabowski *et al.*, 2014). As river science and management look toward restoring function and fostering resilience, understanding dynamic interactions in natural river corridors is imperative for supporting process-based management that targets drivers of natural river function. In this way, effective management and restoration solutions can be developed to recognize the underlying drivers of geomorphic heterogeneity, channel dynamism, and the possible evolutionary trajectories and timelines of change under future management scenarios. Catchment/river basin planning and the assessment of restoration needs and objectives can all benefit from a thorough spatial and temporal analysis of dynamic river corridors.

6. Conclusions

My main objective was to explore how logjams, the movement of channels, and geomorphic heterogeneity interact in a dynamic river corridor. I found that, first, decadal-scale channel dynamism, as reflected in total sinuosity, corresponds to a greater number of logjams and greater persistence of these logjams through time. Second, higher peak discharge is correlated with greater values of logjam presence and distribution density, but not to greater channel dynamism. Third, persistent values of geomorphic heterogeneity, as reflected in patch density, are explained by logjam distribution density, the proportion of beaver meadows, and total sinuosity. Results suggest that these variables interact in a cascade of processes and feedbacks in which high flows recruit and mobilize wood, the presence, distribution, and persistence of logjams aid in the movement and creation of channels as reflected by total sinuosity, and the persistent effects caused by higher total sinuosity, logjam distribution densities, and beaver meadows all help to explain spatial heterogeneity within the river corridor. This points to the important role that spatially and temporally varying inputs of water, sediment, and wood play in creating and maintaining spatial heterogeneity, although the variable(s) that best explain heterogeneity are specific to the metric of interest.

Further research is needed to determine the combined influence of logjams, channel dynamism, and geomorphic heterogeneity in river systems with different disturbance regimes and management histories. This becomes imperative with efforts to protect and restore spatially heterogeneous river networks in order to enhance resilience to disturbance at the scale of entire river networks (Wohl *et al.*, 2018; Wohl *et al.*, 2022). Additional work is also needed to detect thresholds in the relationships between logjams and channel mobility as well as constrain understanding of the timescales at which these variables interact. In this context, rapidly developing two-dimensional models of large wood and planform dynamics might prove particularly useful in differentiating cause and effect relationships.

To conclude, the findings articulated in this study reflect the complex interactions of water, sediment, and large wood in river corridors; the difficulties of interpreting causal relationships among these variables through time; and the importance of spatial and temporal analyses of past and present river processes to understand future river conditions.

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CHAPTER 5: CONCLUSIONS

5.1. Key Findings and Implications

Natural river corridors are inherently dynamic. Spatial and temporal variations in water and sediment fluxes moving within the river corridor drive changes in the three-dimensional geometry of channels and floodplains. In forested river corridors, large wood becomes an integral part of the interactions among water, sediment, and the resulting river corridor form and function. Individual pieces of large wood preferentially accumulate as logjams in more geomorphically heterogeneous portions of the river corridor (e.g., Wyzga and Zawiejska, 2005; Scott and Wohl, 2018; Marshall et al., 2024). Logjams can then drive increases in total sinuosity and the formation of secondary channels/islands that result in greater heterogeneity of floodplain topography, more sites capable of continued wood trapping, and ideal habitat for beaver to further enhance river corridor heterogeneity. Consequently, in forested or historically forested regions, a lack of logjams results in demonstrably simpler and more homogeneous river corridors (e.g., Collins et al., 2012).

The importance of spatial heterogeneity, logjams, and secondary channels/islands to river corridor function has been well documented (e.g., Jeffries et al., 2003; Wohl, 2011). Scientific understanding has translated into management, as efforts to restore river function via process-based strategies utilizing wood increase (e.g., Roni et al., 2015;

Grabowski et al., 2019; Wohl et al., 2024). However, a mechanistic understanding of how logjams interact in a river corridor to create heterogeneity at different spatial and temporal scales remains lacking. This dissertation addresses some of the aforementioned knowledge gap by providing quantitative underpinning to the patterns, processes, and interactions occurring in a naturally dynamic system, highlighting the role of spatially heterogeneous river corridors in fostering hydraulic, ecologic, and geomorphic functions.

Chapter 2 (Marshall and Wohl, 2023) explores the processes driving spatial patterns in bifurcations induced by logjams, emphasizing the continuum of bifurcation types based on erosive force/resistance ratios. Chapter 3 (Marshall and Wohl, in review) builds on this by investigating how accretionary and avulsive processes shape bifurcations over time, emphasizing the temporal progression of logjam-induced features. Chapter 4 (Marshall et al., 2024) dives deeper into the interactions between process and form, demonstrating the relationship between channel dynamism, logjam presence, and spatial heterogeneity at larger temporal and spatial scales.

Results from each of these chapters suggest that logjams can be transient while still having a persistent geomorphic effect. The combination of bank height, bank erosional resistance, and logjams influences where overbank flow and bank erosion can occur. Overbank flow and bank erosion then influence where wood levees, avulsions and secondary channels, or islands and split flow can form. Vegetation established on any of these wood features– wood levees, channel marginal jams at avulsions, or channel-spanning jams at islands – helps stabilize that feature and create persistent areas of flow separation, erosion, and deposition. Vegetated islands may then grow through upstream migration and through lateral accretion. Over time, islands may become blocked with large wood and living vegetation, allowing the channel and the adjoining island to become part of the floodplain through lateral accretion. However, the absence of contemporary logjams at the bifurcation point of some past channel avulsions and the continued presence of the secondary channels suggests that relatively transient logjams may still create persistent secondary channels and islands. Although the correlation between logjams and total sinuosity does not unequivocally indicate cause and effect, results from Chapter 4 indicate that total sinuosity is more conservative than the presence of individual logjams through time and does not change substantially even if logjam presence and distribution nearly double. This suggests that wood reintroduced to the river corridor as individual pieces or engineered logjams does not have to be anchored in place to facilitate formation of geomorphic heterogeneity within the river corridor.

5.2. Opportunities for Future Work

Multi-scale and multi-factor studies, such as the work presented here, are challenging to design and implement, but they are essential to predicting functions of river corridors. There were limitations to the research that could be carried out in each chapter of this dissertation, and those limitations translate to opportunities for future work. Several avenues of future research exist with questions tied to understanding the complex interactions of logjams, channel dynamism, and spatial heterogeneity and their applications for restoring hydraulic, ecologic, and geomorphic function to altered river corridors (Figure 5.1).

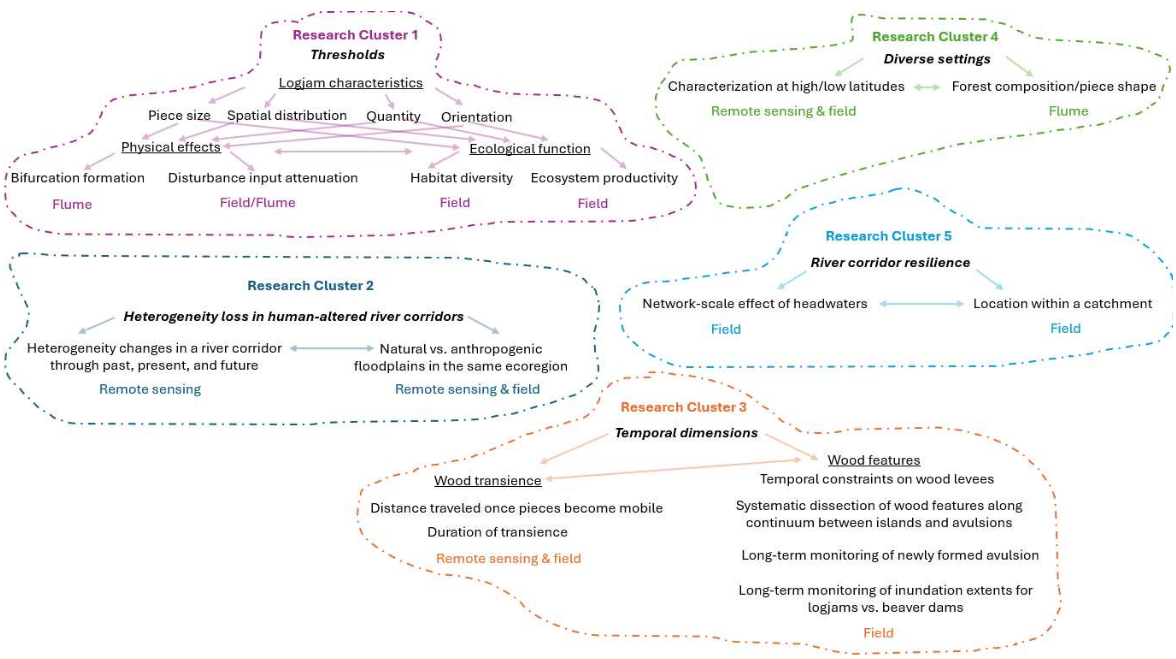

Figure 5.1. Thematic research clusters for future work. Arrows denote connections across future topics within a research cluster and colored text indicates the category of methods used to explore the topic.

One area for future research involves quantifying threshold effects of logjams in relation to physical processes in river corridors. Limited studies suggest thresholds in changes to physical form or function with changes in wood load (e.g., Wohl 2011) and no studies have quantitatively predicted a minimum quantity of logjams or minimum piece size to create desired physical effects. One topic from this dissertation to expand on within this research theme is threshold conditions for forming bifurcations. For example, how many logjams and what characteristics of those logjams are needed to form new bifurcations? How long must logjams persist relative to recurrence of peak flows to create persistent bifurcations? These questions are likely best explored in a flume where logjam characteristics including piece size, orientation, and spatial distribution as well as flow can be directly manipulated. I was not able to directly observe interactions between potentially transient logjams and channel bifurcations with existing field data. I suspect, based on inference and multi-year field observations of some sites along the Swan, that one large peak flow is sufficient to form a new bifurcation, even if the peak flow removes the logjam that initiated the process of bifurcation. However, this inference has not been quantitatively tested. Continuing to monitor field locations along the Swan where newly formed bifurcations have occurred can pair a flume study with field observations. In addition to bifurcation formation, a flume study or a morphodynamic model exploring thresholds of spatial distribution and density of logjams as they relate to sediment storage could provide valuable predictive insight into whether a threshold condition of logjams exists for attenuating inputs such as sediment during flood pulses.

Logjam thresholds could also be explored within this research cluster in relation to ecologic function. The ability to quantify thresholds in a manner relevant to specific river corridor function is a current knowledge gap that has important implications for understanding how different aspects of physical complexity assist or result in ecologic function, including biogeochemical cycling, stream metabolism, stream ecosystem productivity, and habitat availability. For example, does an increase in logjams create a linear increase in a specific ecologic function or is there a threshold quantity/characteristic of logjams at which that function increases substantially? This question can be explored for a range of emergent properties in the field via paired tributaries (e.g., similar drainage basin characteristics) with varying amounts of wood or differing wood characteristics relative to a given ecological function. Although correlations between physical complexity and ecological function have been hypothesized (e.g., McClain et al., 2003; Craig et al., 2008), research has mostly focused on differences between physically more or less complex river segments rather than on quantitative thresholds of how increasing complexity equates to predictable increases in specific measures of ecosystem function.

A second area for future research is considering the legacy of human modification to the river corridor and quantifying the physical implications of historical reductions in wood load due to land use practices and river engineering. One topic to explore within this research cluster is quantifying heterogeneity or heterogeneity loss in human-modified river corridors. Chapter 4 quantified heterogeneity within a natural river corridor and existing work has compared heterogeneity across natural floodplains (e.g., Iskin and Wohl, 2023). Given the documented effects of logjams as drivers of river corridor heterogeneity, it seems logical to assume that historical removal of large wood substantially altered heterogeneity, but this has received very little study (exceptions including research from the Great Raft in Louisiana and the Pacific Northwest). The methods used in Chapter 4 could translate to more modified-river corridors and improving upon temporal methods could allow for a comparison of changes in heterogeneity through time in a single river corridor as well as comparing quantified heterogeneity in human-altered river corridors vs. natural river corridors in similar ecoregions. Such work is driven by questions of how the river corridor form varies from its historic condition, and how we might use past and present form and process within the river corridor to consider future trajectories. Additional collaboration could expand the scope here with numerically modeling such interactions in a manner that facilitates prediction of how changes in wood load alter river corridor form and process.

A third future research area is exploring the temporal dimensions of logjams within the river corridor, both in terms of logjam transience and the duration necessary to create logjam-induced features such as islands/bifurcations. The work presented in this dissertation suggests that logjams can be transient while still having a geomorphic effect on the river corridor. Understanding how far individual pieces of wood move once they become mobile or the temporal dimensions of that transience/storage remains limited. A few studies have used diverse tags to track individual pieces of wood (e.g., MacVicar et al., 2009; Schenk et al., 2014) or have used sequential aerial photographs to track wood movements between the channel and floodplain (e.g., Latterell and Naiman, 2007). Nonetheless, the relative lack of information on wood mobilization on diverse rivers leads to a lack of understanding of transport distances and how transport influences spatial distribution of logjams within river networks. A combination of field and remote sensing methods could be employed to explore this topic. Satellite imagery could be used for multiyear studies of wood movement and distribution in medium to large rivers, but the lack of sufficiently high resolution to detect wood in most imagery prior to ~ 2010 limits the ability to use this approach to study temporal fluctuations in wood during the recent past. Field studies could improve resolution with repeat logjams surveys of a river corridor, but the spatial and temporal resolution of this method is accompanied by limitations as well.

Additionally, another branch of this future research includes better temporal constraints on wood-induced features. I introduced “wood levees” as a term for a river corridor feature in this dissertation, but future work is needed to constrain these features spatially and temporally: specifically, understanding where these features occur spatially within a river corridor and their persistence through time. I observed herbaceous vegetation and no mature trees on wood levees, suggesting that these features are less persistent than islands, but could not constrain their relative effect on river corridors. Documenting additional wood levees features and characterizing how they are shaped by, and influence river corridor processes, could fill a knowledge gap. Similarly, the research presented in Chapter 3 lacked a robust dataset of tree cores due to an absence of mature trees on many of the island sites and consequently limited the quantity of tree cores. Additional cores at island sites would provide further insight into some challenges associated with interpreting results from a small sample size. A systematic 'dissection' of a small population of islands (cores of every tree & samples from every buried log) would be useful, for example, in creating a more robust dataset to temporally constrain features. Collecting tree cores and ^{14}C dating at avulsions and intermediary sites along the continuum between islands and avulsions in addition to those previously collected at island sites would also provide further insight into temporally constraining these features. Although Chapter 3 points to the complexities that exist in constraining island persistence with tree-ring and ^{14}C ages, the methods used have potential for dating organic-rich floodplain sediments and logjams to help constrain the age and rates of change in river corridor morphology and understand geomorphic context in connection with restoration.

Another temporal project of interest within this research cluster is exploring the relative influence of floodplain inundated by logjams vs. beaver dams. I observed one location along the Swan River corridor where logjams aided in creating a new avulsion during peak flow, which inundated the floodplain. I observed another location along the Swan River corridor where beaver dams were inundating the floodplain. Comparing the inundation extent created by these two processes could provide interesting insight into the relative magnitude of inundation extent created by logjams vs. beaver dams. A single field study to create a snapshot in time of the inundation extent as well as long term field monitoring could add insight into the relative desired effects of logjams and beaver dams used to support restoration strategies. The ability to include additional locations would further enhance this work but is limited by available paired sites.

A fourth future research area considers the interactions of spatial heterogeneity, channel dynamism, and wood in river corridors at high and low latitudes in addition to the work in temperate latitudes presented here. Natural river corridors still exist at high (boreal and arctic) and low (tropical) latitudes, providing what may be a relatively brief window of opportunity to gain some insight into the effects of wood in river corridors with different drivers. Field-based studies in natural river corridors at high and low latitudes could further provide insight into the effects of flashier peak flow in rainfall-dominated rivers, highly cohesive silts and clays in floodplain alluvium, or different vegetation communities with greater hydraulic roughness and root resistance. Field studies paired with remote sensing have the potential to add valuable insight into interactions of logjams, channel dynamism, and spatial heterogeneity across diverse settings, even with simple characterization of how logjams interact with the broader river corridor in high- and low-latitude systems. The work presented here largely focuses on a single snowmelt-dominated river corridor with floodplains that are highly erodible (relatively noncohesive upper sediment layers and shallow-rooted conifers), except where willows grow in relatively dense stands. Yet, forested regions throughout the world have different species composition, which impacts the piece shape of wood in the channel (e.g., more relatively columnar conifer pieces vs branching deciduous pieces). The impact of different piece shapes on processes and function is unknown. The ability to test differences in piece characteristics in the field seems unlikely given the broader climate variability (e.g., flow regime, bank resistance). In that regard, a flume experiment manipulating the piece characteristics might provide greater insight into comparative effects.

A fifth and final research direction ties to river resilience and the role of spatial heterogeneity and logjams in promoting resilience and a growing acknowledgement of the importance of incorporating climate change considerations and resiliency into river management (e.g., Beechie et al., 2013; Tullos et al., 2021). Existing studies have shown that more wood-rich and spatially heterogeneous portions of a river corridor can serve as retention zones or "beads" for disturbance inputs, which fosters resilience (e.g. Wohl et al., 2018; Wohl et al., 2022). However, there is limited quantitative understanding of the characteristics and spatial distribution of retention zones. One area to explore within this research theme is the relative spatial distribution, size, and abundance of retention zones across river networks necessary to promote higher levels of resilience. Specifically, some questions include whether a few large retention zones create effects similar to many smaller zones, whether there is a minimum size or abundance of retention zone needed to ensure network-scale resilience to disturbances, and whether retention zones in headwater streams create different levels of resilience than zones in downstream portions of the river network. I see this work as utilizing both remote sensing and field-based methods. Field studies focusing on retention zones within headwater stream networks add insight to an existing knowledge gap, given resolution challenges with remote analysis in headwater locations and the need for additional case studies of headwater response to natural and human-induced disturbances in order to develop a sufficient body of literature to support generalizations and predictions. One way to explore this involves walking catchments from the headwaters to the mouth looking at the relative size and distribution of retention zones. Longer term monitoring utilizing repeat measurements in the field can also add insight into how a river corridor or network responds to overtime following disturbance. Remote sensing methods can support field characterization via mapping retention zones from imagery, which can add insight into the distribution and density of retention zones needed to ensure network-scale resilience to disturbances.

An ongoing challenge for river corridor science is the large, and perhaps expanding, gap between knowledge of processes occurring within river corridors and the ability to use that knowledge for prediction and/or measurement in the context of restoration. Any river scientist understands that, at the most fundamental level, a floodplain is connected to the river channel(s) and the underlying hyporheic zone. This basic scientific understanding is commonly lost in a societal context, however, in which floodplains are treated separately from channels and subsurface water rather than as a dynamic and interacting river corridor. Recognition of the multiple beneficial effects of dynamic and spatially heterogenous river corridors is a primary reason that river management is slowly shifting from a historical emphasis on simplifying and homogenizing channels, toward a process-based approach that reintroduces or conserves wood, multithreads channels, and spatial heterogeneity (e.g., Roni et al., 2015; Grabowski et al, 2019; Wohl et al., 2024). Understanding threshold conditions of wood that promote specific river corridor function, heterogeneity losses in human-modified river corridors, how natural river corridors function across diverse settings, and both the spatial and temporal dimensions of these interactions, are all important components to understanding how to restore and better manage rivers in the present and future. By dissecting the complexities of processes governing naturally dynamic river corridors, this study and future work add quantitative insight to the diverse functionality of heterogenous river systems in forested or historically forested regions. To neglect these interactions, as has been done in many existing conceptualizations of river systems, is to miss a critical component of fluvial dynamics.

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SUPPLEMENTARY INFORMATION FOR CHAPTER 2

Table S1. Raw data used for analyses in results.

Variable	Swan upper	Swan lower	Lost upper	Lost lower	Goat upper	Goat lower	NSV upper	LBC	NSV lower	Ouzel	Cony	Nyack Creek	Hunters
Peak monthly flow (m^3/s)	50.4	50.4	6.8	6.8	7.6	7.6	1.9	1.1	2.1	1.4	1.9	20.6	0.08
Slope m/m	0.004	0.004	0.008	0.008	0.003	0.003	0.06	0.036	0.03	0.05	0.02	0.002	0.06
Drainage area (km^2)	753	1485	50	81	58	94	15	33	18	10	20	213	11
Stream Power (Ω)	1912	1912	533	533	230	230	1118	388	621	682	367	403	45
Erosional resistance (BSTEM)	2.6	2.6	9.9	9.9	11.2	11.2	2.8	2.8	2.8	1.6	1.8	7.7	1.7
F/R (non-normalized)	747	747	54	54	21	21	402	139	223	426	202	52	26
Total sinuosity	6.2	5.5	2.3	3.8	1.8	2.1	5	4	3.1	3.6	2.9	3.9	1.4
Ch. migration width/ch. width	11.2	10.0	1.1	4.64	1.57	4.0	9.0	5.6	8.3	7.0	6.3	7.5	3.3

Table S2. P-values and Correlation Coefficients from Statistical Analysis

Test	Total Sinuosity	Channel Migration Width/Channel Width
Pearson (r)	Correlation coefficient: 0.837 P-value: 0.0003	Correlation coefficient: 0.829 P-value: 0.0005
Spearman (ρ)	Correlation coefficient: 0.767 P-value: 0.002	Correlation coefficient: 0.819 P-value: 0.0006
Kendall (τ)	Correlation coefficient: 0.614 P-value: 0.004	Correlation coefficient: 0.692 P-value: 0.001

SUPPLEMENTARY INFORMATION FOR CHAPTER 3

Table S3. Tree ring and DBH-age curve data

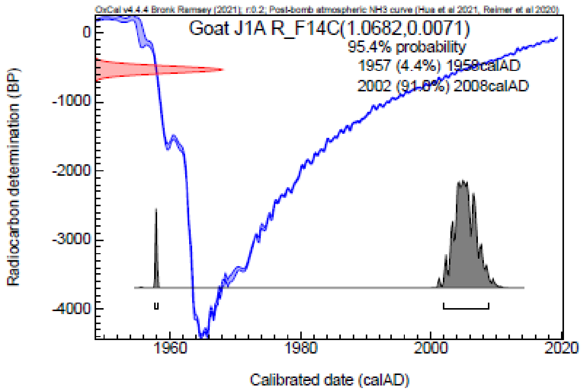
Site	Latitude	Longitude	Species	DBH (in)	Core age (year BP)	DBH-age curve
Goat1	47.749040	-113.824680	spruce	5.5	32	<75
Goat1	47.748860	-113.824540	spruce	15.7	80	<125
Goat2	47.748720	-113.827350	birch	9.8	36	<50
Goat2	47.748900	-113.827420	fir	16.5	39	<100
Goat2	47.749110	-113.828260	spruce	17.3	90	<125
Lost1	47.873070	-113.835070	alder	7.9	21	-
Lost1	47.873070	-113.835070	alder	4.7	25	-
Lost2	47.874250	-113.839500	birch	9.8	16	<50
Lost3	47.873780	-113.843328	spruce	7.1	19	<75
Lost3	47.873810	-113.846730	birch	7.1	15	<30

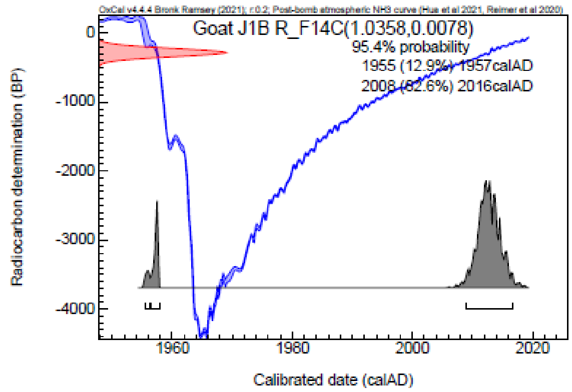
Table S4. Radiocarbon results of large wood samples from tributary islands. The lab numbers were provided by the Yale Analytical and Stable Isotope Center and the Yale Center for Carbon Capture. The IntCal20 curve was used in OxCal 4.4 to obtain calibrated ages. Pink highlighting indicates when pre-1950 calibration curve was used.

Site	Latitude	Longitude	Years BP and % probability	$F^{14}C$	+- (%)
Goat J1A	47.74893	-113.82471	95.4% probability calendar year is between 2002-2008 4.4% probability calendar year is between 1957-1958	1.0682	0.71
Goat J1B	47.74894	-113.82476	82.6% probability calendar year is between 2018-2016 12.9% probability calendar year is between 1955-1957	1.0358	0.78
Goat J1C	47.749	-113.82449	69.6% probability calendar year is between 1983-1987 17.5% probability calendar year is between 1960-1961 8.4% probability calendar year is between 1958-1959	1.1999	0.70
Goat J2A	47.74912	-113.82792	56.6% probability calendar year is between 1795-1950	0.9840	0.76

			39.0 % probability calendar year is between 1666-1784		
Goat J2B	47.7492	-113.82819	90.4% probability calendar year is between 1975-1977 5.0% probability calendar year is 1962	1.3556	0.62
Goat J2C	47.74897	-113.82819	69.1% probability calendar year is between 1979-1980 15.8% probability calendar year is 1981 10.5% probability calendar year is 1962	1.2742	0.66
Goat J2D	47.74861	-113.82719	68% probability calendar year is between 1806-1926 26.9% probability calendar year is between 1687-1731	1.0049	0.74
Lost J1A	47.872953	-113.835144	48.0% probability calendar year is between 1982-1984 47.5% probability calendar year is between 1959-1962	1.2313	0.77
Lost J1B	47.873072	-113.834997	83.8% probability calendar year is between 1973-1975 11.6% probability calendar year is between 1962-1963	1.4132	0.65
Lost J1C	47.873239	-113.835328	95.4% probability calendar year is between 1891-1953 75.5% probability calendar year is between 2013-present 19.9% probability calendar year is between 1955-1957	1.0175	0.74
Lost J2A	47.873958	-113.839697	65.4% probability calendar year is between 1799-1942	0.9918	0.74

Lost J2B	47.873956	-113.839669	76.9% probability calendar year is between 1979-1980 15.1% probability calendar year is 1962 3.5% probability calendar year is 1981	1.2797	0.66
Lost J2C	47.874242	-113.839325	75.3% probability calendar year is between 1979-1980 20.1% probability calendar year is 1962	1.2926	0.68
Lost J3A	47.873772	-113.846886	68.6% probability calendar year is between 1802-1936 28.6% probability calendar year is between 1683-1736	0.9998	0.74
Lost J3B	47.873932	-113.846905	95.4% probability calendar year is between 1888-1950 75.1% probability calendar year is between 2013-present 20.3% probability calendar year is between 1955-1957	1.0165	0.72
Lost J3C	47.873908	-113.846839	88.5% probability calendar year is between 1985-1989 6.9% probability calendar year is between 1958-1959	1.1847	0.71


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Goat J1A R_F14C(1.0682,0.0071)
95.4% probability
1957 (4.4%) 1958calAD
2002 (91.0%) 2008calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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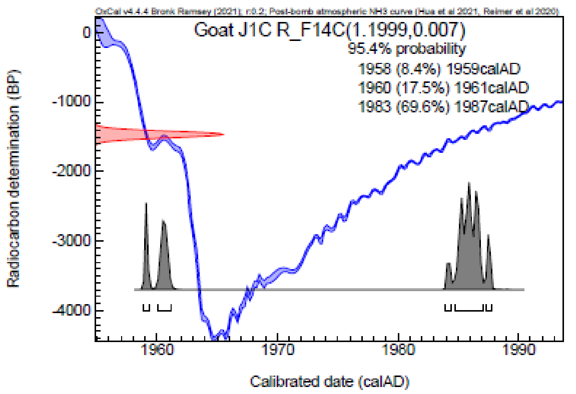
Goat J1B R_F14C(1.0358,0.0078)
95.4% probability
1955 (12.9%) 1957calAD
2008 (82.6%) 2016calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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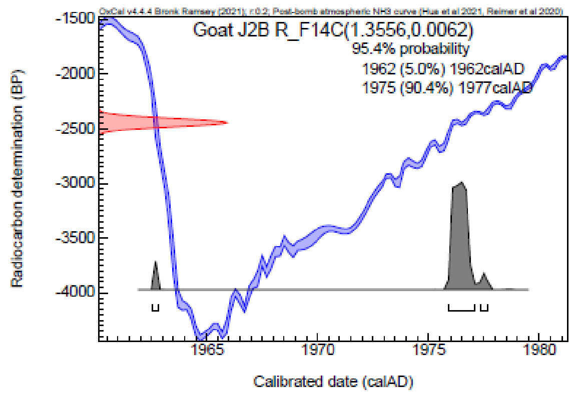
Goat J1C R_F14C(1.1999,0.007)
95.4% probability
1958 (8.4%) 1959calAD
1960 (17.5%) 1961calAD
1983 (69.6%) 1987calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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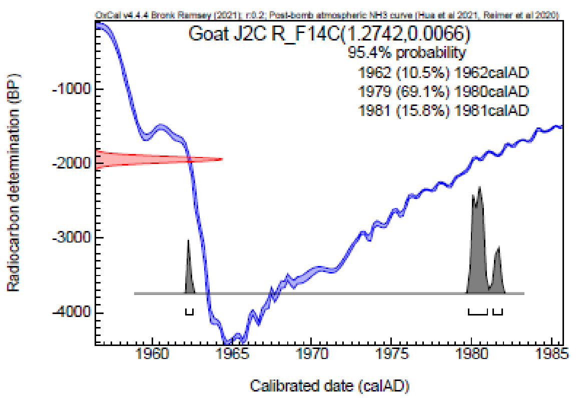
Goat J2B R_F14C(1.3556,0.0062)
95.4% probability
1962 (5.0%) 1962calAD
1975 (90.4%) 1977calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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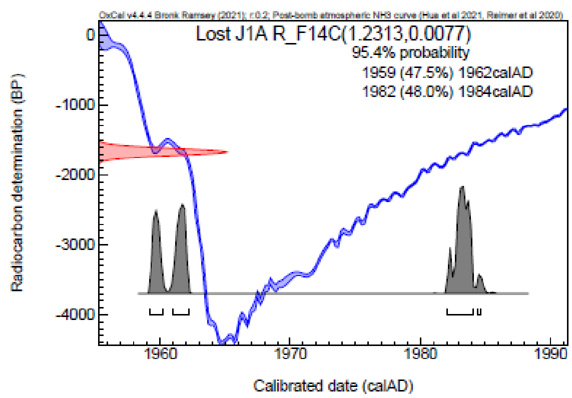
Goat J2C R_F14C(1.2742,0.0066)
95.4% probability
1962 (10.5%) 1962calAD
1979 (69.1%) 1980calAD
1981 (15.8%) 1981calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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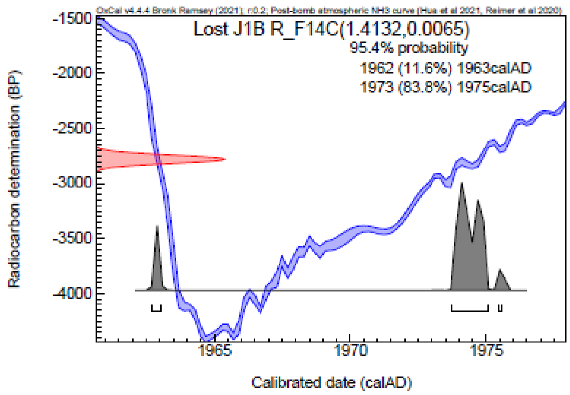
Lost J1A R_F14C(1.2313,0.0077)
95.4% probability
1959 (47.5%) 1962calAD
1982 (48.0%) 1984calAD
Radiocarbon determination (BP)
Calibrated date (calAD)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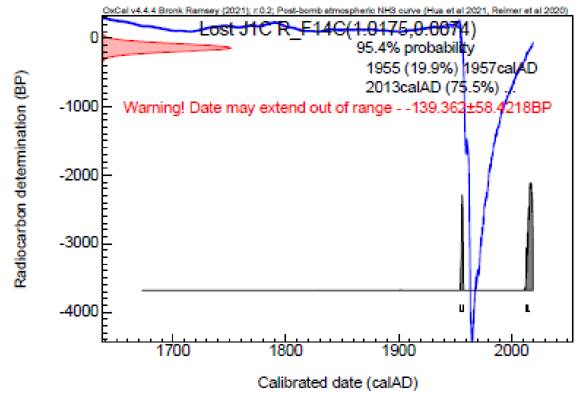
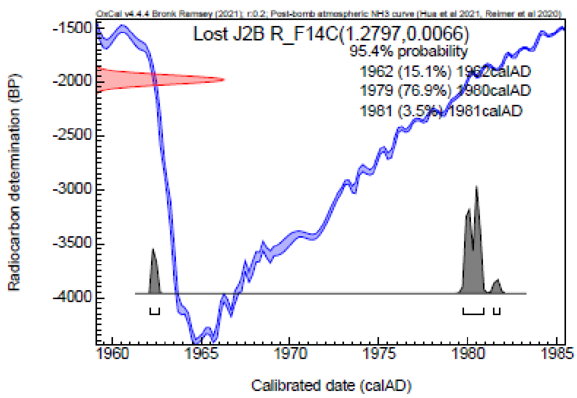
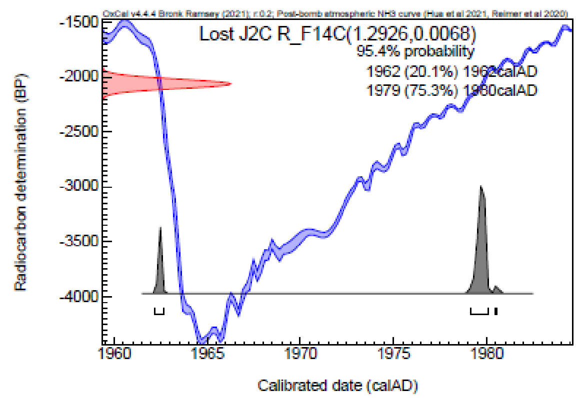
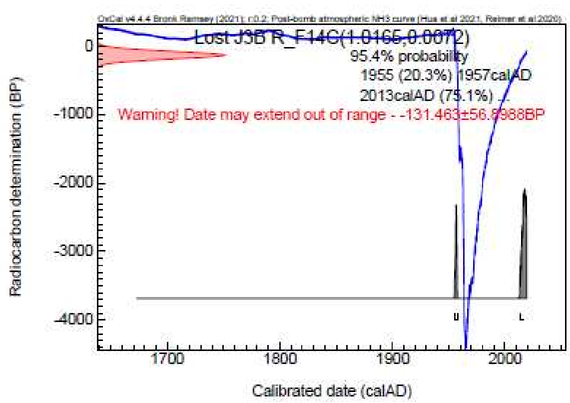
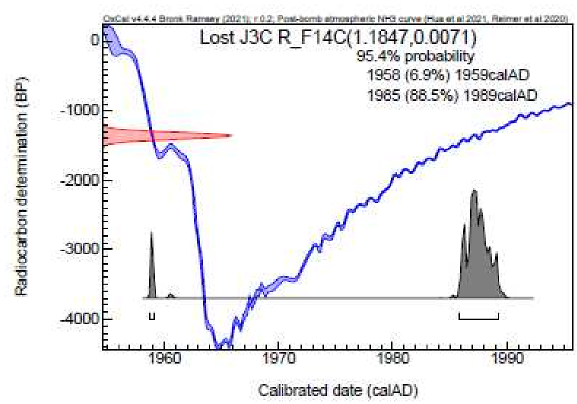
Lost J1B R_F14C(1.4132,0.0065)
95.4% probability
1962 (11.6%) 1963calAD
1973 (83.8%) 1975calAD
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Lost J1C R_F14C(1.0175,0.0074)
95.4% probability
1955 (19.9%) 1957calAD
2013calAD (75.5%) ...
Warning! Date may extend out of range - -139.362±58.4218BP
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Lost J2B R_F14C(1.2797,0.0066)
95.4% probability
1962 (15.1%) 1962calAD
1979 (76.9%) 1980calAD
1981 (3.5%) 1981calAD
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Lost J2C R_F14C(1.2926,0.0068)
95.4% probability
1962 (20.1%) 1962calAD
1979 (75.3%) 1980calAD
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Lost J3B R_F14C(1.0165,0.0072)
95.4% probability
1955 (20.3%) 1957calAD
2013calAD (75.1%) ...
Warning! Date may extend out of range - -131.463±56.8988BP
Radiocarbon determination (BP)
Calibrated date (calAD)


OxCal v4.4.4 Bronk Ramsey (2021); r:0.2; Post-bomb atmospheric NH3 curve (Hua et al 2021, Reimer et al 2020)
Lost J3C R_F14C(1.1847,0.0071)
95.4% probability
1958 (6.9%) 1959calAD
1965 (88.5%) 1989calAD
Radiocarbon determination (BP)
Calibrated date (calAD)

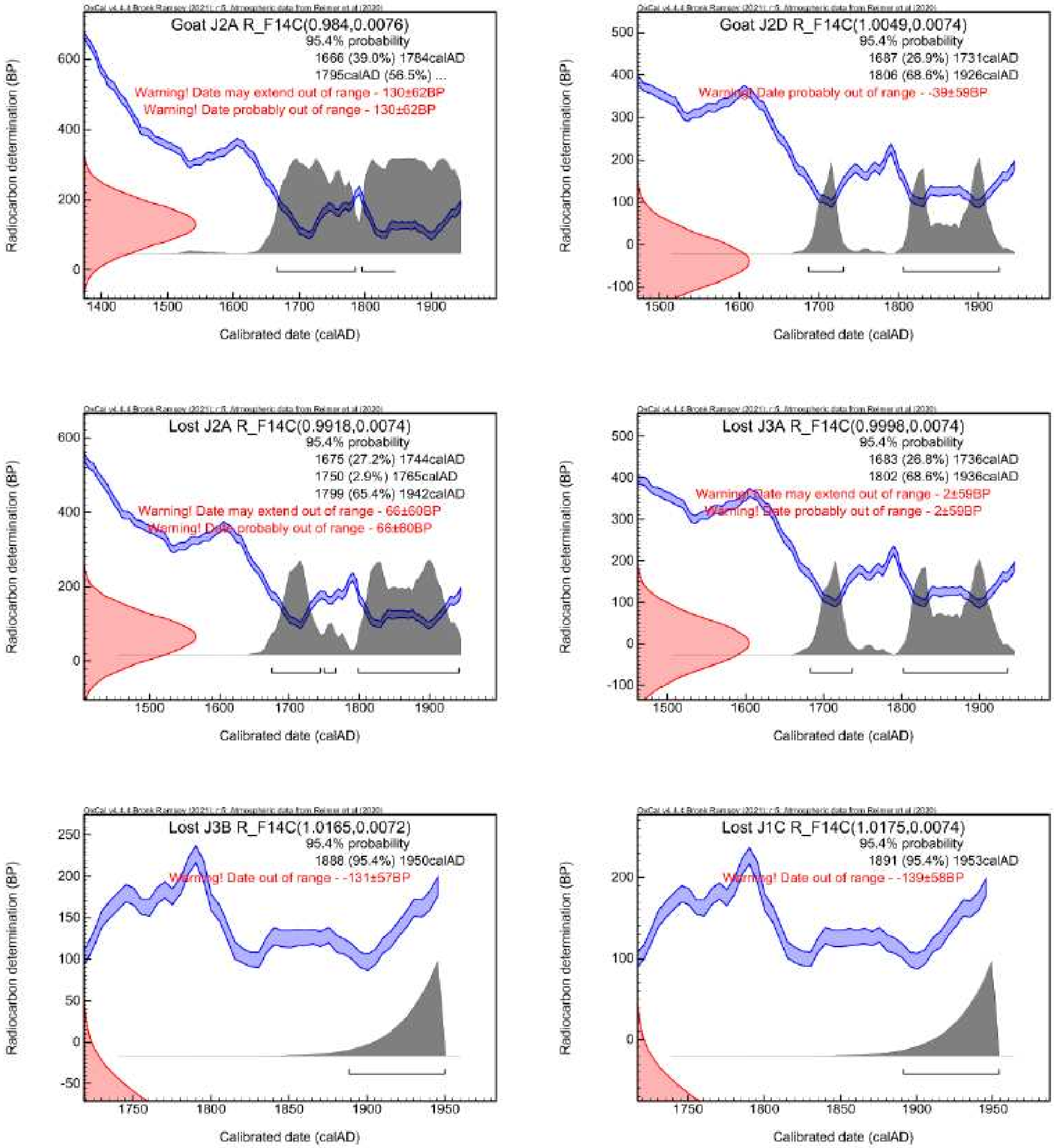


Figure S1. ^{14}C plots with calibration curve.

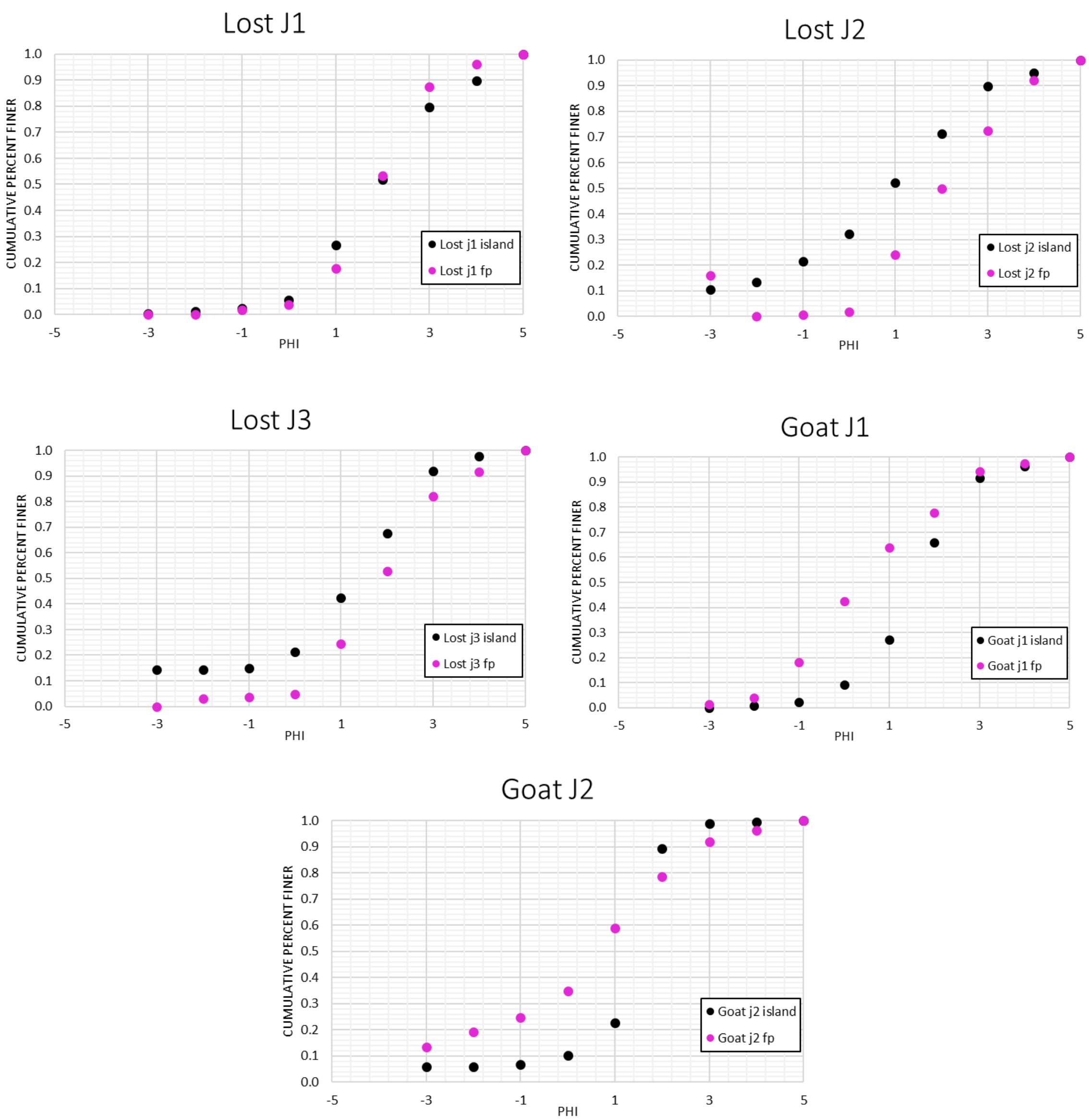


Figure S2. Grain size distribution curves at each accretionary island site. Pink indicates floodplain grain size grab sample and black indicates island grain size grab sample.

The supporting information included in this file provides visualization of exploratory analyses comparing variation in data by year and by segment. It also includes results of additional spatial heterogeneity metrics and subsequent analyses of which river corridor variables best predict each heterogeneity metric. As described in the main text, patch density was used as a primary metric of spatial heterogeneity for clarity, but the additional heterogeneity metrics are described further in the methods section and included as supplemental tables and figures.

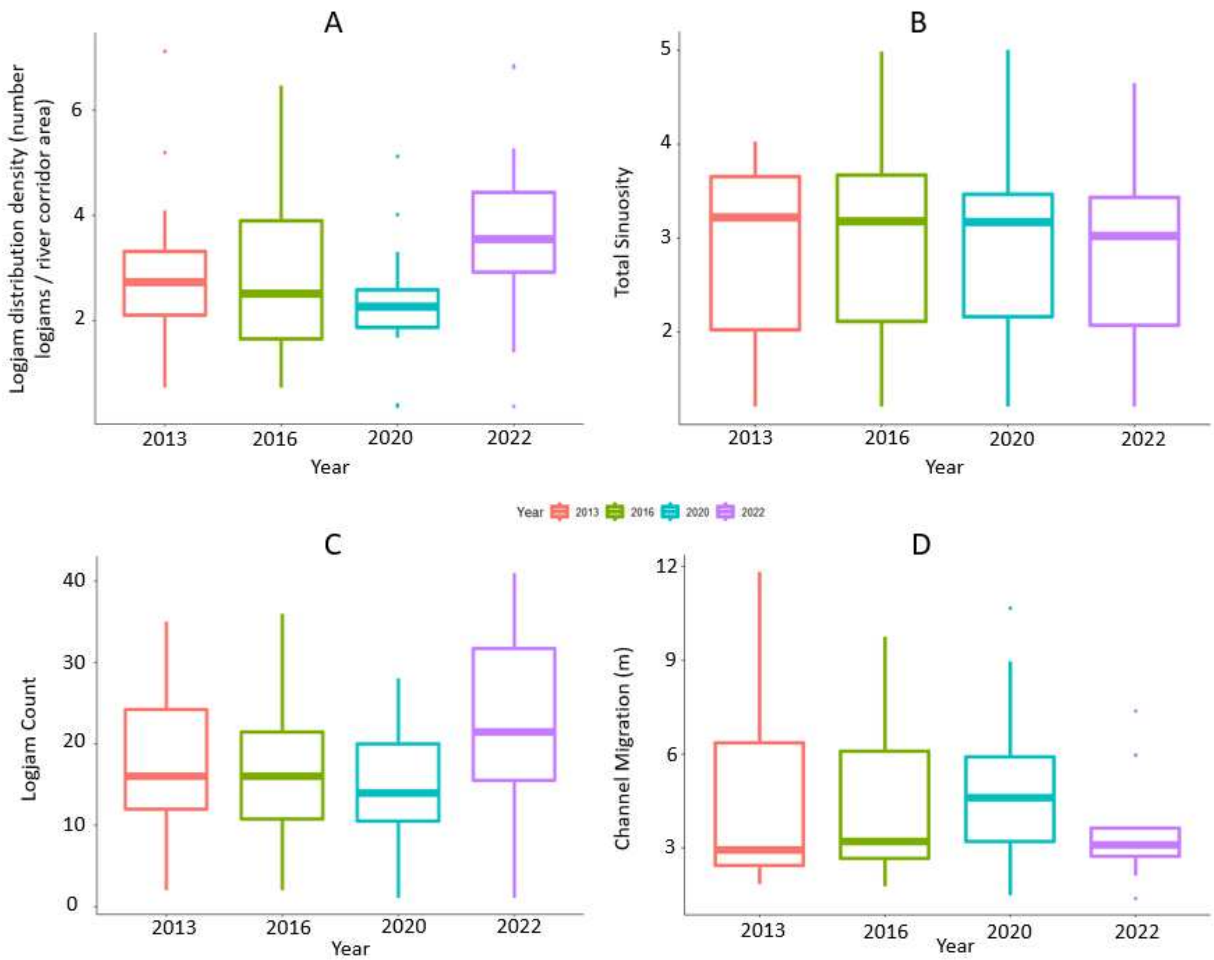


Figure S3. Median river corridor characteristic variables through time (logjam distribution density, logjam count, total sinuosity, and average channel migration). The river corridor variables represented here are the four that have data for each timestep. Each timestep has 16 data points.

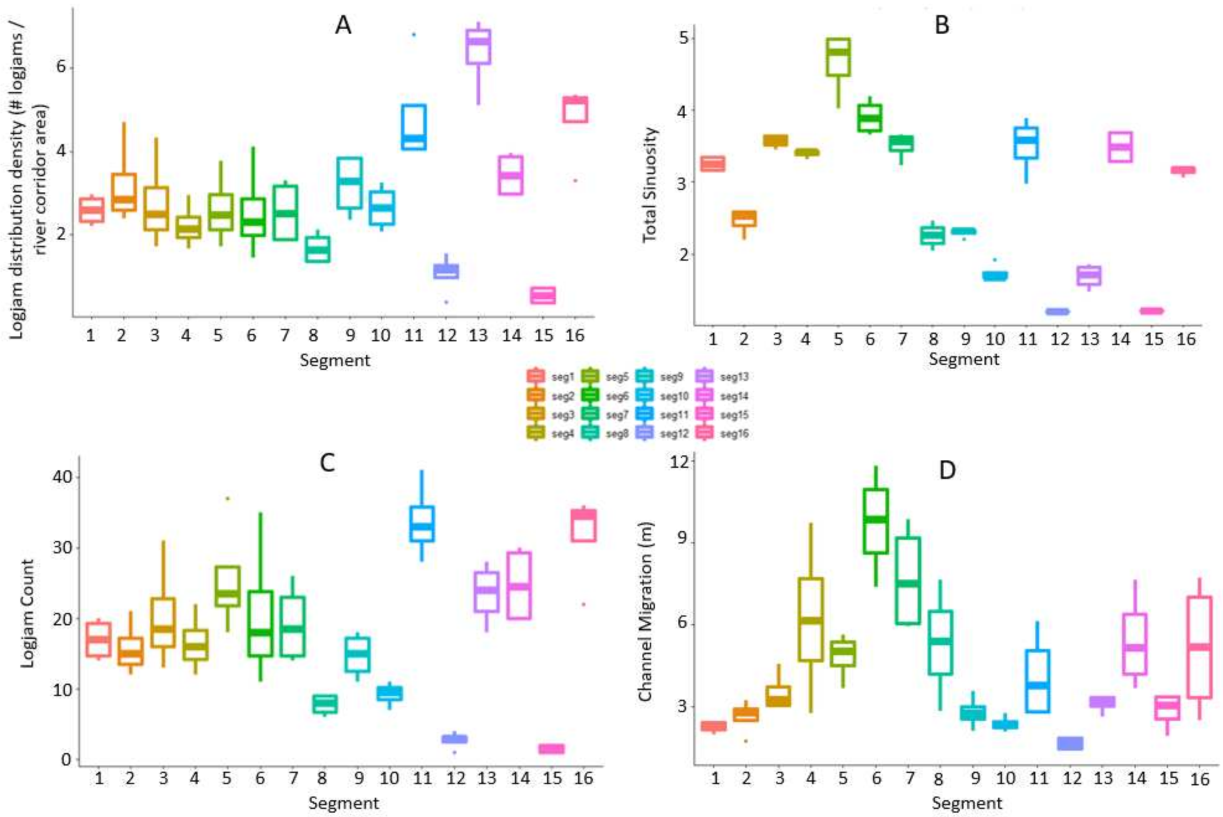


Figure S4. Variation in median river corridor character variables between segments (logjam distribution density, logjam count, total sinuosity, and average channel migration). The river corridor variables represented here are the four that have multiple data points over time for each segment. Each segment has four data points.

Table S5. Spatial heterogeneity metrics for segments within the study reach

Segment	Aggregation (%) (range 0,100)	Interspersion (%) (range 0,100)	Density (patches/100 ha) (range 0, 10^6 patches/100 ha)	Evenness (range 0,1)
seg1	59	72	943	0.90
seg2	64	64	686	0.83
seg3	65	66	720	0.83

seg4	60	71	883	0.89
seg5	62	69	753	0.89
seg6	63	70	736	0.91
seg7	65	74	658	0.94
seg8	61	75	877	0.92
seg9	62	72	781	0.91
seg10	65	71	740	0.86
seg11	57	78	1103	0.95
seg12	60	78	998	0.95
seg13	61	78	920	0.96
seg14	64	77	809	0.96
seg15	73	79	616	0.86
seg16	59	76	964	0.94

Table S6. Mixed-effect model selection for all heterogeneity metrics. Classes were moderately aggregated across the study site (Table S1). Proportion of beaver meadows and logjam distribution density as fixed effects in combination with the random effect of segment explain 46% of variation in the data (conditional R^2=0.47). All segments of our study reach have moderate to high interspersion (Table S1), indicating that there is some preference for one class to occur next to another. We found that a combination of the proportion of beaver meadows and total sinuosity best explained interspersion (conditional R^2=0.45). All the segments have high levels of Shannon's evenness (Table S1). This indicated that the river corridor has abundant, evenly distributed classes. The proportion of beaver meadows combined with the random effect was the best predictor of evenness (conditional R^2=0.37) and explained 37% of variation in evenness across the Swan River corridor. Although our methods differ somewhat from Iskin and Wohl (2023a) (DEM not included and default tool input values), these results align with the results from other natural floodplains that have moderate aggregation, high evenness, and high interspersion (Supplementary Figure S5).

Model	AIC_c	ΔAIC_c
Aggregation		
Random Effect + Beaver Meadow + Logjam Distribution Density	86.0	0

Random Effect + Beaver Meadow	86.2	0.22
Random Effect + Beaver Meadow + Total Sinuosity	88.3	2.35
Random Effect + No Fixed Effects	92.6	6.68
Patch density		
Random Effect+ Beaver Meadow + Logjam Distribution Density + Total Sinuosity	178.7	0
Random Effect+ Beaver Meadow + Logjam Distribution Density	182.9	4.23
Random Effect+ Beaver Meadow + Total Sinuosity	183.4	4.73
Random Effect + No Fixed Effects	200.9	22.16
Interspersion		
Random Effect + Beaver Meadow	89.8	0
Random Effect + Beaver Meadow + Total Sinuosity	90.4	.56
Random Effect + No Fixed Effects	98.6	8.71
Evenness		
Random Effect + No Fixed Effects	-40.6	0
Random Effect + Beaver Meadow	-38.7	1.89

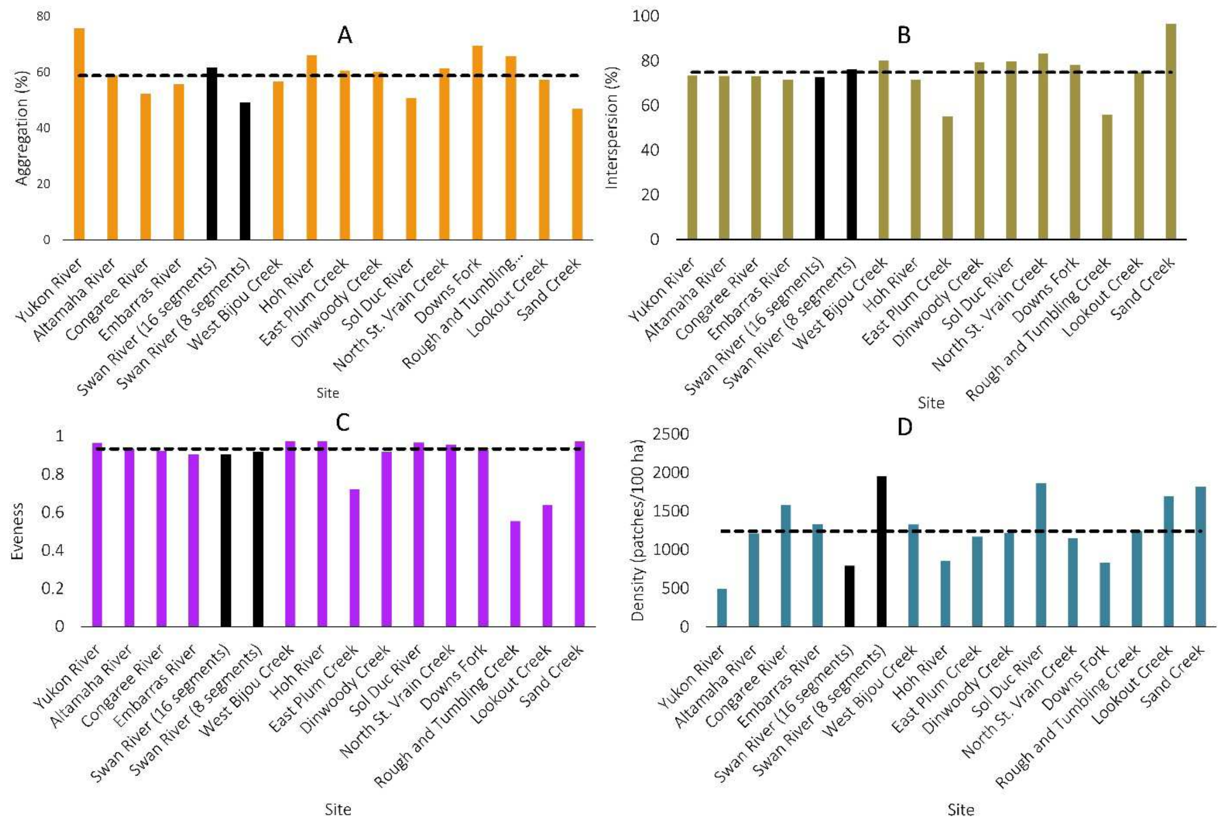


Figure S5. Comparison of Swan River corridor heterogeneity metrics to 14 other rivers in the United States from Iskin and Wohl (2023a). Sites differ in relative channel mobility, flashiness of flood peaks, and biome to provide insights into the fluvial and ecological processes that create and maintain spatial heterogeneity in natural river corridors. All non-Swan sites and the "Swan River (8 segments)" depict heterogeneity metrics calculated in Iskin and Wohl (2023a). "Swan River (16 segments)" depicts heterogeneity metrics calculated for the 16 segments used in this study. The dashed line represents the median value across all sites for each heterogeneity metric.