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Key Points:
- Decadal-scale channel dynamism, as reflected in total sinuosity, corresponds to greater logjam presence and persistence through time
- Higher peak discharges correspond with a greater number and distribution of logjams, but not with greater channel dynamism
- Logjams, channel dynamism, and beaver meadows increase spatial heterogeneity, as reflected in landscape patch density

Supporting Information:
Supporting Information may be found in the online version of this article.

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Interactions of Logjams, Channel Dynamics, and Geomorphic Heterogeneity Within a River Corridor

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Abstract 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. We analyze 16 two-km 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. We hypothesize that (a) more dynamic river segments correlate with a greater presence, persistence, and distribution of logjams; (b) higher annual peak discharges correspond with greater channel dynamism and logjam presence and distribution; and (c) greater logjam distribution densities and channel dynamism are predictive of more spatially heterogeneous sections of the river corridor. Our 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. Our results 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.

Plain Language Summary Natural rivers inherently experience changes in their shape, channel locations, and floodplain compositions across space and time due to variations in water, sediment, and wood fluxes. We analyze 16 two-km segments of the Swan River in Montana, USA to examine relationships between logjams (the total count, persistence over a decade, and distribution density), how much the main and secondary channels move with time, and how patchy the river corridor is. We hypothesize that (a) where there is more channel movement, there will be more logjams; (b) years with higher flow correspond with more logjams and channel movement; and (c) logjams and channel movement play a role in explaining the patchiness of the river corridor. Our results suggest that there is a positive relationship between channel movement and logjams. Second, higher flows correspond to greater values of logjams, but not to channel movement. Third, persistent values of river corridor patchiness are explained logjam density, beaver meadows, and channel movement. Our results reflect the complex interactions of water, sediment, and wood in rivers 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. We 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 (Harvey & Gooseff, 2015; Hynes, 1975). 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 (Fryirs & Brierley, 2022; Scott et al., 2022; Wheaton et al., 2015; Wohl et al., 2019). Relationships between river corridor process and form determine the type, spatial distribution, and formation and maintenance of geomorphic units (Fryirs & Brierley, 2022) (Figure 1). We 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.

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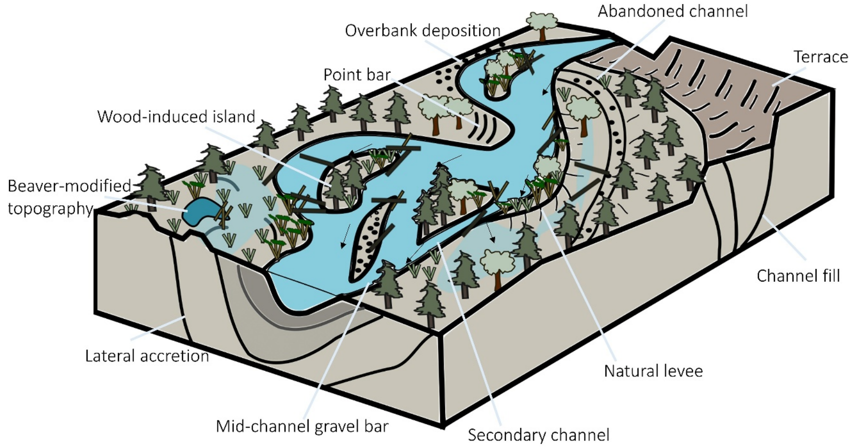

Figure 1. Block diagram of geomorphic units within a dynamic river corridor where logjams are both causing and responding to geomorphic heterogeneity across space and time. Black arrows represent flow direction.

Individual pieces of large wood (≥10-cm in diameter, ≥1-m in length) and logjams (≥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 (Collins et al., 2012; Marshall & Wohl, 2023; Montgomery & Abbe, 2006; Polvi & Wohl, 2013)
- Meander geometry and rate/direction of meander migration (Abbe & Montgomery, 1996; Daniels & Rhoads, 2004; Gurnell et al., 2002; Hickin, 1984; Piégay, 1993)
- 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 (Collins et al., 2012; Jeffries et al., 2003; Marshall & Wohl, 2023; Wohl, 2011; Wohl & Iskin, 2022)
- Floodplain roughness (Wohl, 2013, 2020)
- Channel-floodplain connectivity (Keys et al., 2018; Sear et al., 2010; Wohl, 2013)
- 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 (Collins et al., 2012; Scott & Wohl, 2018; Wyżga & Zawiejska, 2005). 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 & Heffernan, 2014); organic carbon storage (Lininger et al., 2018); hydrologic and other forms of connectivity (Ward & 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 (Klaver, 2018; Peipoch et al., 2015; Poff et al., 2007).

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 (Montgomery & Bolton, 2003; Sedell & Froggatt, 1984; 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 (Graf, 2006; Knox et al., 2022; Thoms, 2003). Removal of wood from the river corridor has caused a fundamental shift in channel and floodplain process and form (Figure 2; Wohl, 2013). With this loss in geomorphic heterogeneity comes a loss of river corridor function via disruption of

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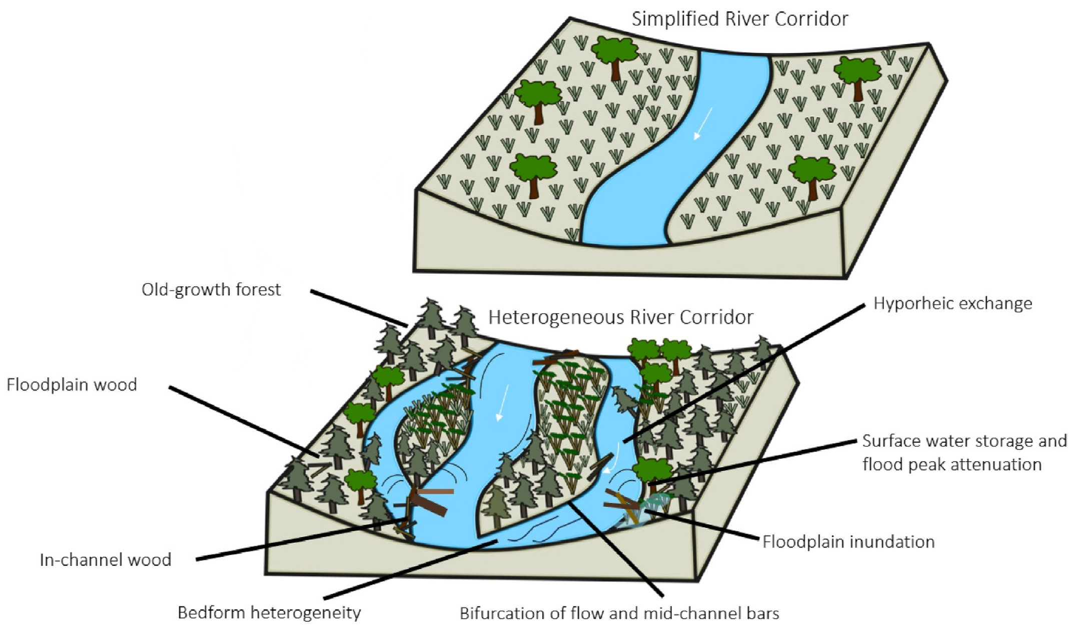

Figure 2. Illustrative example of a simplified river corridor where logjams have been historically removed (top) and a forested heterogeneous river corridor where logjams are present (bottom). White arrows indicate flow.

lateral, longitudinal, and vertical connectivity between aquatic, wetland, and terrestrial ecosystems (DeBoer et al., 2020; Kuiper et al., 2014; Tockner et al., 2010). Failure to adequately consider the historical effects of wood in river corridors, along with loss of these effects, distorts our understanding of contemporary river process and form.

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 we can more effectively restore function in river corridors that have lost substantial geomorphic heterogeneity. Through an evaluation of the interactions between logjams, channel dynamism, and geomorphic heterogeneity, here, we attempt to peel back layers in time and tease apart spatial details to investigate how form and process interact in a natural river corridor.

Our objective is to examine relations between logjams, channel movement, and spatial heterogeneity. Our data covers a range of spatial and temporal resolutions, which limits our ability to conduct a single, integrated analysis of the multiple variables that we examine. Consequently, we test three hypotheses that each focus on a limited number of variables. We hypothesize that (a) more dynamic sections of the river corridor will correlate with a greater presence, persistence, and distribution of logjams; (b) higher peak annual discharges will correspond with greater channel dynamism and logjam presence and distribution; and (c) 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 our hypotheses is that: (a) logjams promote channel migration, bifurcation, and avulsion, leading to a more dynamic channel through time; (b) 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 (c) logjams alter flow and sediment deposition patterns, creating and maintaining more spatially heterogeneous sections of the river corridor.

In the subsequent sections, we 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), we 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 our 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 Land Cover Change Index (J. 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 & 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 our data collection, we 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 our analyses, we segmented the reach into 2-km sub-reaches (Figure 3). Physical and vegetation characteristics of the Swan River are included in Table 1.

3. Methods

We 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 2 for collection dates). For analyses where higher spatial resolution was needed, our temporal range was limited. We 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 our hypotheses.

To provide spatial context for the measurements of logjams, geomorphic heterogeneity, and channel dynamism along our 32-km study reach, we 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 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). We focused on these segments for ground-based measurements. We subsequently expanded analyses to include an additional eight upstream segments. These segments were included because of anecdotal evidence of bank stabilization and large wood removal from the active channel. We included these sites to provide a greater range of values within some of the variables analyzed and thus potentially increase the power of our statistical analyses.

3.1. Logjams and Beaver Modifications

We conducted aerial logjam surveys using available Google Earth imagery between 2013 and 2022 (4 years of available imagery: 2013, 2016, 2020, and 2022). We mapped all logjams within the active channel that could be detected via the aerial imagery. We 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. We also noted the occurrence of persistent logjams that were continually present in the Google Earth imagery, in what we refer to as "sticky sites" (Wohl & Iskin, 2022). GPS coordinates of logjams were collected in the field during August 2022 to verify imagery identification.

We also manually identified active and remnant beaver meadows using Google Earth. 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.

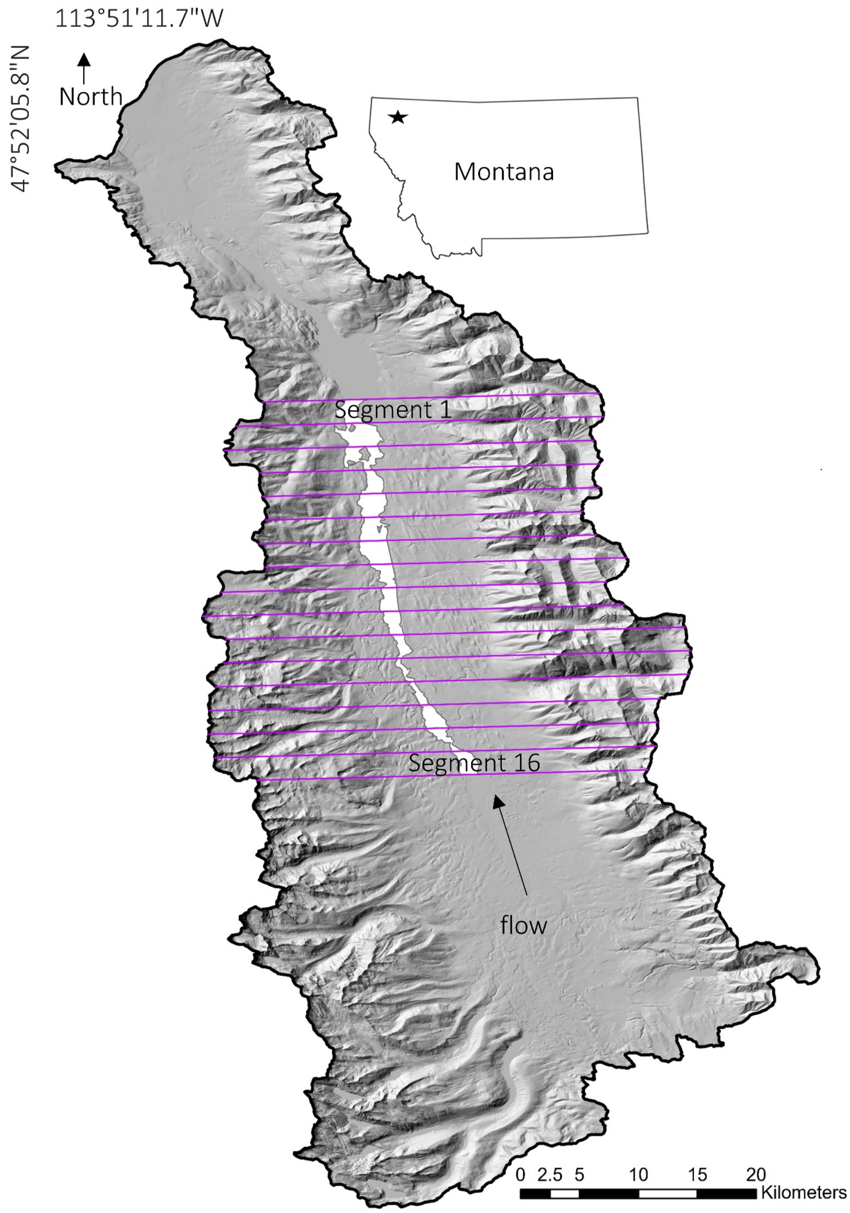

Figure 3. Study area within the Swan River catchment in northwestern Montana, USA. Perpendicular lines represent the 32-km reach extent, segmented at 2-km intervals to provide spatial context in data analysis. The white shaded area represents the floodplain extent of the Swan River through the study area.

3.2. 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, we 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). We followed existing methodologies using base flow conditions as a conservative delineation of planimetric change (O'Connor et al., 2003), given our goal of looking at relative channel change over time to understand which segments of our study area were the most dynamic.

Surface water extent was delineated for 2013, 2016, 2020, and 2022 to keep the timestep consistent with our wood surveys. Imagery collected for the National Agriculture Imagery Program (NAIP) was used when available (2013–2016) (Maxwell et al., 2017). For 2020 and 2022, cloud-free multispectral composite images were created

Table 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 and 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 and Hendrix (2010)
Soil type	Gravelly loamy sand	USDA (2023)
Dominant vegetation	Mesic montane conifer forests and wetlands, with some areas of subalpine forest	Antos and Habeck (1981)

in Google Earth Engine (GEE) (Gorelick et al., 2017) from Sentinel-2 imagery from average base flow months (August to October). Surface water was classified using the normalized difference water index (NDWI) (Gao, 1996) for NAIP imagery, and modified normalized difference water index (Xu, 2006) for Sentinel-2 imagery (Tobón-Marín & 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.

We delineated centerlines of our 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, our 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

Table 2
Data Used in Analyses

Variable	Time interval or time span	Number of data points (n)	Source data
Logjam distribution density[a]	2013, 2016, 2020, 2022	64 (16 segments for each year)	Google Earth imagery, field verification
Logjam count[b]	2013, 2016, 2020, 2022	64 (16 segments for each year)	Google Earth imagery, field verification
Logjam sticky sites (logjam persistence)[a]	Integrated based on 2013–2022	16	Google Earth imagery
Beaver meadows	Integrated based on 2013–2022	16	Google Earth imagery
Active channel migration[a]	2013, 2016, 2020, 2022	64 (16 segments for each year)	NAIP and Sentinel-2 imagery
Total sinuosity[a]	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

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

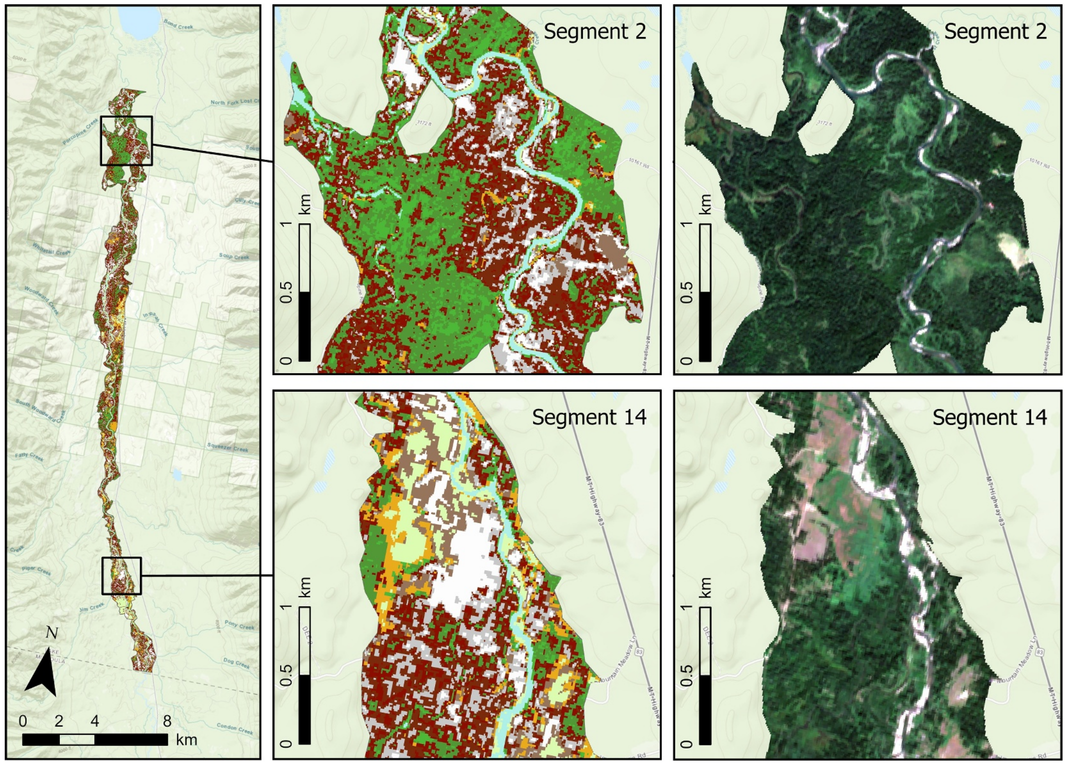

Figure 4. Unsupervised classification of the Swan River floodplain with detail insets of Segment 2 (top) and Segment 14 (bottom), including Sentinel-2 imagery mosaic. Colors here do not represent specific geomorphic units, but rather simply differentiate the pixels between the 10 classes that were identified by the classification tool.

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.

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

We obtained annual peak discharge from the nearest US Geological Survey gauge (12,370,000, Swan River near Bigfork, MT). The gauge is located below Swan Lake, a natural lake, into which our study site portion 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. We used annual peak discharge for the same time intervals used for analyzing channel position. We 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

We modified the workflow developed by Iskin and Wohl (2023a, 2023b) to quantify geomorphic heterogeneity for the Swan River corridor. We 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 and normalized difference moisture index rasters calculated from the Sentinel-2 mosaic in ArcGIS Pro (Figure 4). The Sentinel−2 mosaic was prepared for the approximate growing season in Montana, USA (June 1–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), we 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

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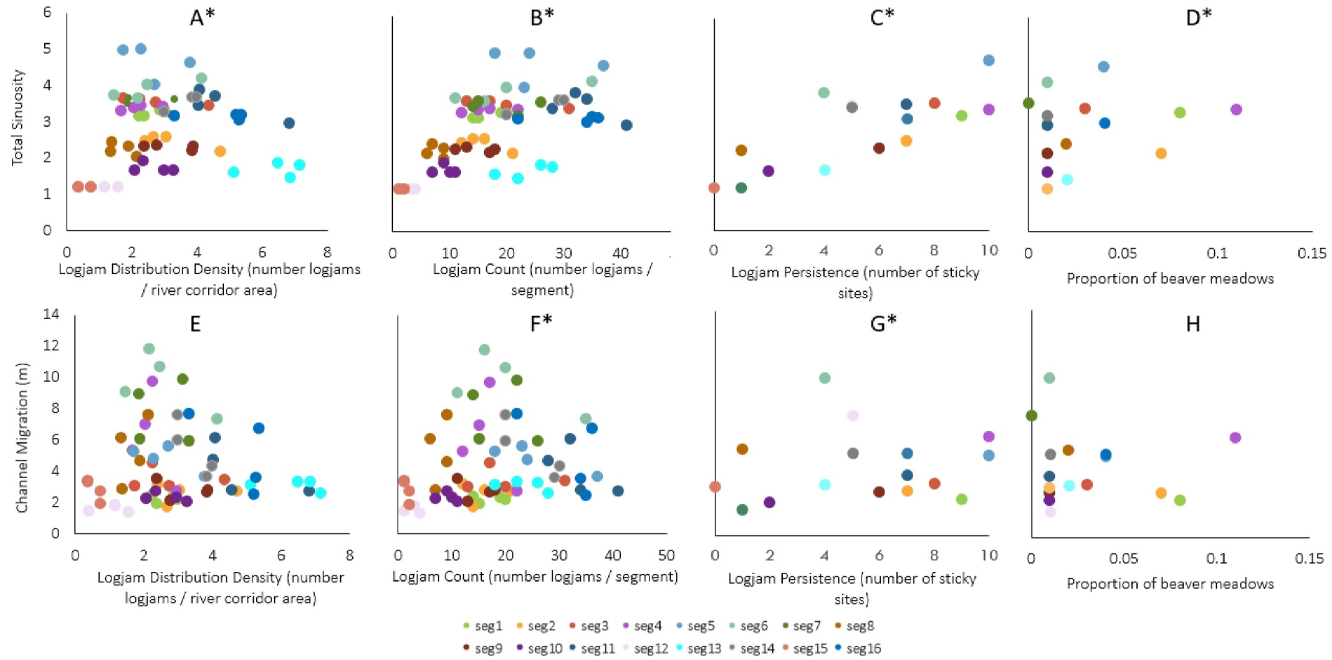

Figure 5. Relationship between logjam variables and channel dynamism variables. Panels (a–c) depict the relationship between total sinuosity and logjam variables. Panels (d–f) depict the relationship between average channel migration and logjam variables. Note, plot (c and f) (sticky sites) have fewer data available compared to the other plots because they have an integrated time step (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.

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, backswamp, natural levees, old-growth forest, wetlands, and beaver meadows (Figure 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 5). 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 (Hijmans, 2023; H. Wickham et al., 2019).

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. We calculated patch density as our primary metric of spatial heterogeneity for each of the 16 segments, where we 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). We 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 (Hesselbarth et al., 2019; McGarigal & Marks, 1995). Evenness is a measure of diversity and distribution of classes across a landscape (Hesselbarth et al., 2019). All heterogeneity metrics were calculated using the landscape metrics package (Hesselbarth et al., 2019) using the eight-neighbor rule (the Queen's case). For clarity, we 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 Supplemental Information.

3.4. Statistical Analyses

Statistical analyses were conducted in R (R Core Team, 2023). The data we collected span different time intervals (Table 2), and we conduct our statistical analyses to match the temporal and spatial scales of data we have for each of our hypotheses. We used an alpha (probability of rejecting the null hypothesis when the null hypothesis is true) of 0.05 in all statistical analyses.

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

To address hypotheses *i* and *ii*, we calculated both Pearson (r) and Kendall (τ) correlation coefficients. Given our small sample, we 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, we 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. We 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., 2014).

To address hypothesis *iii,* we 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, we accounted for a lack of independence in data from the same river corridor in our mixed-effect models by creating a random variable with the same value for all observations given that we did not have a grouping variable for heterogeneity data. We only used data from 2022 when addressing hypothesis *iii* to keep a consistent time step across all variables. We used AICc to select the model that best predicted each heterogeneity metric.

4. Results

We first conducted an exploratory analysis of logjam and channel dynamism variables through time. We 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 in Supporting Information S1). We did not include beaver meadows, logjam sticky sites, or heterogeneity metrics in our 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.

We also conducted an exploratory spatial analysis of logjam and channel dynamism variables across segments. We 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) (Figure S2 in Supporting Information S1). We 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 2). We 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, we 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.

Table 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 AIC_c 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

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

We examined correlations between logjam metrics and channel dynamism metrics (Figure 5). Our data showed a significant positive correlation between total sinuosity and logjam count ($r = 0.63$, $\tau = 0.45$, $p < 0.01$) (Figure 5b), a significant positive correlation between total sinuosity and logjam persistence ($r = 0.69$, $\tau = 0.47$, $p < 0.01$) (Figure 5c), and a weak positive correlation between total sinuosity and logjam distribution density ($r = 0.14$, $\tau = 0.12$, $p = 0.1$) (Figure 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 our hypothesis. We observed a weak but significant positive correlation between channel migration and logjam count ($r = 0.18$, $\tau = 0.21$, $p = 0.01$) (Figure 5f), a weak but insignificant positive correlation between channel migration and logjam sticky sites ($r = 0.11$, $\tau = 0.09$, $p = 0.6$) (Figure 5g), and no correlation between channel migration and logjam distribution density ($r = -0.07$, $\tau = 0.03$, $p = 0.7$) (Figure 5e). We reiterate that our 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.

We 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 ($r = 0.25$, $\tau = 0.18$, $p = 0.3$) and was not correlated with average channel migration ($r = -0.06$, $\tau = -0.009$, $p = 0.9$) (Figures 5d and 5h).

We identified 86 logjam sticky sites that persisted throughout the Google Earth imagery between 2013 and 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.

We 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 we expect to see more channel movement? We included segment as a random effect in our mixed effect models and found that our 16 segments are a strong indicator of random variation in the models, making it important to leave segment as a random effect in our 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 3). As the distribution density of logjams increases in the Swan River corridor, so does

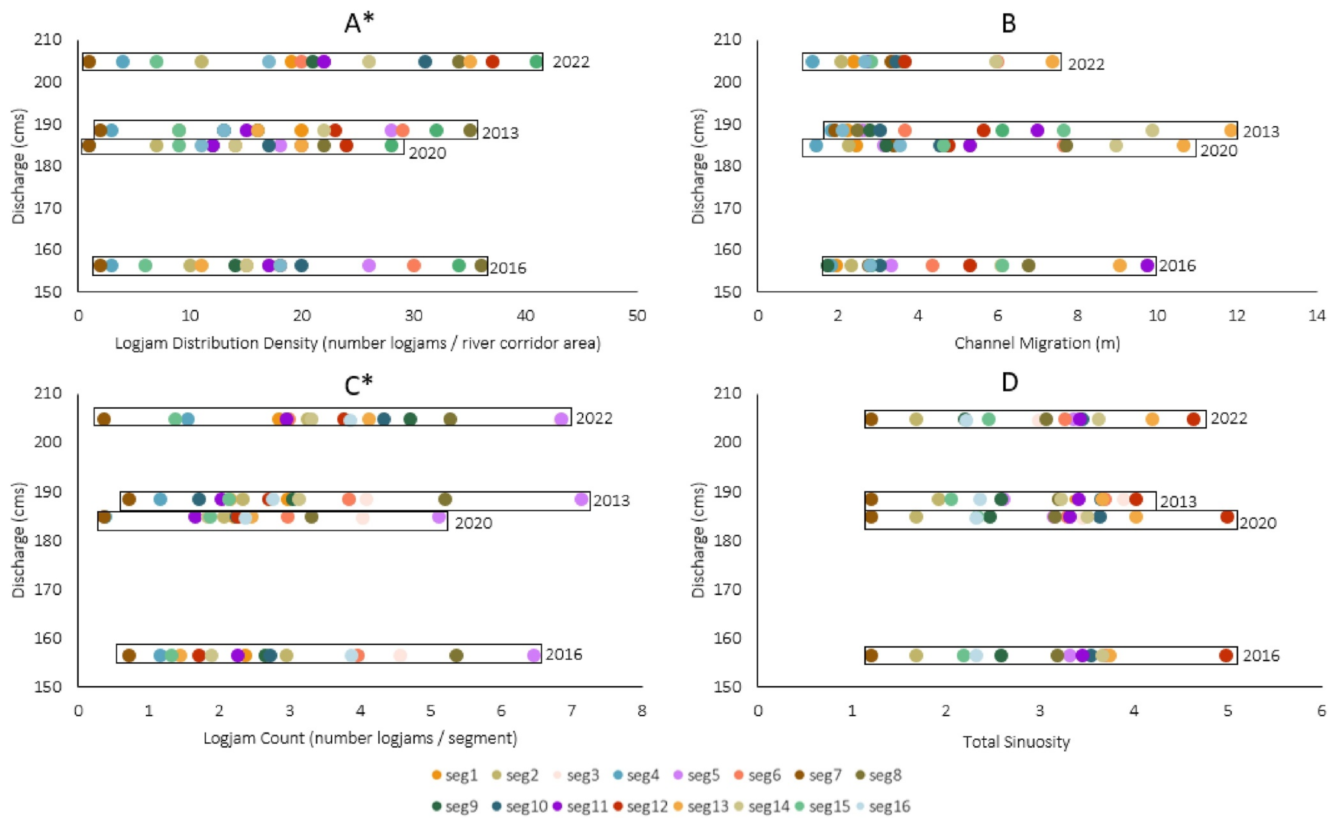

Figure 6. (b and d) Relationship between peak discharge and channel dynamism and (a and c) logjam variables. Note, comparison by segments for any given peak annual discharge is not applicable here given the use of a constant discharge rather than point-discharge measurements. Asterisks at top of each plot indicate where there is any correlation between variables, including weak correlations.

total sinuosity and average channel migration. An increase in logjam count also typically results in an increase in total sinuosity.

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

We tested the correlations between peak discharge and channel dynamism and logjam variables (Figure 6). Higher annual peak discharges were weakly but significantly correlated with greater logjam distribution densities ($r = 0.16$, $\tau = 0.19$, $p = 0.05$) and weakly but not significantly correlated with a greater number of logjams ($r = 0.14$, $\tau = 0.14$, $p = 0.1$) (Figures 6a and 6c). In the field, we 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 2013 was a 5-year flow recurrence interval, and peak discharge in 2016 was a 1-year flow recurrence interval.

We did not observe any significant correlation between annual peak discharge and channel migration ($r = -0.09$, $\tau = -0.07$, $p = 0.4$) or between peak annual discharge and total sinuosity ($r = -0.04$, $\tau = -0.04$, $p = 0.7$) (Figures 6b and 6d). In our mixed-effect models, we 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 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. We did not test the correlation between logjam

Table 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

persistence and discharge because our sticky site data are integrated over multiple years (2013–2022) and therefore cannot be associated with unique peak annual discharge values.

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*, we 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 our mixed-effect models was explained by the effect of spatial similarities in the data and we included a random effect in all models to account for this.

Patch density varied across the segments within our study area (Table S1 in Supporting Information 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). Logjam distribution density, beaver meadows, and total sinuosity, combined with the random effect, explained 39% of the variation in patch density (conditional $R^2 = 0.39$).

In summary, our 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

Our 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. We distill the interactions of logjams, channel dynamism, and spatial heterogeneity into a conceptual model (Figure 7). Our results suggest that these variables interact in a cascade of processes and feedbacks in which (a) high flows recruit and mobilize wood in the river corridor, (b) the presence, distribution, and persistence of logjams aid in the formation and movement of channels, as reflected by total sinuosity, and (c) 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 7).

Significant differences exist among segments of the Swan River corridor with respect to channel dynamism and logjams. As mentioned in the methods, we initially selected the downstream-most 8 segments of our study area based on the naturalness of the river corridor and the presence of abundant logjams in the active channel(s). We subsequently expanded analyses to include an additional eight upstream segments. These segments were included because of anecdotal evidence of bank stabilization and large wood removal from the active channel. We included these sites to provide a greater range of values within some of the variables analyzed. We

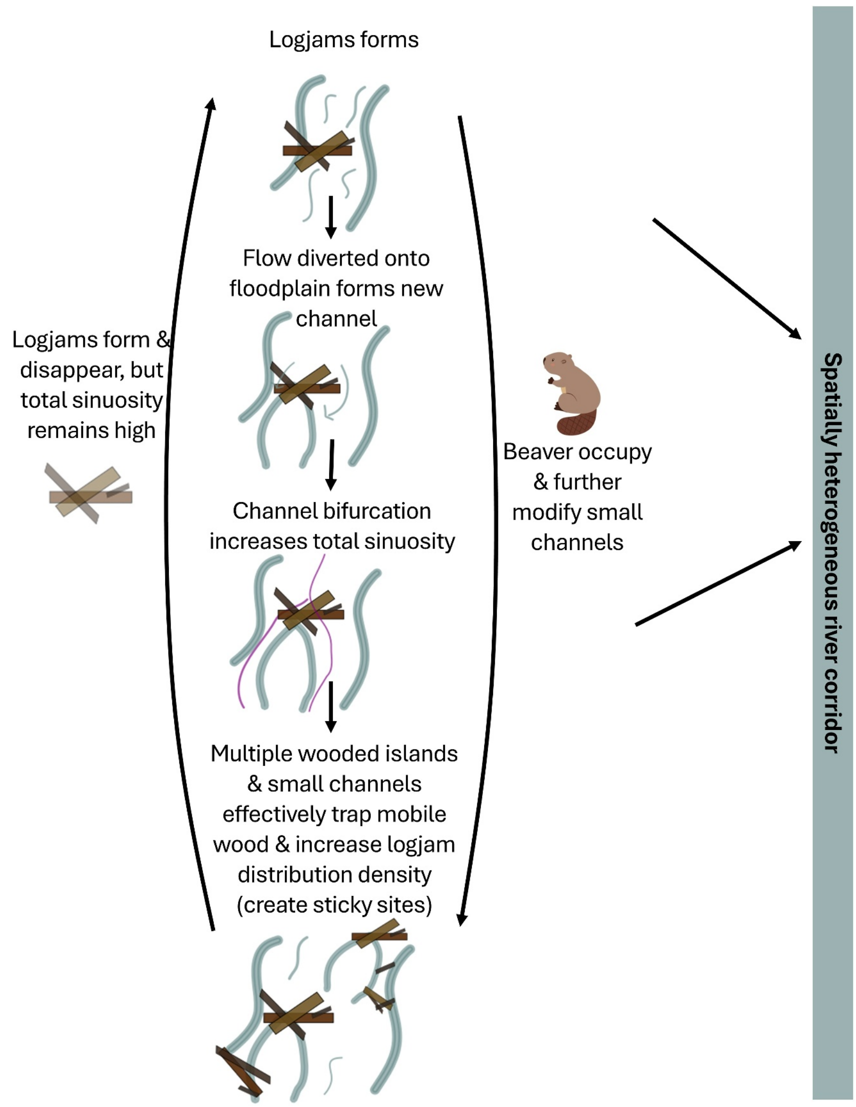

Figure 7. Schematic illustration of the river corridor interactions that we infer for the Swan River study site. Arrows indicate feedback between processes.

expected significant differences in the variables we analyzed between the upper 8 and lower 8 segments, but instead we found variation throughout the 16 segments. Although we added an additional eight segments upstream of our initial site selection to include segments that might include variation in river corridor variables due to human impacts, we were not able to distinguish with enough certainty which reaches were impacted and are unable to report those findings in our results. We 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, August 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. We 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 8 captures the variation in channel dynamism variables by segment. The differences we observed among segments facilitate the statistical analyses that indicate three key findings.

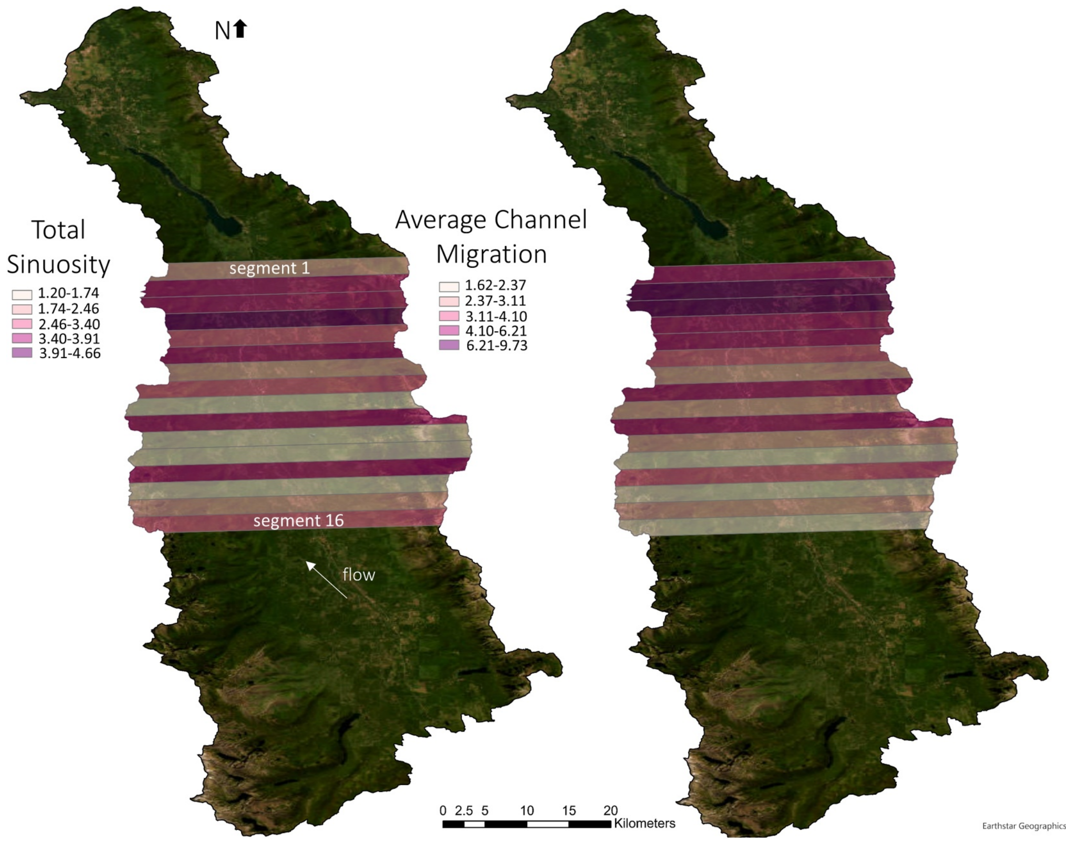

Figure 8. Total sinuosity and average channel migration values for each segment, averaged across years. Darker shades of pink correspond with greater values of total sinuosity or average channel migration and are conceptualized as more dynamic segments of the river corridor. Lighter shades of pink correspond 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

Our 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 & 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. We 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 we 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.

Figure 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 (4 m channel spanning logjam for scale). (b) New logjams transported onto the floodplain during peak discharge and pinned against existing floodplain forest (1 m measuring tape for scale). (c) More established channels at the same location in summer 2023 (4 m channel spanning logjam for scale). (d) Logjam that previously spanned the channel and burst during 2022 flows, redirecting water onto the floodplain (2.5 m person for scale).

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, our 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. We observed a newly inundated portion of the floodplain forest in July 2022 (Figure 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 we returned to the site in July 2023, we found new secondary channels as well as enlargement of the secondary channels that were present prior to 2022. We only observed this type of secondary channel formation in association with logjams that deflected flow onto the floodplain.

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). To interpret the third key finding, we compared patch density values calculated by Iskin and Wohl (2023a) for natural river corridors across the United States to our values for the Swan River (Figure 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 10). When comparing the full 16 segments of the Swan River to other locations in the U.S., we see a lower patch density. We 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, we opted to keep all

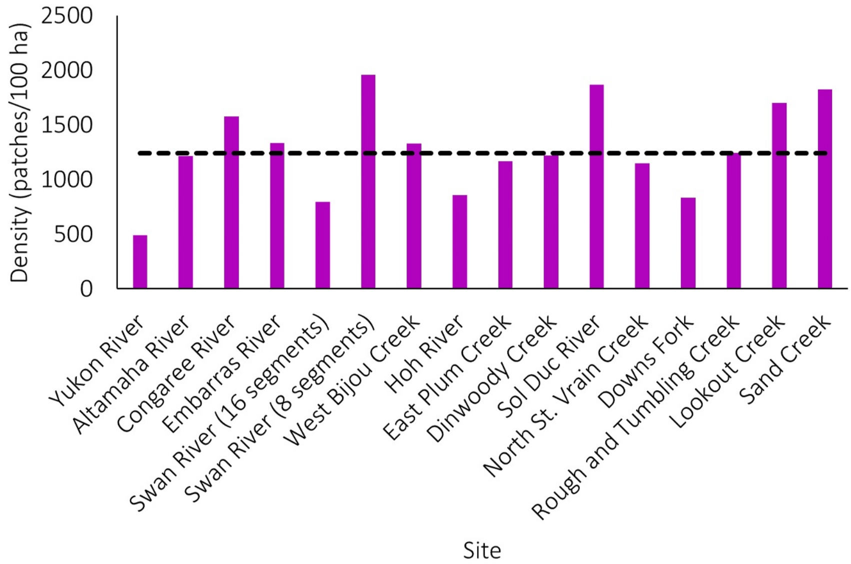

Figure 10. Comparison of Swan River corridor patch density to 14 other rivers in the United States from Iskin and Wohl (2023a). Sites differ in relative channel mobility, flashiness of flood peaks, and biome to provide insights into the fluvial and ecological processes that create and maintain spatial 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.

16 segments in our statistical analysis to both increase our statistical power and because we 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 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 our 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 our data points. Although we account for these effects in our statistical analyses, our 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 & Heffernan, 2014) and flow paths (Helton et al., 2014).

5.4. Implications for River Management

Our 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 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, we 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 & Iskin, 2022). We 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 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 9 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

Our main objective was to explore how logjams, the movement of channels, and geomorphic heterogeneity interact in a dynamic river corridor. We 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. Our 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., 2017, 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.

Data Availability Statement

The data analyzed for this paper are available as Marshall et al., 2023 and can be accessed via Dryad as Marshall et al. (2023) “Data Associated with “Interactions of logjams, channel dynamics, and geomorphic heterogeneity within a river corridor”” via the following link: https://doi.org/10.5061/dryad.k0p2ngff3. Google Earth Engine (Gorelick et al., 2017) was used to create and download NAIP and Sentinel-2 raster mosaics as well as for surface water extent mapping. ArcGIS Pro (Esri, 2023) was used with an academic license to run the spatial heterogeneity classification workflow and for average channel migration centerlines. R (R Core Team, 2023) was used to calculate heterogeneity metrics and conduct statistical analyses. A link to the scripts developed for analysis in GEE code as well as the scripts developed for calculating spatial heterogeneity metrics are available via Dryad as Marshall et al. (2023).

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References

Abbe, T. B., & Montgomery, D. R. (1996). Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research and Management*, *12*(2–3), 201–221. https://doi.org/10.1002/(SICI)1099-1646(199603)12:2/3<201::AID-RRR390>3.0.CO;2-A

Antos, J. A., & Habeck, J. R. (1981). Successional development in Abies grandis (Dougl.) Forbes forests in the Swan Valley, Western Montana. *Northwest Science*, *55*, 26–39.

Appling, A. P., & Heffernan, J. B. (2014). Nutrient limitation and physiology mediate the fine-scale (de)coupling of biogeochemical cycles. *The American Naturalist*, *184*(3), 384–406. https://doi.org/10.1086/677282

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823. https://doi.org/10.48550/arXiv.1406.5823

Beechie, T. J., Liermann, M., Pollock, M. M., Baker, S., & Davies, J. (2006). Channel pattern and river-floodplain dynamics in forested mountain river systems. *Geomorphology*, *78*(1–2), 124–141. https://doi.org/10.1016/j.geomorph.2006.01.030

Bellmore, J. R., Baxter, C. V., Martens, K., & Connolly, P. J. (2013). The floodplain food web mosaic: A study of its importance to salmon and steelhead with implications for their recovery. *Ecological Applications*, *23*(1), 189–207. https://doi.org/10.1890/12-0806.1

Boothroyd, R. J., Williams, R. D., Hoey, T. B., Barrett, B., & Prasojo, O. A. (2021). Applications of Google Earth Engine in fluvial geomorphology for detecting river channel change. *WIREs Water*, *8*(1), e21496. https://doi.org/10.1002/wat2.1496

Brooks, A. P., Brierley, G. J., & Millar, R. G. (2003). The long-term control of vegetation and woody debris on channel and flood-plain evolution: Insights from a paired catchment study in Southeastern Australia. *Geomorphology*, *51*(1–3), 7–29. https://doi.org/10.1016/s0169-555x(02)00323-9

Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed.). Springer.

Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, *139–140*, 460–470. https://doi.org/10.1016/j.geomorph.2011.11.011

Collins, B. D., Montgomery, D. R., & Haas, A. D. (2002). Historical changes in the distribution and functions of large wood in Puget Lowland rivers. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(1), 66–76. https://doi.org/10.1139/f01-199

Daniels, M. D., & Rhoads, B. L. (2004). Effect of large woody debris configuration on three-dimensional flow structure in two low-energy meander bends at varying stages. *Water Resources Research*, *40*(11), W11302. https://doi.org/10.1029/2004WR003181

DeBoer, J. A., Thoms, M. C., Delong, M. D., Parsons, M. E., & Casper, A. F. (2020). Heterogeneity of ecosystem function in an “Anthropocene” river system. *Anthropocene*, *31*, 100252. https://doi.org/10.1016/j.ancene.2020.100252

Egozi, R., & Ashmore, P. (2008). Defining and measuring braiding intensity. *Earth Surface Processes and Landforms*, *33*(14), 2121–2138. https://doi.org/10.1002/esp.1658

Esri. (2023). ArcGIS Pro [Software]. *Graphical Information Systems*. Retrieved from https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

Fryirs, K., & Brierley, G. (2022). Assemblages of geomorphic units: A building block approach to analysis and interpretation of river character, behaviour, condition and recovery. *Earth Surface Processes and Landforms*, *47*(1), 92–108. https://doi.org/10.1002/esp.5264

Gao, B. C. (1996). NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, *58*(3), 257–266. https://doi.org/10.1016/S0034-4257(96)00067-3

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Grabowski, R. C., Surian, N., & Gurnell, A. M. (2014). Characterizing geomorphological change to support sustainable river restoration and management. *WIREs Water*, *1*(5), 483–512. https://doi.org/10.1002/wat2.1037

Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, *79*(3), 336–360. https://doi.org/10.1016/j.geomorph.2006.06.022

Gurnell, A., Tockner, K., Edwards, P., & Petts, G. (2005). Effects of deposited wood on biocomplexity of river corridors. *Frontiers in Ecology and the Environment*, *3*(7), 377–382. https://doi.org/10.1890/1540-9295(2005)003[0377:EODWOB]2.0.CO;2

Gurnell, A. M., Piégay, H., Swanson, F. J., & Gregory, S. V. (2002). Large wood and fluvial processes. *Freshwater Biology*, *47*(4), 601–619. https://doi.org/10.1046/j.1365-2427.2002.00916.x

Harvey, J., & Gooseff, M. (2015). River corridor science: Hydrologic exchange and ecological consequences from bedforms to basins. *Water Resources Research*, *51*(9), 6893–6922. https://doi.org/10.1002/2015WR017617

He, H. S., DeZonia, B. E., & Mladenoff, D. J. (2000). An aggregation index (AI) to quantify spatial patterns of landscapes. *Landscape Ecology*, *15*(7), 591–601. https://doi.org/10.1023/A:1008102521322

Helton, A. M., Poole, G. C., Payn, R. A., Izurieta, C., & Stanford, J. A. (2014). Relative influences of the river channel, floodplain surface, and alluvial aquifer on simulated hydrologic residence time in a montane river floodplain. *Geomorphology*, *205*, 17–26. https://doi.org/10.1016/j.geomorph.2012.01.004

Hesselbarth, M. H. K., Sciaini, M., With, K. A., Wiegand, K., & Nowosad, J. (2019). Landscapemetrics: An open-source R tool to calculate landscape metrics. *Ecography*, *42*(10), 1648–1657. https://doi.org/10.1111/ecog.04617

Hickin, E. J. (1984). Vegetation and river channel dynamics. *Canadian Geographies / Géographies Canadiennes*, *28*(2), 111–126. https://doi.org/10.1111/j.1541-0064.1984.tb00779.x

Hijmans, R. (2023). terra: Spatial data analysis. R package version 1.7-39. Retrieved from https://CRAN.R-project.org/package=terra

Hofmann, M. H., & Hendrix, M. S. (2010). Depositional processes and the inferred history of ice-margin retreat associated with the deglaciation of the Cordilleran Ice Sheet: The sedimentary record from Flathead Lake, Northwest Montana, USA. *Sedimentary Geology*, *223*(1–2), 61–74. https://doi.org/10.1016/j.sedgeo.2009.10.004

Hong, L. B., & Davies, T. R. H. (1979). A study of stream braiding. *GSA Bulletin*, *90*(12_Part_II), 1839–1859. https://doi.org/10.1130/GSAB-P2-90-1839

Hynes, H. B. N. (1975). The stream and its valley. *SIL Proceedings, 1922–2010*, *19*(1), 1–15. https://doi.org/10.1080/03680770.1974.11896033

Iskin, E., & Wohl, E. (2024). Interpreting floodplain heterogeneity: Using field data to understand unsupervised floodplain classifications. *Journal of Hydrology*, *628*, 130508. https://doi.org/10.1016/j.jhydrol.2023.130508

Iskin, E. P., & Wohl, E. (2023a). Beyond the case study: Characterizing natural floodplain heterogeneity in the United States. *Water Resources Research*, *59*(8), e2023WR035162. https://doi.org/10.1029/2023WR035162

Iskin, E. P., & Wohl, E. (2023b). Quantifying floodplain heterogeneity with field observation, remote sensing, and landscape ecology: Methods and metrics. *River Research and Applications*, *39*(5), 911–929. https://doi.org/10.1002/rra.4109

Jeffries, R., Darby, S. E., & Sear, D. A. (2003). The influence of vegetation and organic debris on flood-plain sediment dynamics: Case study of a low-order stream in the new forest, England. *Geomorphology*, *51*(1), 61–80. https://doi.org/10.1016/S0169-555X(02)00325-2

Keys, T. A., Govenor, H., Jones, C. N., Hession, W. C., Hester, E. T., & Scott, D. T. (2018). Effects of large wood on floodplain connectivity in a headwater Mid-Atlantic stream. *Ecological Engineering*, *118*, 134–142. https://doi.org/10.1016/j.ecoleng.2018.05.007

Klaver, I. J. (2018). Reclaiming rivers from homogenization: Meandering and Riverspheres. In R. Rozzi, R. H. May Jr., F. S. Chapin III, F. Massardo, M. Gavin, I. Klaver, et al. (Eds.), *From biocultural homogenization to biocultural conservation* (pp. 49–69). Springer International Publishing (Ecology and Ethics). https://doi.org/10.1007/978-3-319-99513-7_3

Knox, R. L., Morrison, R. R., & Wohl, E. E. (2022). A river ran through it: Floodplains as America's newest relict landform. *Science Advances*, *8*(25), eabo1082. https://doi.org/10.1126/sciadv.abo1082

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*(260), 583–621. https://doi.org/10.1080/01621459.1952.10483441

Kuiper, J. J., Janse, J. H., Teurlincx, S., Verhoeven, J. T. A., & Alkemade, R. (2014). The impact of river regulation on the biodiversity intactness of floodplain wetlands. *Wetlands Ecology and Management*, *22*(6), 647–658. https://doi.org/10.1007/s11273-014-9360-8

Lesica, P. (1996). Using fire history models to estimate proportions of old growth forest in Northwest Montana, USA. *Biological Conservation*, *77*(1), 33–39. https://doi.org/10.1016/0006-3207(95)00130-1

Lininger, K. B., Wohl, E., & Rose, J. R. (2018). Geomorphic controls on floodplain soil organic carbon in the Yukon flats, interior Alaska, from reach to river basin scales. *Water Resources Research*, *54*(3), 1934–1951. https://doi.org/10.1002/2017WR022042

MacDonald, L. H., & Hoffman, J. A. (1995). Causes of peak flows in Northwestern Montana and Northeastern Idaho. *Water Resources Bulletin*, *31*(1), 79–95. https://doi.org/10.1111/j.1752-1688.1995.tb03366.x

Marshall, A., & Wohl, E. (2023). The continuum of wood-induced channel bifurcations. *Frontiers in Water*, *5*, 1155623. https://doi.org/10.3389/frwa.2023.1155623

Marshall, A., Wohl, E., Iskin, E., & Zeller, L. (2023). Data associated with interactions of logjams, channel dynamics, and geomorphic heterogeneity within a river corridor. https://doi.org/10.5061/dryad.k0p2ngff3

Maxwell, A. E., Warner, T. A., Vanderbilt, B. C., & Ramezan, C. A. (2017). Land cover classification and feature extraction from National Agriculture Imagery Program (NAIP) Orthoimagery: A review. *Photogrammetric Engineering and Remote Sensing*, *83*(11), 737–747. https://doi.org/10.14358/PERS.83.10.737

McGarigal, K., & Marks, B. J. (1995). FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure. In *General Technical Report PNW-GTR-351* (Vol. 122, p 351). U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/PNW-GTR-351

Montgomery, D. R., & Abbe, T. B. (2006). Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest Valley, Queets River, Washington, USA. *Quaternary Research*, *65*(1), 147–155. https://doi.org/10.1016/j.yqres.2005.10.003

Montgomery, D. R., & Bolton, S. M. (2003). 3. Hydrogeomorphic variability and river restoration.

O'Connor, J. E., Jones, M. A., & Haluska, T. L. (2003). Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology*, *51*(1–3), 31–59. https://doi.org/10.1016/S0169-555X(02)00324-0

Peipoch, M., Brauns, M., Hauer, F. R., Weitere, M., & Valett, H. M. (2015). Ecological simplification: Human influences on riverscape complexity. *BioScience*, *65*(11), 1057–1065. https://doi.org/10.1093/biosci/biv120

Piégay, H. (1993). Nature, mass and preferential sites of coarse woody debris deposits in the lower Ain Valley (Mollon Reach), France. *Regulated Rivers: Research and Management*, *8*(4), 359–372. https://doi.org/10.1002/rrr.3450080406

Poff, N. L. R., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(14), 5732–5737. https://doi.org/10.1073/pnas.0609812104

Polvi, L. E., & Wohl, E. (2013). Biotic drivers of stream planform: Implications for understanding the past and restoring the future. *BioScience*, *63*(6), 439–452. https://doi.org/10.1525/bio.2013.63.6.6

PRISM Climate Group (PRISM). (2022). United States average total precipitation, 1991-2020 (800m; ASCIWe Grid) [Dataset]. *Precipitation data for the continental United States. Oregon State University*. Retrieved from https://prism.oregonstate.edu/normals/

R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Rowland, J. C., Shelef, E., Pope, P. A., Muss, J., Gangodagamage, C., Brumby, S. P., & Wilson, C. J. (2016). A morphology independent methodology for quantifying plainview river change and characteristics from remotely sensed imagery. *Remote Sensing of Environment*, *184*, 212–228. https://doi.org/10.1016/j.rse.2016.07.005

Scott, D. N., Shahverdian, S., Flitcroft, R., & Wohl, E. (2022). Geomorphic heterogeneity as a framework for assessing river corridor processes and characteristics. *River Research and Applications*, *38*(10), 1893–1901. https://doi.org/10.1002/rra.4036

Scott, D. N., & Wohl, E. E. (2018). Natural and anthropogenic controls on wood loads in river corridors of the Rocky, Cascade, and Olympic Mountains, USA. *Water Resources Research*, *54*(10), 7893–7909. https://doi.org/10.1029/2018WR022754

Sear, D. A., Millington, C., Kitts, D., & Jeffries, R. (2010). Logjam controls on channel: Floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. *Geomorphology*, *116*(3–4), 305–319. https://doi.org/10.1016/j.geomorph.2009.11.022

Sedell, J. R., & Froggatt, J. L. (1984). Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, U. S. A., from its floodplain by snagging and streamside forest removal. *SIL Proceedings, 1922–2010*, *22*(3), 1828–1834. https://doi.org/10.1080/03680770.1983.11897581

Stanford, J. A., Lorang, M. S., & Hauer, F. R. (2005). The shifting habitat mosaic of river ecosystems. *SIL Proceedings, 1922-2010*, *29*(1), 123–136. https://doi.org/10.1080/03680770.2005.11901979

Thoms, M. C. (2003). Floodplain–river ecosystems: Lateral connections and the implications of human interference. *Geomorphology*, *56*(3), 335–349. https://doi.org/10.1016/S0169-555X(03)00160-0

Tobón-Marín, A., & Cañón Barriga, J. (2020). Analysis of changes in rivers planforms using google Earth engine. *International Journal of Remote Sensing*, *41*(22), 8654–8681. https://doi.org/10.1080/01431161.2020.1792575

Tockner, K., Lorang, M. S., & Stanford, J. A. (2010). River flood plains are model ecosystems to test general Hydrogeomorphic and ecological concepts. *River Research and Applications*, *26*(1), 76–86. https://doi.org/10.1002/rra.1328

USA National Phenology Network. (2023). Phenology visualization tool. Retrieved from https://www.sciencebase.gov/catalog/item/60c2ee5bd34e86b93896a6d1

USDA. (2023). Natural resource conservation Service web soil survey. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/

U.S. Geological Survey (USGS). (2021). USGS 1/3 arc second n48w114 20210607. Retrieved from https://www.usanpn.org/data/visualizations

U.S. Geological Survey (USGS). (2023). StreamStats. Retrieved from https://streamstats.usgs.gov/ss/

Ward, J. V., & Stanford, J. A. (1995). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research and Management*, *11*(1), 105–119. https://doi.org/10.1002/rrr.3450110109

Ward, J. V., Tockner, K., & Schiemer, F. (1999). Biodiversity of floodplain river ecosystems: Ecotones and connectivity. *Regulated Rivers: Research & Management*, *15*(1–3), 125–139. https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<125::AID-RRR523>3.0.CO;2-E

Wheaton, J. M., Fryirs, K. A., Brierley, G., Bangen, S. G., Bouwes, N., & O'Brien, G. (2015). Geomorphic mapping and taxonomy of fluvial landforms. *Geomorphology*, *248*, 273–295. https://doi.org/10.1016/j.geomorph.2015.07.010

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., et al. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wickham, J., Stehman, S. V., Sorenson, D. G., Gass, L., & Dewitz, J. A. (2021). Thematic accuracy assessment of the NLCD 2016 land cover for the conterminous United States. *Remote Sensing of Environment*, *257*, 112357. https://doi.org/10.1016/j.rse.2021.112357

Wieting, C., Friedman, J. M., & Rathburn, S. (2023). River channel response to invasive plant treatment across the American Southwest. *Earth Surface Processes and Landforms*, *48*(3), 569–581. https://doi.org/10.1002/esp.5503

Wohl, E. (2011). Threshold-induced complex behavior of wood in mountain streams. *Geology*, *39*(6), 587–590. https://doi.org/10.1130/G32105.1

Wohl, E. (2013). Floodplains and wood. *Earth-Science Reviews*, *123*, 194–212. https://doi.org/10.1016/j.earscirev.2013.04.009

Wohl, E. (2014). A legacy of absence: Wood removal in US rivers. *Progress in Physical Geography: Earth and Environment*, *38*(5), 637–663. https://doi.org/10.1177/0309133314548091

Wohl, E. (2019). Forgotten legacies: Understanding and mitigating historical human alterations of river corridors. *Water Resources Research*, *55*(7), 5181–5201. https://doi.org/10.1029/2018WR024433

Wohl, E. (2020). Wood process domains and wood loads on floodplains. *Earth Surface Processes and Landforms*, *45*(1), 144–156. https://doi.org/10.1002/esp.4771

Wohl, E. (2021). An integrative conceptualization of floodplain storage. *Reviews of Geophysics*, *59*(2), e2020RG000724. https://doi.org/10.1029/2020RG000724

Wohl, E., & Iskin, E. P. (2022). The transience of channel-spanning logjams in mountain streams. *Water Resources Research*, *58*(5), e2021WR031556. https://doi.org/10.1029/2021WR031556

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D. N., Comiti, F., Gurnell, A. M., et al. (2019). The natural wood regime in rivers. *BioScience*, *69*(4), 259–273. https://doi.org/10.1093/biosci/biz013

Wohl, E., Lininger, K. B., & Scott, D. N. (2017). River beads as a conceptual framework for building carbon storage and resilience to extreme climate events into river management. *Biogeochemistry*, *141*(3), 365–383. https://doi.org/10.1007/s10533-017-0397-7

Wohl, E., Marshall, A., Scamardo, J., White, D., & Morrison, R. (2022). Biogeomorphic influences on river corridor resilience to wildfire disturbances in a mountain stream of the Southern Rockies, USA. *Science of the Total Environment*, *820*, 153321. https://doi.org/10.1016/j.scitotenv.2022.153321

Wohl, E., Scott, D. N., & Lininger, K. B. (2018). Spatial distribution of channel and floodplain large wood in forested river corridors of the Northern Rockies. *Water Resources Research*, *54*(10), 7879–7892. https://doi.org/10.1029/2018WR022750

Wyżga, B., & Zawiejska, J. (2005). Wood storage in a wide mountain river: Case study of the Czarny Dunajec, Polish Carpathians. *Earth Surface Processes and Landforms*, *30*(12), 1475–1494. https://doi.org/10.1002/esp.1204

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, *27*(14), 3025–3033. https://doi.org/10.1080/01431160600589179