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The continuum of wood-induced channel bifurcations

Anna Marshall* and Ellen Wohl

Department of Geosciences, Colorado State University, Fort Collins, CO, United States

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EDITED BY
Mohammad Safeeq,
University of California, Merced, United States

REVIEWED BY
Masato Kobiyama,
Federal University of Rio Grande do Sul, Brazil
David E. Rheinheimer,
California Natural Resources Agency,
United States

*CORRESPONDENCE
Anna Marshall
✉ amarsh01@colostate.edu

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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. We 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. We 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). We use field data to quantify F/R and compare varying F/R to bifurcation types across sites. Our 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.

KEYWORDS

large wood, channel planform, bifurcations, anastomosing, river restoration, resilience, connectivity

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, Figures 1, 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). We 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. We briefly review the conditions facilitating the formation of anastomosing channels and the role of logjams in creating channel bifurcations.

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 1). Here, we 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. We 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).

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, 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

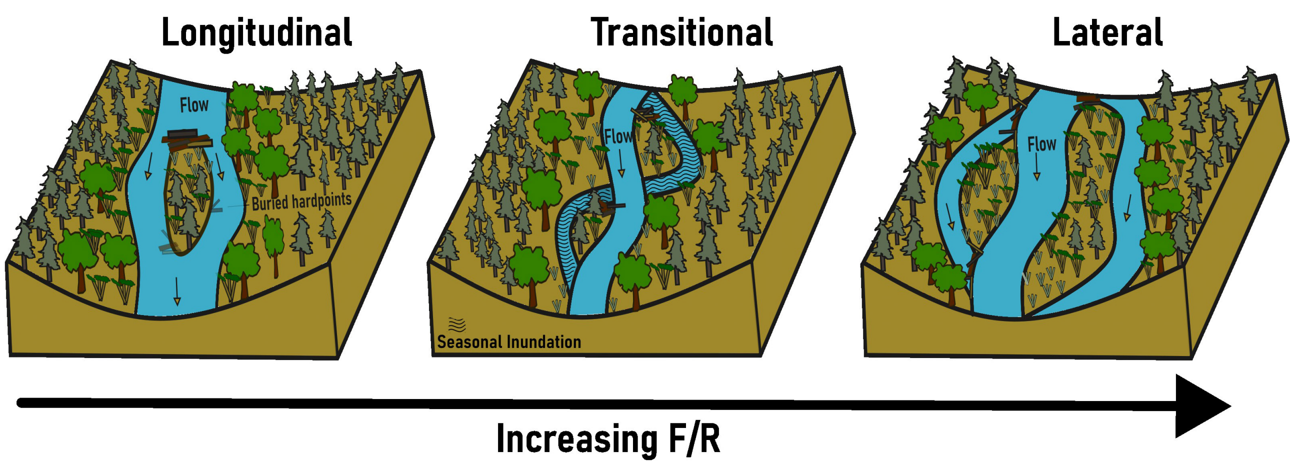

FIGURE 1
Conceptual illustration of jam-induced channel bifurcations. Lateral bifurcations (avulsive) form as a logjam forces overbank flow and bank erosion and the channel avulses laterally around the logjam. Longitudinal bifurcations (accretionary-bar splitting) form as a logjam creates lee deposition 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.

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

Our primary objective 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. We focus on systems where valley confinement, and thus hydrologically connected width, is not limited and where wood obstructions are abundant. We hypothesize that (1) wood-induced bifurcations exist as a continuum of different patterns in anastomosing rivers, as illustrated in Figures 1, 2, and the position of a river segment along this continuum correlates with F/R.

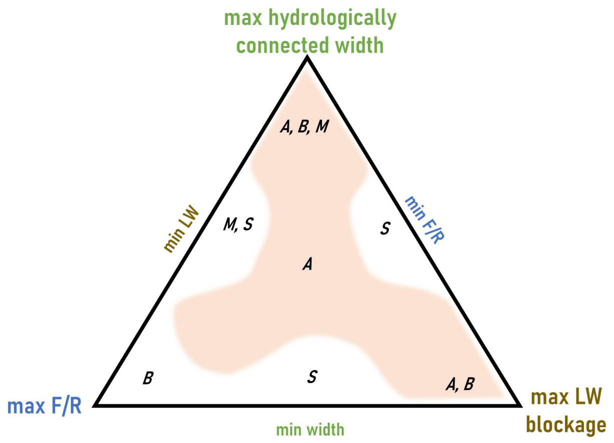

FIGURE 2
A ternary diagram illustrating how we conceptualize the interactions among three primary controls influencing wood-induced channel bifurcations. The maximum value of each of these controls occurs at a triangle vertex and the minimum at the mid-point of the opposite side of the triangle. Letters 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.

2. Study area

We focus our work across nine rivers and streams of diverse size within the montane and mesic montane zone of the Rocky Mountains in Colorado and Montana, USA. We 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.

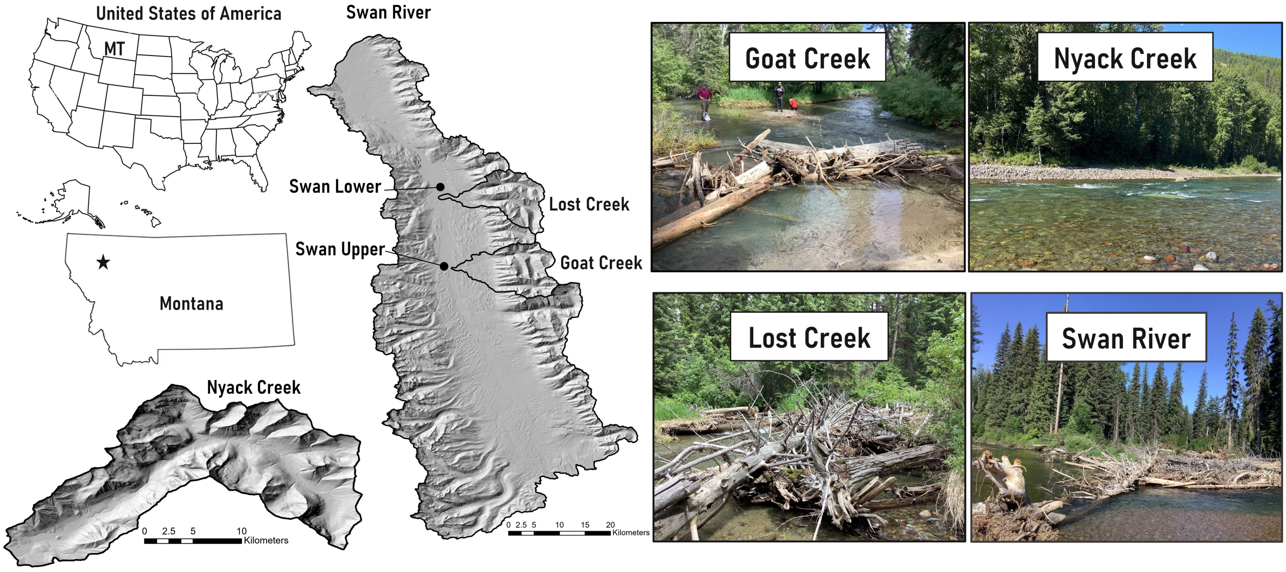

FIGURE 3
Montana field sites (Goat Creek, Lost Creek, Nyack Creek, Swan River). Note the different scale bars for the Nyack Creek and the Swan River watershed maps. Photos depict representative reach characteristics. We include two sites at Lost Creek, Goat Creek, and the Swan River in our results, but only show a photo of the upper reach for each site here.

2.1. Montana field sites

Study sites in Montana include Nyack Creek, the Swan River and two tributaries, Lost Creek and Goat Creek (Figure 3). We distinguish between upper and lower sites along the Swan River, Lost Creek, and Goat Creek. The Swan River (1,676 km^2 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.

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 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 km^2) lie within the watershed of the South Platte River in the Colorado Front

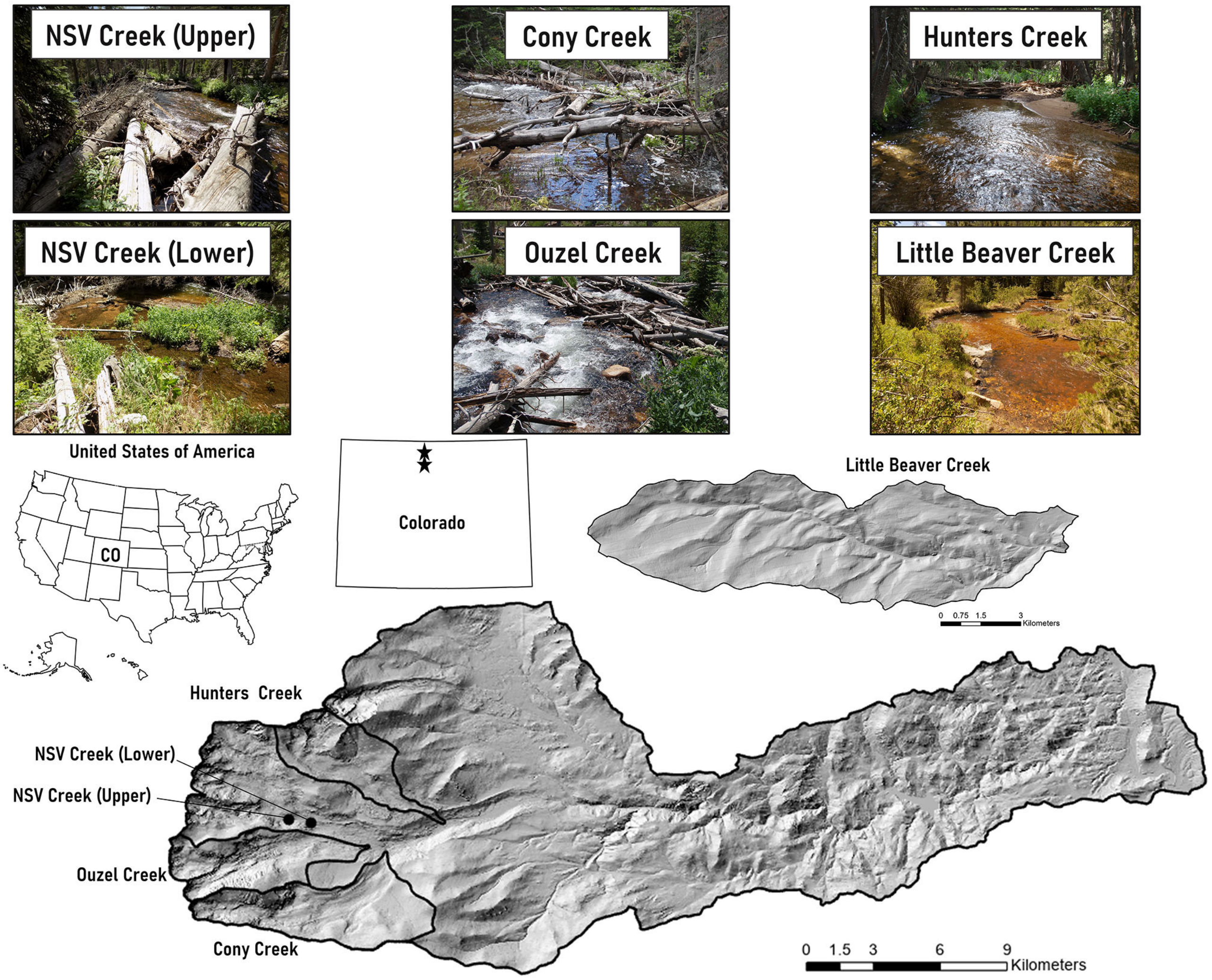

FIGURE 4
Colorado field sites (Cony Creek, Hunters Creek, Ouzel Creek, North Saint Vrain Creek, and Little Beaver Creek). Note different scale bars for Little Beaver Creek and the sites within the North Saint Vrain Creek watershed. Photos depict representative reach characteristics.

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).

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 10^1-10^2 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

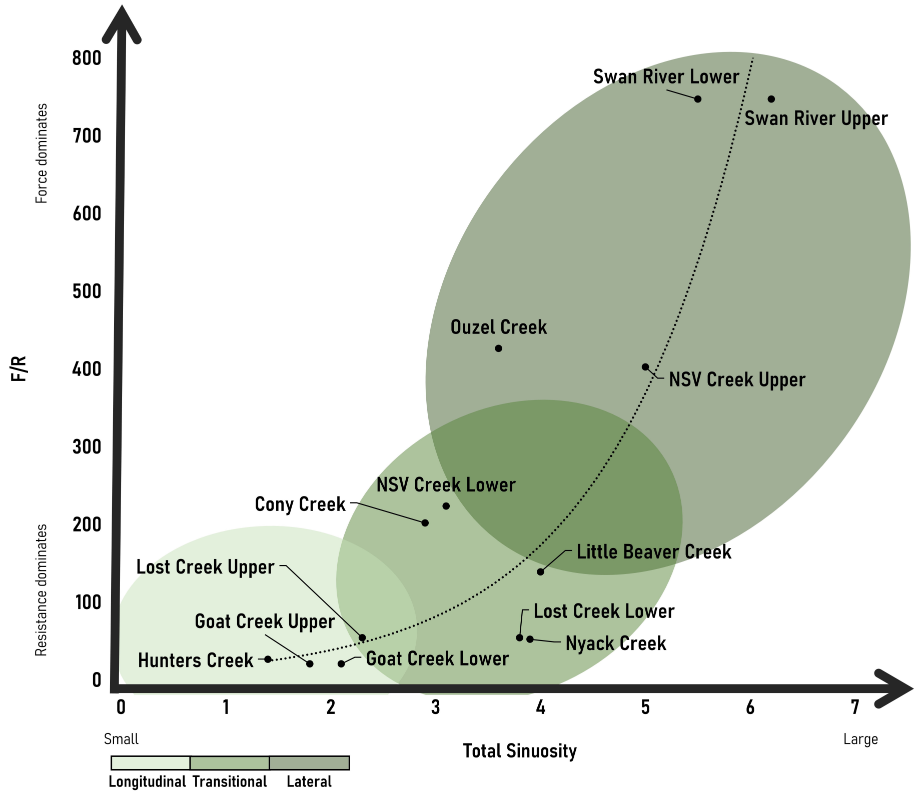

FIGURE 5
Observed continuum of channel bifurcations based on total sinuosity and F/R with an exponential line of best fit.

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 of our study sites, we characterized channel bifurcations and associated jams. We 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. We 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/).

We used our field data to quantify metrics of F and R. Our primary indicator of F is total stream power, 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). We 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. We used field measurements and LiDAR data to extract reach-scale channel gradient for each study site. We 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). We use F/R to determine how much force relative to resistance is acting at each site and to compare the relative ratios across sites. We did not attempt to calculate a dimensionally correct ratio with respect to units. Rather, we use this ratio as an indicator of potential excess energy available for bank and floodplain erosion associated with channel bifurcations.

We 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

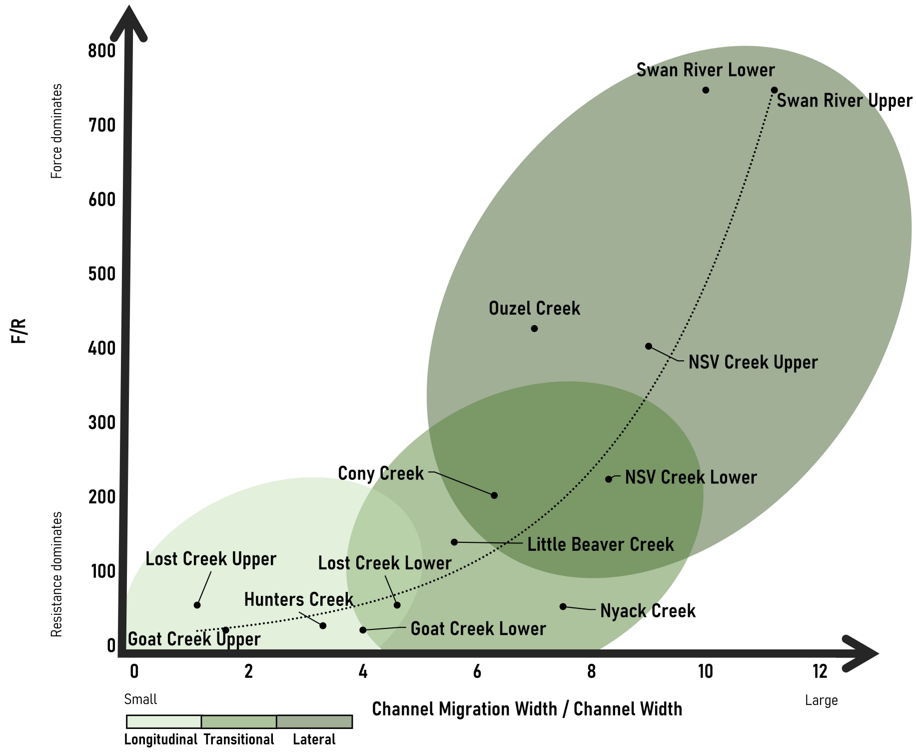

FIGURE 6
Observed continuum of channel bifurcations based on channel migration width/channel width and F/R with an exponential line of best fit.

averaged across 500-m reaches at our 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. We 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 1; smaller values indicate the longitudinal bifurcation endmember.

Given our small dataset, we ran both parametric and non-parametric statistical analyses to assess the relationship between F/R and bifurcations. We used RStudio to perform the statistical analyses (R Core Team., 2022). We ran a simple linear regression and calculate the Pearson correlation coefficient (r) from the multiple R-squared. We 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, we also calculated the Kendall rank correlation coefficient (τ) to ensure there is no impact from ties in our analyses (Hollander et al., 2014). All correlation coefficients were calculated using the *cor.test()* function in base R. We 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. We 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 our 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. Our full dataset is included as Supplementary Table 1. We plot F/R with both total sinuosity and channel migration width/channel width as proxies for the types of bifurcations. Our results for both suggest that bifurcation types exist as a continuum based on the ratio of F/R. We 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 2. 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 (Figures 5, 6). At lower values of F/R, jam bifurcations are transitional or longitudinal but are not lateral (Figures 5, 6). The relationship between F/R and bifurcation type is not linear, but it is progressive.

5. Discussion

Our results suggest that bifurcation types exist as a continuum based on F/R. We 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. We 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 highest transport capacity for wood. Visual observations in the field suggest that wood is regularly reworked within the Swan. We 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. We 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? We were not able to directly observe interactions between potentially transient wood accumulations and channel bifurcations. We 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. Our observations also indicate that diffuse overbank flow across the floodplain can concentrate into secondary channels over multiple seasons of peak flow. We 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. Our 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

Our 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 our 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.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AM and EW contributed to the conception and design of this study. AM collected field data in MT. EW collected field data in CO. Both authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2023.1155623/full#supplementary-material

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