Received: 9 March 2024 | Revised: 6 August 2024 | Accepted: 8 August 2024

DOI: 10.1002/esp.5968

RESEARCH ARTICLE

ESPL WILEY

Islands in the stream: Wood-induced deposition and erosion in the river corridor

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Funding information
Funding from an AGU Horton Research Grant, awarded to AM, supported field data collection.

Abstract

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

KEYWORDS

14C, aggradation, anastomosing river, fluvial geomorphology, island accretion, island age, large wood, logjam, river corridor, tree rings

1 | INTRODUCTION

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

Understanding the spatial and temporal dynamics of wood-induced features is important to understanding the formation and persistence of river corridor morphology in natural channels. We know that both wood jams and islands/secondary channels increase spatial heterogeneity in a channel, which promotes resilience to disturbances such as floods, drought, and wildfire (Wohl et al., 2022, 2023). The lateral connectivity between active channel(s) and floodplain driven by wood-induced islands and avulsions provides ecological refugia and resilience during disturbances (Benda et al., 2004). Higher water tables, deep pools, and lateral connectivity provide drought refugia and more stable base flows (Bêche et al., 2009; Boulton et al., 1998; Dixon, 2016; Puttock et al., 2017). Increased lateral connectivity facilitated by wood jams and secondary channels helps to attenuate flood peaks and diffuse flood flows across the floodplain (Junk et al., 1989; Poff et al., 1997), making habitats persistent and more resistant to natural and anthropogenic disturbances (Amoros & Bornette, 2002; Henning et al., 2006; Jeffres et al., 2008). Multiple wood-rich channels laterally connected to the floodplain and vertically connected to the hyporheic zone support abundant and diverse habitats and species (Dolloff & Warren, 2003; Herdrich et al., 2018; Venarsky et al., 2018). Frequent, minor channel adjustments and a high, reliable water table also create optimal settings for the germination and growth of aquatic and riparian vegetation (Braudrick et al., 2009; Nadler & Schumm, 1981; Tal & Paola, 2007). Wet woodlands on islands and floodplains supply and retain wood and widespread vegetation proximal to the channel (Fetherston et al., 1995; Gurnell et al., 2001; Montgomery & Abbe, 2006), supporting habitat and increased retention of organic matter and nutrients for other organisms (Bilby, 1981; Flores et al., 2011). Dense, diverse riparian vegetation provides abundant shade, which, together with an efficient hyporheic exchange, ameliorates water temperatures (Beechie et al., 2005; Montgomery et al., 1999). As efforts to restore natural processes are emphasized in river restoration, understanding the spatial and temporal conditions that facilitate different types of wood-induced features has important implications for the broader physical and biological processes in a river corridor.

1.1 | Previous work on large wood and channel dynamics

The details of the volume and grain-size distribution of sediment stored in association with wood in the river corridor vary across geomorphic settings. Wohl & Scott (2017), for example, distinguished channel-spanning wood jam steps and backwater sediment wedges (e.g., Short et al., 2015) in steep channels from more widespread channel aggradation associated with wood-induced increases in bed hydraulic roughness (e.g., Brooks et al., 2003). Other studies have documented wood rafts and associated floodplain sedimentation in large, low-gradient rivers (e.g., Boivin et al., 2015; Triska, 1984). We can conceptualize these interactions between large wood and sediment to include six basic forms of wood-induced deposition in river corridors, which can be paired with wood-induced erosion in river corridors (Figure 1).

Wood-induced deposition can occur: (i) in a backwater upstream from a wood jam (Mao et al., 2008; Welling et al., 2021); (ii) across and along a channel in which dispersed wood pieces increase bed roughness (Brooks et al., 2003); (iii) as bar deposition

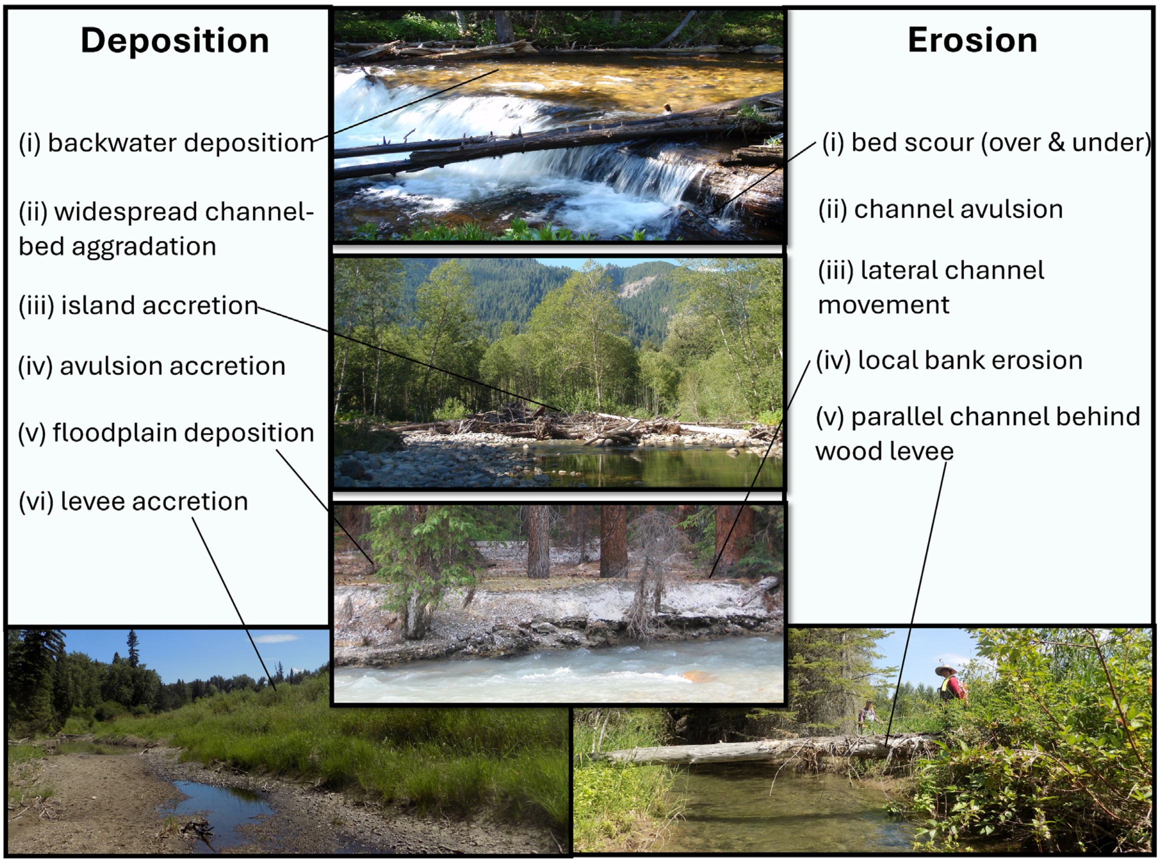

FIGURE 1 Basic forms of wood-induced deposition and erosion in the river corridor. [Color figure can be viewed at wileyonlinelibrary.com]

downstream from a wood jam, which can lead to island accretion as vegetation colonizes the bar and traps additional large wood at the upstream end of the island (e.g., Abbe & Montgomery, 1996; Gurnell et al., 2005); (iv) as accretion at the upstream end of a portion of the floodplain where the channel bifurcates as a result of wood-induced channel avulsion; (v) as localized or widespread floodplain deposition where large wood obstructs flow in the channel (Jeffries et al., 2003; Oswald & Wohl, 2008); and (vi) as levee accretion where relatively long, narrow wood accumulations form at the channel-floodplain boundary (Figure 1). At any of these locations, the amount and grain-size distribution of sediment stored depends on factors such as the degree to which transport capacity is reduced by greater roughness and obstruction of flow, the persistence of the large wood, and the amount of sediment in transport within the river corridor.

Wood-induced erosion can occur where: (i) flow is concentrated over, around, or under large wood, creating localized bed scour (Ravazzolo et al., 2015; Webb & Erskine, 2005); (ii) wood jams promote sufficient overbank flow to create channel avulsion on the floodplain (Sear et al., 2010); (iii) flow around large wood is sufficient to enhance channel lateral migration (Brummer et al., 2006); (iv) flow around large wood creates localized bank erosion (Phillips, 2012); and (v) secondary channels parallel to the main channel form on the floodplain side of a wood levee (Figure 1). The magnitude of erosion reflects the degree to which flow is deflected by wood, the erosional forces exerted against channel and floodplain boundaries, and the erosional resistance of those boundaries.

Many of these types of wood-induced deposition and erosion have been extensively described in existing studies, except for wood levees. Existing studies examining wood-induced bar and island formation come from gravel-bed, lowland rivers of the northwestern United States (Abbe & Montgomery, 2003; Collins et al., 2012; Maser & Sedell, 1994; Naiman et al., 2010; O'Connor et al., 2003), sand-bed, lowland rivers of the interior western United States (Osterkamp, 1998), the gravel-bed, braided Tagliamento River in Italy (e.g., Bertoldi et al., 2009; Edwards et al., 1999; Gurnell et al., 2001; Gurnell et al., 2019; Gurnell & Bertoldi, 2020; Gurnell & Petts, 2006; Kollmann et al., 1999; Moggridge & Gurnell, 2009; Zanoni et al., 2008), and gravel-bed rivers in the Polish Carpathians (e.g., Mikuś et al., 2013; Mikuś et al., 2019; Wyżga & Zawiejska, 2005; Wyżga & Zawiejska, 2010). Much of the work published thus far is descriptions of the relationship between bar/island development and wood jams, including conceptual models. For example, over 17 years, Gurnell et al. (2019) documented bar/island development on the Tagliamento River in Italy. Kollmann et al. (1999) found that succession from bar to established island takes approximately 20 years in the same system. Zanoni et al. (2008) looked at the age/turnover of islands based on air photos of the Tagliamento River and found that most islands persisted for less than 24 years. Mikuś et al. (2013) used tree-ring dating to estimate the time of island inception on Czarny Dunajec, Poland, and observed trees aged approximately 45 years or younger. Mikuś et al. (2019) observed island development over about a decade in response to floods and passive restoration in the Raba River of Poland. In the U.S. Pacific Northwest, Naiman et al. (2010) developed a conceptual diagram with a general timeline for rates of island development of approximately 70 years.

1.2 | Distinguishing channel avulsion versus island formation

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

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

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

1.3 | Objectives of this study

Our objectives here are to (i) compare the temporal dimensions of wood-induced island versus avulsion deposition and erosion and (ii) to introduce and briefly describe a new form of wood-induced deposition and erosion feature observed in the field (wood levees and associated backchannels). We build on the work of Marshall & Wohl (2023), identifying a continuum of spatial patterns in wood-induced accretionary and avulsive bifurcations along the Swan River of northwestern Montana, USA, and its tributaries. Marshall & Wohl (2023) found that the ratio of erosive force to erosional resistance present at each site was important in dictating accretionary vs. avulsive processes and the subsequent pattern of wood-induced bifurcations that occur. Here, we consider whether a temporal continuum exists between wood-induced accretionary and avulsive features. We

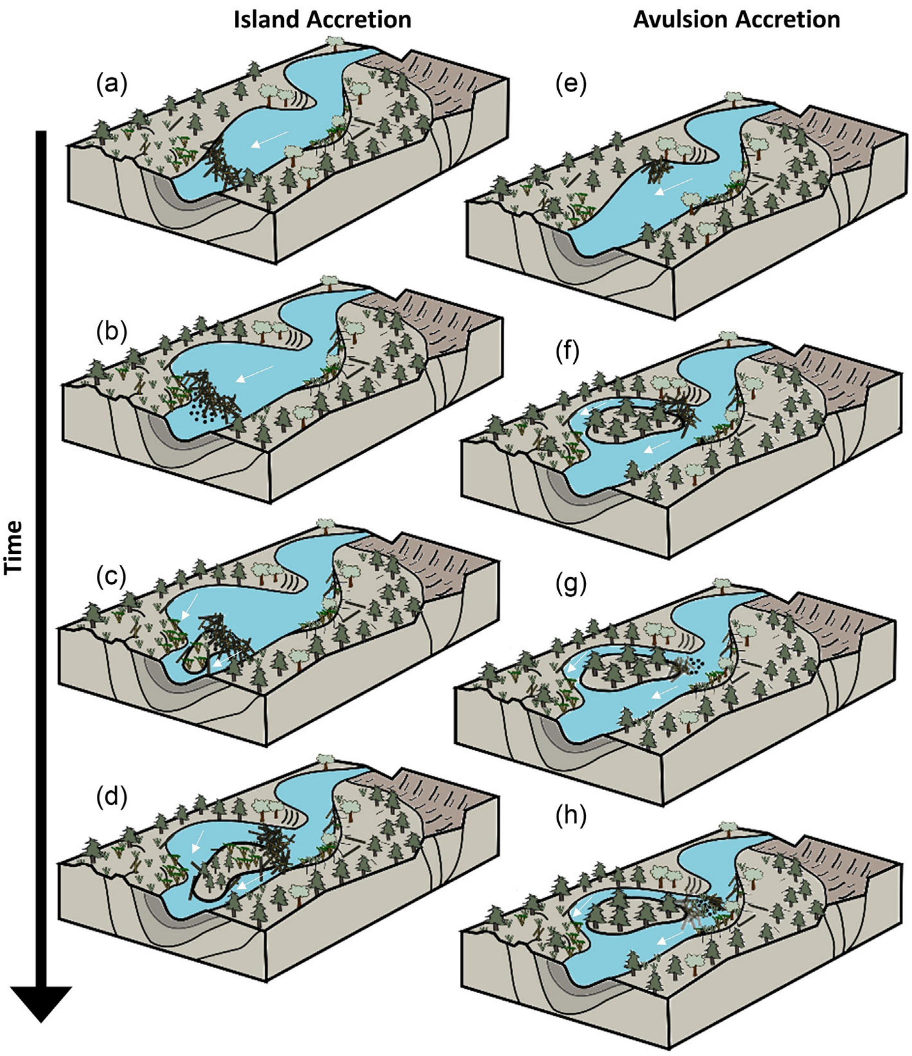

FIGURE 2 (a–d) Conceptual model of island growth upstream with time. Arrows within the block diagram indicate flow direction. Initial wood deposition (a) creates a low-velocity zone in the lee of the jam in which sediment is deposited and on which plants can germinate (b). The first obstacle wood meets in transport downstream, however, is the upstream face of the jam. As the jam grows upstream, downstream portions of the jam/island could be covered in sediment and vegetation (c). Consequently, we expect ages to be progressively older downstream on an island (d). (e–h) Conceptual model of avulsion accretion with time. Initial wood deposition along the channel margin (e) facilitates overbank flow, creating a much narrower secondary channel than the channel from which it splits (f). The newly isolated portion of the floodplain can accumulate additional wood at the upstream end, growing upstream with time as described for islands (g–h). [Color figure can be viewed at wileyonlinelibrary.com]

constrain tributary island persistence (via ^{14}C dates) and document rates of vegetation establishment (via tree rings) for islands as we examine what causes island persistence vs. avulsions through time.

2 | STUDY AREA

We focus on the Swan River (1,676 km^2 drainage area) in northwestern Montana, USA, and two of its tributaries, Goat Creek (~94 km^2 drainage area) and Lost Creek (~85 km^2 drainage area). We selected five wood-induced tributary island study sites along Goat and Lost Creeks based on existing locations delineated by Marshall & Wohl (2023) (Figure 3). Our study area is uncommon as a contemporary river corridor in the contiguous US because of its natural flow (Poff et al., 1997), sediment (Wohl et al., 2015), and wood (Wohl et al., 2019) regimes. However, the Swan likely represents formerly widespread conditions across forested river corridors in the temperate latitudes.

The Swan catchment receives ~750 mm of mean annual precipitation. The most significant annual peak flow is associated with spring snowmelt, but rainfall and rain-on-snow precipitation can also produce peak flows (MacDonald & Hoffman, 1995). The region was shaped by Pleistocene glaciation and is underlain by the Proterozoic-age Belt Supergroup, which mainly consists of weakly metamorphosed, fine-grained sedimentary rocks. The mean elevation in the catchment is 950 m. Valley width throughout the catchment is ~1–2 km with an average channel gradient of 0.5%. The Swan River has an anastomosing planform and Goat and Lost Creeks have meandering planforms. Channels primarily have cobble to boulder bed substrate with pool-riffle sequences. Along Goat Creek and Lost Creek, banks heights average around 0.5 m and along the Swan River, bank heights average around 1 m. Soils have poorly developed profiles (Antos & Habeck, 1981), and are mostly gravelly loamy sand (SI Figure 1) with some observed longitudinally discontinuous clay units ~1 m thick exposed along cutbanks in Goat Creek and Lost Creek. Channel width averages 5 to 15 m in Lost and Goat Creeks and 20 to 40 m in the Swan River.

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

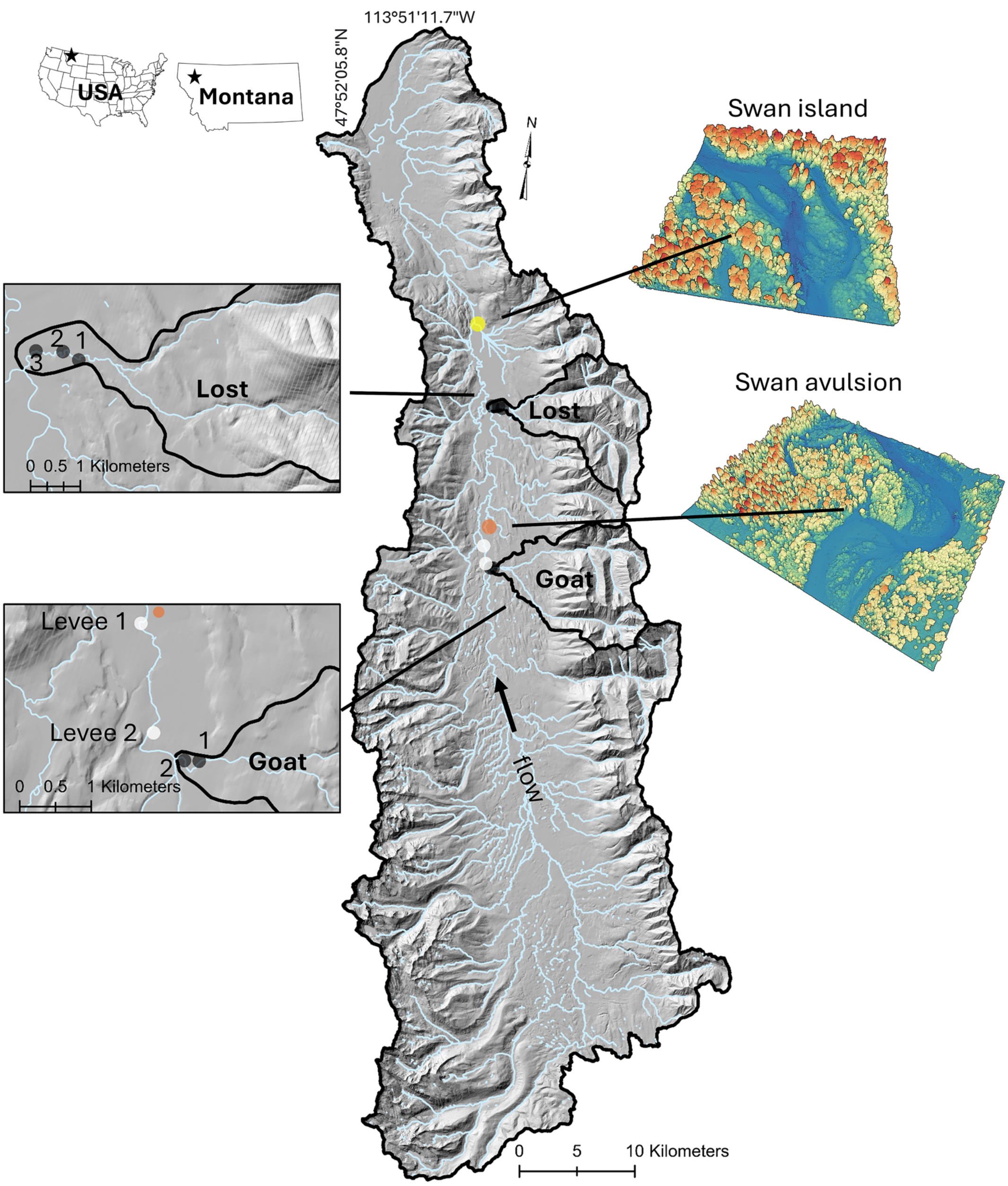

FIGURE 3 Lost creek and Goat Creek catchments within the Swan River catchment of Montana, USA. The portion of each of the three catchments included in our study is outlined in black in the central part of the figure. Black dots represent tributary island sites, white dots represent wood levee sites, the yellow dot represents the Swan River Island site, and the red dot represents the Swan River avulsion site. There are three island study sites on Lost Creek (Lost 1, Lost 2, Lost 3) and two on Goat Creek (Goat 1, Goat 2), depicted in the inset maps on the left side of the figure. The Swan River avulsion and island accretion are shown as insets on the right side of the figure. [Color figure can be viewed at wileyonlinelibrary.com]

channel and floodplain (Wohl et al., 2018) and is a highly dynamic and spatially heterogeneous river corridor (Marshall et al., 2024). Sections of the river with greater presence and persistence of large wood exhibit more channel movement laterally on both a seasonal and decadal time scales as well as a greater number of secondary channels and spatial heterogeneity (Marshall et al., 2024).

3 | METHODS

3.1 | Characterizing wood-induced features

We mapped a subset of accretionary wood deposits associated with avulsions and islands in the field using a handheld GPS (Garmin eTrex with ± 3 m horizontal resolution). Data were collected along the Swan River, Goat Creek, and Lost Creek (Figure 3). Locations were overlain onto 1 m resolution lidar collected for the study area (Figure 3; Marshall, 2023).

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

We also mapped a subset of locations along the Swan River with deposition and erosion associated with wood levees using a handheld GPS. Recognition of wood levees as a feature was an unanticipated outcome of field work and we made observations of vegetation and sediment characteristics as well as dimensional measurements at two observed wood levee locations but did not use tree-ring and ^{14}C dating to further constrain ages of those wood-induced features.

3.2 | Dendrochronology data collection and processing

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

3.3 | ^{14}C data collection and processing

Samples for ^{14}C analysis were collected at accretionary island sites from the outer 5 cm of wood pieces (tree trunks) in jams or buried wood from upstream, middle, and downstream locations at each island site. Samples were dried and sent to the Yale Analytical and Stable Isotope Center for processing. A subsample was selected from each bag of samples. Sample preparation involved grinding the subsample to powder with a mortar and pestle. The standard Acid Base Acid sample treatment for wood follows: Inorganic carbon is dissolved in a 1.5 M HCl acid treatment and rinsed. Base treatment with 0.5 M NaOH removes base-soluble organic acids. A final acid treatment removes residual base and inorganic carbon potentially absorbed into solution before neutralization and drying. Once dry, samples are weighed into tin capsules and introduced to the Mini Carbon Dating System (MICADAS) using an Elemental Analyzer connected to a Gas Interface System. The MICADAS uses Bats version 4.30 to produce the final data. We provided results in F14C (SI Table 2). The IntCal20 curve was used in OxCal 4.4 to obtain calibrated ages. Where F14C values were less than 1, we used a pre-bomb calibration curve, where F14C values were >1, we used post-bomb NH3 curve, where F14C values were right around 1, we used both calibration curves (SI Figure 2).

4 | RESULTS

4.1 | Island accretion

Tributary island ages based on tree rings and ^{14}C dates are provided in SI Table 1 and SI Table 2. Figure 4 summarizes minimum island ages derived from tree rings and ^{14}C dating. Ages derived from tree cores ranged from 16 to 90 years old, and ages derived from ^{14}C dating ranged from 38 to over 150 years old (Figure 4). The ^{14}C ages summarized in Figure 4 are a simplification of age range variability using the average year within the highest probability age range for each ^{14}C sample (SI Table 2) and are not intended as absolute ages. Older samples (before 1950) have a much greater range of variability given that the atmospheric line was relatively flat between 1700 and 1950, which decreases our ability to do high-precision measurements during that time. The full range of variability in ^{14}C ages is included as SI Table 2 and SI Figure 2. We observed no significant difference between grain size samples at each island site relative to the adjacent floodplain (SI Figure 1).

We also observed a site that appears to be transitional between avulsion and island accretion along the mainstem Swan River (Figure 3). Although we did not obtain tree-ring or ^{14}C ages for this site, we observed an upstream progression of apparently younger vegetation and significant wood accumulation, similar to those on the tributary islands (Figure 5). Specifically, this site has (i) a contemporary wood jam at the upstream end of the feature, (ii) an older wood jam (based on buried wood and decay state) among herbaceous vegetation and shrubby willows at the midpoint, and (iii) mature conifers (about 20–25 m tall) at the downstream end. This feature's special characteristics resemble those of an island, but we do not know whether there was once a channel-spanning or marginal wood jam here. The dimensions of the secondary channel on one side of the feature (∼15 m wide) are quite small relative to the mainstem (∼40 m wide) and relative to the length of the feature (∼210 m), which is more similar to an avulsion (Figure 5). Also, the mature conifers at the downstream side of the feature are similar in height (and probably age) to the adjacent floodplain forest. This site may be transitional between an island and an avulsion.

4.2 | Avulsion accretion

Numerous sites of channel avulsion along the Swan River during the past 20 years appear in aerial imagery. We examined one site of wood-induced avulsion with recently formed accretion in the field (Figure 6). We first observed this site during the summer of 2022, when relatively high flows had inundated much of the left-bank floodplain. The overbank flow was initially poorly organized but was steered into distinct secondary channels by floodplain topography, living vegetation, significant wood accumulations, and pre-existing

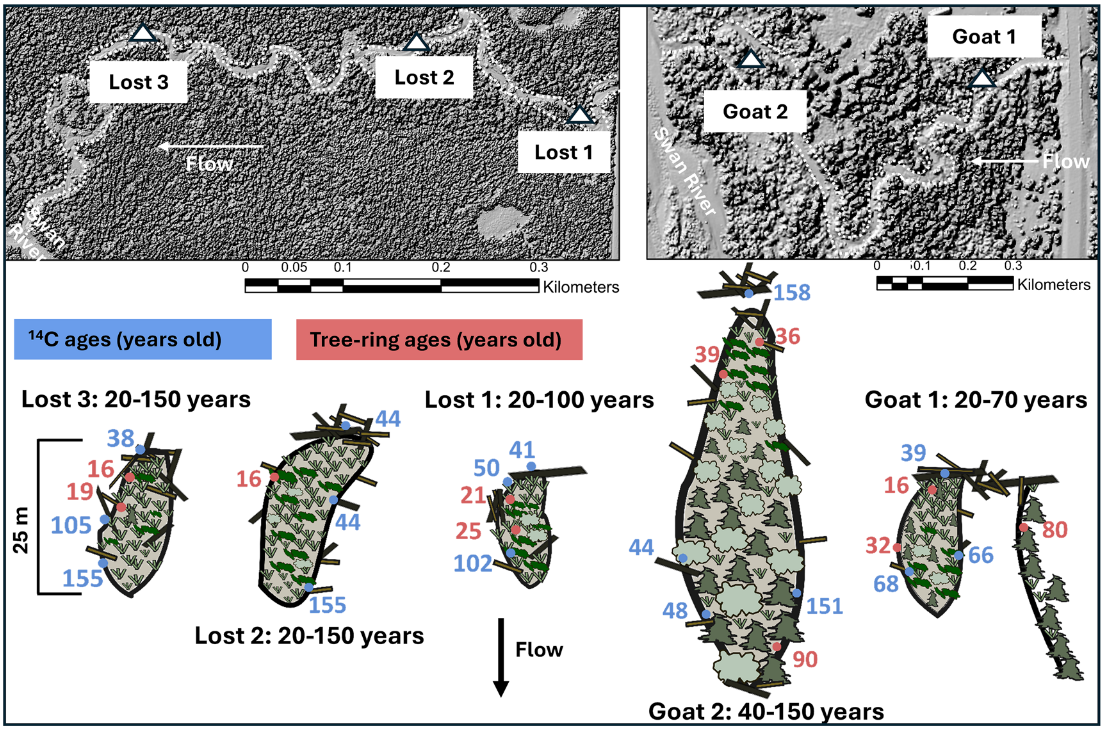

FIGURE 4 Tree-ring and ^{14}C-derived island ages along Goat and Lost Creek (tributary islands). The upper portion of Figure 4 depicts the locations of each tributary island within Lost or Goat Creek. The lower portion of Figure 4 illustrates each island's bird's eye schematic, scaled relative to the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

FIGURE 5 Accretion along the mainstem Swan River, downstream of Goat Creek confluence (Figure 3 for location within the catchment). This feature may be transitional between an island, as described for the tributaries, and an avulsion on the Swan River. The ground view is on the left, the first-return hillshade from lidar is at the centre, and the drone photograph is on the right. The pink box denotes the location of the accretionary feature, and the star indicates the contemporary wood jam. Arrows indicate flow direction. [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 6 An avulsion on the Swan River downstream of Goat Creek (Figure 3 for location within catchment). The first return hillshade from lidar is on the left, ground view of floodplain vertical accretion during 2022 peak flows is at the centre, and the drone photograph is on the right. The pink box denotes the location of the avulsion. Arrows indicate flow direction. [Color figure can be viewed at wileyonlinelibrary.com]

secondary channels. By summer 2023, well-established secondary channels contained all flow outside the mainstem. Sand and finer sediment had vertically accreted to > 20 cm depth in portions of the floodplain inundated during 2022.

4.3 | Wood levees

During our field data collection, we observed linear depositional wood features with associated erosional backchannels, which we call wood levees (Figure 7). The two wood levees occurred on the Swan River mainstem, adjacent to the Goat Creek confluence at avulsion sites. Each wood levee was a linear accumulation of large wood parallel to the flow direction, 1–2 m in vertical thickness, 3–5 m wide, and a few tens of meters in length. The levees are now partly covered with sand-sized and finer sediment, herbaceous vegetation, and grasses. A small secondary channel parallels each levee on the floodplain side. Although their size makes wood levees difficult to distinguish in satellite imagery, review of historical imagery and lack of mature woody vegetation on the wood levees suggests that these features have been present for less than a decade.

5 | DISCUSSION

5.1 | Chronology of tributary island accretion

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

Goat 1 has deciduous and coniferous trees with ages suggesting upstream island formation with time. We interpret the older tree core (80 years) taken at a parallel island as indicating a portion of the floodplain isolated by avulsion (Figure 4). Goat 2 was the largest island we examined and included deciduous and mature coniferous trees. The tree ring ages at Goat 2 suggest island accretion upstream with time. The oldest ^{14}C sample for Goat 2 was taken at the contemporary wood jam upstream, suggesting older pieces of large wood were likely re-mobilized upstream and more recently deposited at the upstream end of the island. The two younger ^{14}C samples (44 and 48 years) on the river right side of the island likely represent more recent pieces of wood that have been transported and re-deposited from upstream. Taken together with the tree ages, these suggest later lateral/

FIGURE 7 Ground view (left and right) and hillshade view (centre) of wood levees observed on the mainstem of the Swan River, delineated here by pink lines. Panel (a) shows levee 2 on a secondary channel of the Swan River, and panel (b) shows levee 1 on the main channel (refer to Figure 3 for location within the river corridor). Both sites have a backchannel running parallel to the wood levee. White arrows indicate flow direction. [Color figure can be viewed at wileyonlinelibrary.com]

downstream addition of wood. Wood jams are not complete wood traps, so wood is likely transported beyond them and could well accrete to the sides of the island or, potentially, the downstream end with time. Similarly, sediment and plant propagules might accrete to the sides with time, leading to younger tree ages than in the centre.

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

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

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

5.2 | Where does wood-induced accretion occur?

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

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

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

5.3 | The temporal continuum of wood-induced deposition

We interpret the three wood-induced forms of deposition that we describe here as reflecting a temporal continuum of accretion (Figure 8). Wood levees have primarily non-woody living vegetation and may be more transient features than forested islands or secondary channels created by avulsion. However, while wood levees persist, they influence near-channel floodplain topography and channel bank erosional resistance in a manner that can limit overbank flow by increasing bank height and erosional resistance at the wood levee but concentrate overbank flow immediately upstream and downstream from the levee. We have observed unvegetated linear deposits of wood along the top of a channel bank outside bends and in relatively straight channel segments (and without the backchannels present along the Swan) on boreal rivers in Alaska and Canada. These features can occur when a wood raft forms in a channel, completely blocking the channel over a length several times the average channel width. Wood rafts can form via the gradual accumulation of wood at a persistent blockage or via mass transport during wood floods (Kramer et al., 2017). The rivers along which we noted wood levees have abundant supply and relatively high transport capacity for large wood because of wood abundance in relation to flow width and depth. Although we introduce wood levees here, future work is needed to provide spatial and temporal constraints.

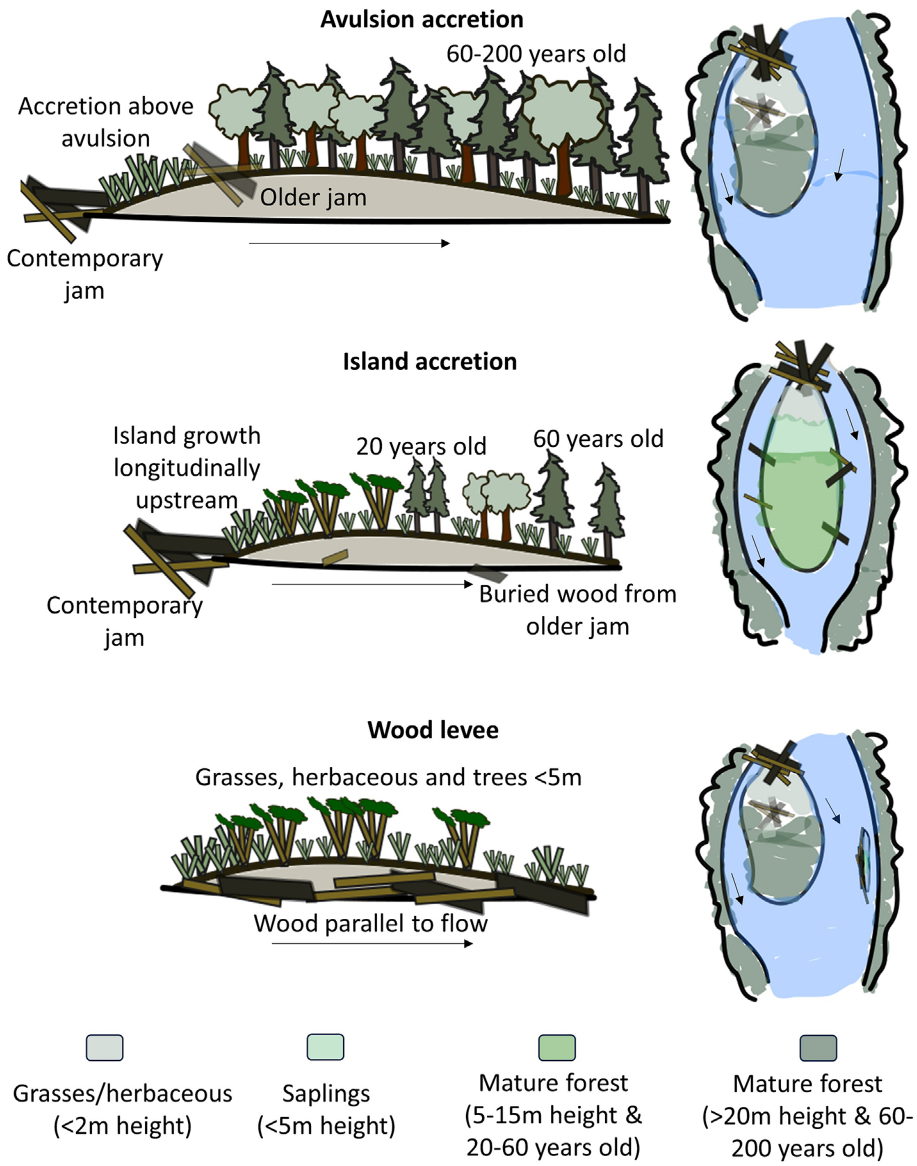

FIGURE 8 Wood-induced island and avulsion accretion, and wood levee erosion and deposition (side views at left, planform views at right). Arrows indicate flow direction in plan view and side view illustrations. [Color figure can be viewed at wileyonlinelibrary.com]

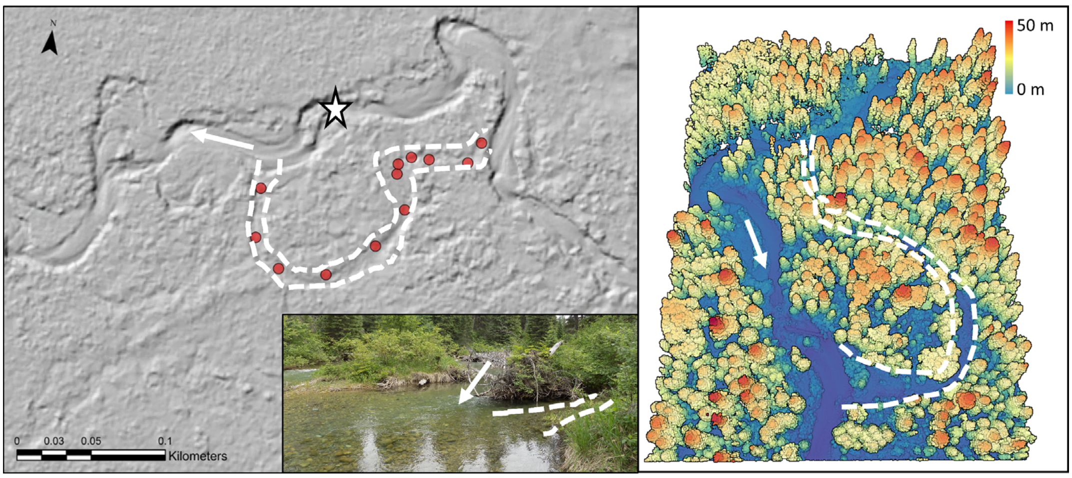

FIGURE 9 An inactive relict channel is present between the left side channel of Lost 2 (white star) and the floodplain. Red points indicate GPS points tracing the channel, arrows indicate flow direction, and dashed lines indicate approximate channel outline. The inset photo shows the outlet of the relict channel downstream of Lost 2. [Color figure can be viewed at wileyonlinelibrary.com]

Islands appear to persist for more than a decade to a century. At the Lost Creek islands, we see the most unambiguous indication of island accretion and upstream growth with time, as exhibited by tree and radiocarbon ages (Figure 4). The Goat Creek islands suggest that wood may also accrete laterally to the downstream portion of islands. The similar sequence of mature conifers downstream and younger woody deciduous trees upstream at the Swan Island site suggests a similar temporal sequence. However, our work lacked a robust dataset of tree cores because of a lack of mature trees on many of our island sites. Additional cores would provide further insight into some challenges associated with interpreting results from a small sample size.

What happens to islands as they continue to age? Observations at the Lost 2 site suggest that one of the channels beside an island may become blocked with large wood and living vegetation, allowing that channel and the adjoining island to become part of the floodplain through lateral accretion (Figure 9). We observed a large, mostly inactive relict channel between the left side channel around Lost 2 and the floodplain, which suggests this scenario. The relict channel still had some surface hydrologic connectivity with Lost Creek via backflooding at the downstream end of the relict channel. The upstream end of the relict channel, although still discernible as a linear surface depression, was elevated above the stage of normal peak flow and was covered with woody vegetation. Between the relict channel and the contemporary active channel, there was a higher, forested floodplain that presumably was once an island. The conifers growing on this former island's surface are comparable in size and apparent stand age to the adjacent floodplain forest, suggesting that the former island has been abandoned for over a century.

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

The wood jam at the point of bifurcation between the mainstem and the avulsion (Figure 9) may continue to accumulate large wood and sediment and undergo the type of upstream deposition that we describe for islands, but this is likely to be limited in spatial area relative to the size of the newly isolated floodplain. This is a primary difference between an avulsion and an island. All the vegetated surfaces of an island result from wood-induced flow separation. In contrast, most of the vegetated surface between the main and secondary channels in an avulsion is floodplain forest, and only a small proportion of the vegetated surface at the bifurcation point of an avulsion results from wood-induced flow separation.

6 | CONCLUSIONS

The combination of bank height, bank erosional resistance, and wood jams all influence where deposition and erosion can occur (e.g. Brummer et al., 2006; Marshall & Wohl, 2023; Sear et al., 2010). Overbank flow and bank erosion then influence where wood-induced features such as wood levees, avulsion and secondary channels, or islands and split flow can form. Vegetation established on any of the wood features we examined – wood levees, channel-marginal jams at avulsions, or channel-spanning jams at islands – helps stabilize the feature and create persistent areas of flow separation, erosion, and deposition. However, the absence of contemporary wood jams at the bifurcation point of some past channel avulsions on the Swan and the continued presence of the secondary channels suggests that relatively transient wood jams may still create persistent secondary channels. In contrast, we did not observe any islands without wood jams on the tributaries, perhaps because the island blocks such a substantial portion of the channel width that, even if the original channel-spanning wood jam is somehow removed, the island will quickly trap and store new wood.

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

AUTHOR CONTRIBUTIONS

Anna Marshall: Conceptualization; funding acquisition; methodology; investigation; resources; writing—initial draft; writing—reviewing and editing. **Ellen Wohl:** Conceptualization; methodology; investigation; resources; writing—reviewing and editing.

ACKNOWLEDGEMENTS

We thank Peter Raymond and Robert O. Hall, Jr. for facilitating radiocarbon data processing and Brad Erkkila for processing radiocarbon samples and providing feedback on a draft of this manuscript. This research made use of the Yale Analytical and Stable Isotope Center and Yale Center for Natural Carbon Capture. Funding for field research was provided by an American Geophysical Union Horton Research Grant, awarded to AM. This manuscript was improved by feedback from two anonymous reviewers and the Associate Editor.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are available as Supplemental Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Marshall, A. & Wohl, E. (2024) Islands in the stream: Wood-induced deposition and erosion in the river corridor. *Earth Surface Processes and Landforms*, 49(13), 4310–4323. Available from: https://doi.org/10.1002/esp.5968