



Wood Equilibrium: A Conceptual Framework for Assessing the Wood Regime

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Abstract The wood regime describes the recruitment, transport, and retention of wood in rivers. While there are data-intensive methods for understanding these processes, such as wood budgeting and transport modeling, it remains difficult to holistically assess the wood regime, especially over large spatial and temporal scales. To address this difficulty, we present the conceptual framework of wood equilibrium. Like sediment equilibrium, wood equilibrium posits that wood load can be in equilibrium with supply, a state characterized by a consistently positive correlation between wood load and wood retention capacity (i.e., the capability of a reach to retain wood). Likewise, there also exist transport-limited and supply-limited states, in which wood retention is greater or less than capacity, respectively. We apply the wood equilibrium framework to understand the wood regime of two large, lowland rivers in Washington State, USA by comparing wood load to retention capacity and the spatial distribution of wood recruitment. We find evidence for wood equilibrium state varying in both space and time in response to changes in wood recruitment, transport, and retention capacity. We discuss how the wood equilibrium framework can be used to understand the wood regime and potential responses to wood reintroduction and river restoration.

Non-technical summary Trees enter rivers as logs and help rivers form habitat, move their bed and banks, and alter patterns of flooding. How logs enter, move through, and are retained in rivers determines how they affect the river and the living things that depend on it, including humans. Here, we suggest the wood equilibrium framework as a way of understanding how logs enter, move through, and are retained in rivers. This framework supposes that a portion of river will only retain as much wood as it can if there is enough wood being supplied to it. When more logs get to the river than it can retain, then wood retention will be over capacity, forcing the river to adjust to retain more or reduce its retention via log transport downstream or decay. If not enough logs get to the river, then the river will retain less wood than it otherwise could, again forcing it to adjust to a lower retention capacity or making it ripe for trapping logs that come from upstream. We apply this framework to two rivers in Washington, USA to show how it can be used to understand how wood gets to and moves through the river.

1 Introduction

Wood supply, transport, and retention (alternatively, storage) define the wood regime of a river corridor and frame our understanding of how wood influences ecologic, geomorphic, and hydrologic processes (Wohl et al., 2019). Wood is transient in the riverscape: it sporadically moves downstream during wood-mobilizing floods but remains stable in the riverscape during intervening periods. Throughout periods of retention and transport, wood decays and interacts with flow, sediment, and biota. In doing so, it creates aquatic and riparian habitat and serves a multitude of ecologic, geomorphic, and hydraulic functions that affect biota dependent on riverine ecosystems, including humans (Collins et al., 2012; Gurnell, 2013; Poledniková and Galia, 2021; Wohl, 2017; Wohl et al., 2023).

While the function of riverine wood is a complex result of wood characteristics and surrounding ecogeo-

morphic context, wood function and the location of that function fundamentally depend on how wood is transported and transiently retained throughout the river network. Thus, a fundamental challenge in understanding wood function is understanding the spatial distribution, magnitude (i.e., wood load), and duration of riverine wood retention and, conversely, wood transport. Past studies of wood load variability have established that wood load correlates with watershed and reach-scale characteristics, wood supply, wood-induced feedbacks (e.g., wood jams acting as stable obstructions and trapping more wood), and transport conditions, all of which can vary significantly through space and time (Cienciala et al., 2024; Hough-Snee et al., 2016; Lininger and Hilton, 2022; Scott and Wohl, 2018; Wohl et al., 2017). However, we lack a conceptual framework for characterizing and understanding both spatial and temporal variability in wood load. Studies that quantify controls on parts of the wood regime and establish wood budgets (e.g., Galia et al., 2023; Marcus et al., 2002; Piton

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et al., 2024; Sigdel et al., 2023) hint at, but do not fully reveal, a unified conceptual model that would allow us to interpret wood load dynamics in terms of the interactions of wood supply and transport capacity.

The concept of a system tending towards equilibrium is the foundation for geomorphology's understanding of landscape formation via the movement and storage of sediment (Chartrand et al., 2019; Gilbert, 1877; Pfeiffer et al., 2017; Phillips, 2011; Schumm and Lichty, 1965). More recently, geomorphologists have employed the ratio of sediment supply to transport capacity as a key determinant of sediment (dis)equilibrium, with aggradation, or accumulation of sediment, resulting from supply outweighing transport capacity and degradation, or loss of sediment, resulting from transport capacity outweighing supply (Dietrich et al., 1989; Pfeiffer et al., 2017; Stroth et al., 2017; Wohl et al., 2015). It stands to reason that equilibrium concepts could also be used to describe changes in wood retention as a function of the wood regime, a potential that has yet to be realized.

Here, we propose and examine the concept of wood equilibrium, which can explain wood load (i.e., the quantity of wood retained in the riverscape) as a function of wood supply (i.e., the amount of wood reaching a given part of the riverscape) and wood transport capacity. Like the equilibrium terms used to describe sediment dynamics, we can conceive of a river as being in a supply-limited state with respect to wood — analogous to either degrading alluvial rivers or bedrock-bedded rivers receiving less sediment than their transport capacity — or a transport-limited state with respect to wood — analogous to alluvial rivers that are aggrading due to a lack of capacity to transport all of the supplied sediment (Gilbert, 1877, 1914; Konold, 1997). Researchers already imply this equilibrium framework and use equilibrium-related terms (supply- and transport-limited) when interpreting observations of wood supply, transport, and deposition (Galia et al., 2023; Marcus et al., 2002; Scott and Wohl, 2018; Wohl and Jaeger, 2009). Wood budgeting likewise implies this framework as it explains changes in wood load as a function of the relative difference between wood supply and transport capacity (Benda and Sias, 2003; Boivin et al., 2017; Lininger and Hilton, 2022; Ruiz-Villanueva et al., 2016a; Schenk et al., 2014; Tonon et al., 2018). What is missing is an explicit framing of the equilibrium concept and description of how it can be applied to answer key questions about wood retention and restoration in riverscapes.

1.1 The Wood Equilibrium Concept

Wood load is a predictable function of wood supply and wood transport capacity (Benda and Sias, 2003; Scott and Wohl, 2018), or its more readily estimable inverse: wood retention capacity (i.e., the capability of a reach to retain wood; see section 2.4 below). As such, there should exist a wood equilibrium state in which wood supply and retention capacity are balanced, with sufficient supply to fill the retention capacity of a reach. For a river segment (i.e., a length of river comprised of multiple reaches) in wood equilibrium, wood load

should be positively, although not necessarily linearly, correlated with retention capacity over a defined timespan; there should be neither a limitation on wood load from a lack of wood supply nor an excess in wood load caused by a lack of wood transport capacity. If such an equilibrium condition exists, then there should be three conceptual states of wood retention: transport-limited, equilibrium, and supply-limited (Figure 1). While Figure 1 represents the equilibrium state as a linear correlation between wood load and retention capacity, the actual nature of this relationship likely varies across wood process domains and bioclimatic regions, and is likely nonlinear (Kramer and Wohl, 2017; Malakoff et al., 2025; Ruiz-Villanueva et al., 2016b; Wohl, 2011).

A transport-limited state is characterized by wood load greater than the riverscape's wood retention capacity can sustain. Transport-limited conditions could result from a pulse of wood recruitment (i.e., adjustment upward along arrow *a* in Figure 1), such as that from fire (e.g., Praskievicz and Sigdel, 2021), a major storm (e.g., Wohl and Jaeger, 2009), or a tree-felling snow avalanche (e.g., Kemper and Scamardo, 2023) in the absence of a wood-mobilizing flood. Subsequent flows could mobilize wood downstream (Comiti et al., 2016; Kramer and Wohl, 2017) or into overbank areas previously incapable of transporting wood (Wohl et al., 2024) or wood decay could similarly reduce wood load over a longer timeframe until it returns to a level commensurate with retention capacity (i.e., adjustment downward along arrow *a* in Figure 1). Alternatively, if such adjustment is possible given the valley context and sediment supply, the reach may adjust to increase its retention capacity (e.g., widening, avulsions and braiding, etc.; Pavlowsky et al., 2023; Rathburn et al., 2017, adjustment rightward along arrow *b* in Figure 1). Transport-limited conditions within the channel may also adjust towards wood equilibrium via channel migration away from retained wood, whereby that wood is integrated into nascent floodplain (Collins et al., 2012) until the migrated channel has a lower wood load. While transition from a high wood load equilibrium state to transport limitation without a change in wood load (i.e., leftward along arrow *b* in Figure 1) is possible, it would likely require a persistent change in the flow or sediment regime that reduces retention capacity (e.g., a persistent increase in the frequency, magnitude, or duration of high flows). Some combination of these forms of adjustment may also occur simultaneously.

A supply-limited state is characterized by less wood load than is likely possible given a riverscape's retention capacity. Supply limitation could result, for example, from a sudden direct reduction in wood load or supply, perhaps by anthropogenic wood removal or forest harvest, or simply a temporary reduction in wood recruitment processes that lasts sufficiently long to cause wood load depletion via mobilization and/or decay (i.e., adjustment downward along arrow *d* in Figure 1). After a loss of retained wood, wood load could recover following wood-mobilizing floods, provided sufficient upstream supply exists to replace lost wood (i.e., adjustment upward along arrow *d* in Figure 1). However, a sustained loss of wood supply may drive reach adjust-

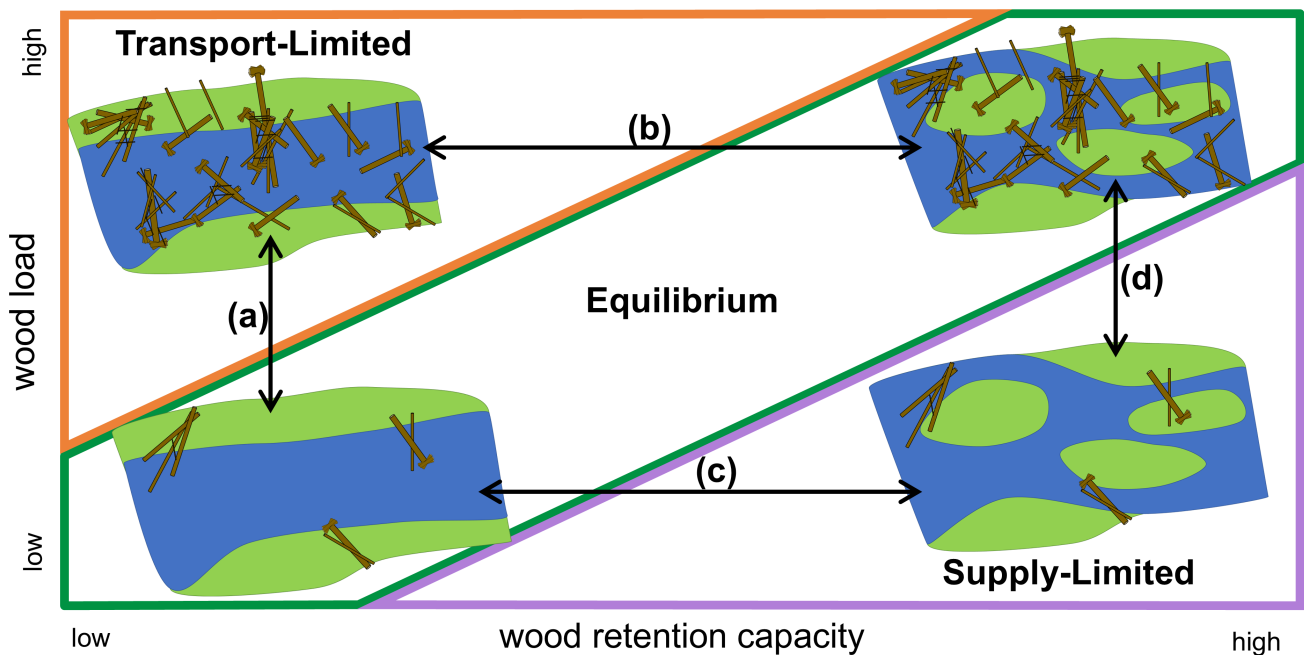


Figure 1 Conceptual plot of wood load versus wood retention capacity illustrating wood equilibrium and the two disequilibrium states: transport-limited and supply-limited. Illustrations show four end-member conditions, and lettered arrows show potential adjustments between states. Adjustments a and d involve changes in wood load, and adjustments b and c involve changes in wood retention capacity.

ment to a loss of hydraulic roughness via incision, narrowing, and other changes (Brooks et al., 2003; Castro and Thorne, 2019; Schumm et al., 1984), generally resulting in a loss of wood retention capacity and thus a transition towards wood equilibrium (i.e., adjustment leftward along arrow c in Figure 1). This adjustment towards lower retention capacity via incision and simplification of riverscapes has played out across the world in response to widespread degradation of wood supply and load (Brooks et al., 2006; Collins and Montgomery, 2002; Peipoch et al., 2015; Schanz et al., 2019; Wohl, 2014). Conversely, a shift in channel morphology, such as a sediment supply-induced increase in braiding (Kemper et al., 2023; Mueller and Pitlick, 2013), or width (Rachelly et al., 2022) could transition an equilibrium reach into supply limitation by increasing its wood retention capacity (i.e., adjustment rightward along arrow c in Figure 1). Like adjustment from transport-limited to equilibrium conditions, these adjustments may occur together to varying degrees.

1.2 Wood Equilibrium in Time and Space

Wood equilibrium is defined over a time and space of interest determined by the consistency of wood supply, transport, and retention (i.e., a single wood process domain; Wohl, 2019). In the channel, for example, wood supply may come primarily from upstream flux, and wood load may be a function of the abundance of upstream-facing obstructions that trap wood (Okitsu et al., 2021). In contrast, floodplain wood may come primarily from local tree fall or hillslope processes, and wood load may be determined more by factors that inhibit decay or enable vegetation to grow around and prevent downed wood from mobilizing (Wohl et al., 2009). Different wood process domains require sepa-

rate wood equilibrium evaluations (or at least treatment of wood retention capacity and supply in a normalized way) to avoid spurious inferences of process from observed wood load patterns.

Wood equilibrium state is fundamentally determined by whether wood load is commensurate with wood retention capacity. The spatial distribution of wood load reflects recruitment and transport processes over a time period set by the frequency and magnitude of those processes and possibly rates of decay and breakage. As such, wood equilibrium will reflect the time period over which the observed wood load spatial distribution has developed. This time period may be short (e.g., the preceding year) after a large flood that mobilizes all previously retained wood, moderate (e.g., the preceding 10 wood-mobilizing floods over many years) if each preceding flood only mobilizes a portion of retained wood, or long (e.g., the decadal timescale over which wood pieces may fully decay) if wood load is a primarily a function of recruitment with minimal fluvial transport. Generally, the time period integrated by any inference of wood equilibrium will be set by the occurrence and magnitude of wood-mobilizing floods or, if those are rare or decay is rapid, the timescale of decay.

The spatial and temporal scale reflected by wood equilibrium can be linked. The timescale over which wood equilibrium state applies may vary within a single riverscape across wood process domains, which can change depending on area of interest (e.g., the low-flow channel, bankfull channel, or floodplain) or longitudinally (e.g., from confined canyons to unconfined lowlands). Similarly, timescale may directly correlate with spatial scale: at the scale of a few reaches, wood equilibrium might reflect recent local recruitment, whereas at a longer spatial scale, wood equilibrium might reflect dynamics of wood redistribution occurring over many

years of flood-induced transport.

Determining the timescale and processes reflected by a wood equilibrium assessment requires information about wood provenance (i.e., local recruitment or fluvial transport), mobility, decay rate, and the magnitude of recent wood-transporting floods. This can come from existing data, such as stream gages, historical imagery, or local knowledge, or inference via examination of the nature of retained wood and generalizations from other sites (e.g., the factors that tend to regulate wood transport; [Kramer and Wohl, 2017](#)).

1.3 Objectives and Hypotheses

Our objectives were: 1) Introduce and detail the concept of wood equilibrium, then demonstrate how it can be used as a framework for assessing the wood regime. 2) Test for the existence of wood equilibrium and, if it existed, whether wood equilibrium state can change over both time and space in response to changing wood recruitment and transport conditions.

We assessed wood equilibrium to test the hypothesis that riverine wood load can be a predictable function of wood retention capacity (i.e., there exists a wood equilibrium state in which wood load is neither supply- nor transport-limited; H1). As we were evaluating H1, we iteratively refined two subsidiary hypotheses regarding how wood equilibrium state can change over space (H2) and time (H3). We hypothesized that changes in wood recruitment and transport processes, which together determine wood supply, can cause a longitudinal change in wood equilibrium state (H2). We also hypothesized that the shifting spatial distribution of wood recruitment within a river segment can cause wood equilibrium state to change over time (H3).

In testing these hypotheses, we present a methodological framework for assessing wood load, retention capacity, and supply that enables interpretation of wood (dis)equilibrium state. We show how the wood equilibrium framework can synthesize observed patterns in wood retention, recruitment, and transport to predict potential trajectories in wood retention and function, which can provide guidance for riverine wood management.

2 Methods

The two metrics that can be used to assess wood equilibrium are wood load and wood retention capacity. Wood load is easily measured; wood retention capacity is not. It is also difficult to interpret the relationship between wood load and retention capacity without at least some understanding of wood supply, which is determined by the magnitude, spatial distribution, and mechanisms of wood recruitment and transport. Our methods attempt to address these difficulties. However, this methodology is by no means the only way of assessing wood equilibrium.

Here, we use wood load to mean the quantity of wood within an area of interest. Wood load is determined by the difference between wood supply to that area of interest and wood depletion from it ([Benda and Sias,](#)

[2003](#)). Wood supply is generally a combination of the local recruitment of trees falling into the area of interest from either the floodplain or adjacent hillslopes and fluvial transport of wood into the area of interest from upstream. Wood depletion is generally a combination of wood decay, fluvial transport out of the area of interest, and other mechanisms that remove wood from the area of interest (e.g., wood burial in accreting floodplain). Anthropogenic wood placement could contribute to wood supply, and anthropogenic wood removal or combustion, anthropogenic or otherwise, could contribute to wood depletion.

2.1 Study Sites

We tested for wood equilibrium (i.e., H1) along two rivers in western Washington State, USA: the Snoqualmie River and its tributary, the Tolt River ([Figure 2](#)). The wood regimes of the Snoqualmie and Tolt have been altered by human activities, especially following European colonization and attempted killing, cultural assimilation, and forced removal of the indigenous occupants of the watersheds, the sduk^walbix^w (Snoqualmie) people, which began around 1855 ([Tollefson, 1992, 1996](#)). Post-colonization forest harvest across the entirety of the Tolt and primarily the North Fork of the Snoqualmie, but also to a lesser extent in the South and Middle Forks of the Snoqualmie, combined with direct wood removal, have likely reduced wood supply and load in both watersheds ([Collins and Sheikh, 2002; Scott and Wohl, 2018; Sisler and Lauer, 1939](#)). While forest harvest intensity and extent have decreased over time, especially since the 1970s and in the forks of the Snoqualmie, recovery of wood supply may lag decades behind ([Stout et al., 2018](#)). Forests in both watersheds are dominated by conifer species on hillslopes and drier portions of the valley bottom, including western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), and western redcedar (*Thuja plicata*), as well as deciduous species in wetter portions of the valley bottom, including black cottonwood (*Populus trichocarpa*), red alder (*Alnus rubra*), and bigleaf maple (*Acer macrophyllum*).

The Snoqualmie River flows from the crest of the Cascade Mountains as three major tributaries: the North, Middle, and South Forks of the Snoqualmie, which converge in the Three Forks reach ([Figure 2a](#)). We studied 45 km of the Snoqualmie and Middle Fork Snoqualmie (together referred to here simply as the Snoqualmie). In this segment, bankfull widths tend to range from 75 to 100 m, and drainage area ranges from 422 to 1,603 km². The Snoqualmie has extensive bank armoring along many of its outer bends, limiting channel migration. This portion of the Snoqualmie includes the 82 m-tall Snoqualmie Falls, which sets the base level of the broad alluvial plain over which the Snoqualmie and its tributaries flow. Downstream of Snoqualmie Falls, legacy effects of continental glaciation have created a low-gradient (0.1% slope), meandering river with low in-channel wood load ([Collins and Montgomery, 2011; Porter and Swanson, 1998](#)). Above the Falls, the Snoqualmie is steeper (0.3% slope) and ranges

from an artificially constrained single-thread channel to a multi-thread, anastomosing channel with high in-channel wood load. We sought to assess wood equilibrium on the Snoqualmie to understand why wood load decreased downstream of Snoqualmie Falls and thus test H2, that wood equilibrium state could change longitudinally due to a change in wood recruitment and/or transport. While we initially suspected that the Falls themselves might be powerful enough to pulverize logs in transport and limit the supply of large wood downstream, initial field observations revealed that not to be the case (see section 3.1 for details).

The Tolt River is a major tributary to the lower Snoqualmie. The Tolt flows west from the Cascade Mountains through confined valleys in its upper reaches, then through wider valleys lined with steep glacial terrace bluffs, and finally through a broad, low-gradient alluvial fan formed on the valley bottom of the Snoqualmie River before meeting the Snoqualmie. Our study extent on the Tolt varied over time, but generally covered the lower 8 to 10 km, including the alluvial fan and the widest portions of the valley lined by glacial terraces (Figure 2). The studied portion of the Tolt is primarily anastomosing where it flows between glacial terraces, then becomes single thread as it flows through a confining levee system on its fan (i.e., the lower 2.6 km). Its slope averages 0.4%, bankfull width is typically 55 m, and drainage area at the confluence is 262 km².

Our objective on the Tolt was to examine not only spatial variability in wood equilibrium, as on the Snoqualmie, but also how wood equilibrium can vary over time (H3). Despite the basin's history of diminished wood supply from logging, there have been examples of transiently high wood retention (e.g., anecdotal reports from a flood in 2009 described a wood raft at the Tolt-Snoqualmie confluence, which was no longer present in 2023). To test H3, we assessed wood equilibrium in three points in time: 1994, 2009, and 2023.

2.1.1 Area of Interest and Reach Delineation

Here, we focus our wood equilibrium assessment on the portion of the river corridor within which wood was mobile during recent floods preceding each observation, which we refer to as the wood-mobile area. This area includes the active channel and low or nascent floodplain surfaces that appeared to have conveyed wood during recent floods. In these study sites, and in this wood-mobile area, the dominant process that depletes wood load is mobilization and downstream transport, as decay tends to occur over a longer timeframe than is reflected by the wood load distributions examined here.

For each study site and time period, we first delineated the wood-mobile area in aerial imagery and, when available, digital elevation models collected close to the time of aerial imagery. We then split that area into reaches of locally consistent wood retention capacity (i.e., reach breaks separated reaches of noticeably different wood retention capacity because of having different abundances of in-channel obstructions such as bars, different sinuosity, different width, etc.; see section 2.4 below for explanation of how retention capacity

was measured). Reaches were thus of unequal length with no length constraints. We measured reach distance upstream using a manually delineated centerline that ran through the middle of the wood-mobile area. To assign reach length to each wood-mobile area reach and compute distance upstream, we split the centerline using the same reach breaks as the wood-mobile area and spatially joined the length of the centerline for each reach to the wood-mobile area reach to which it corresponded. We then measured wood load, retention capacity, and local wood supply for each reach of the wood-mobile area (sections 2.3 through 2.5).

2.1.2 Timescale

The length of time reflected by each of our observations (see section 1.2 above) varied depending on preceding wood-mobilizing floods and the availability of historical aerial imagery prior to each observation that we used to detect local wood supply (see section 2.5). This timeframe was 1989–1994 for the Tolt 1994 observation, 2007–2009 for the Tolt 2009 observation, 2019–2023 for the Tolt 2023 observation, and 2015–2019 for the Snoqualmie observation. Based on historical imagery showing frequent wood mobilization and redistribution of retained wood at these sites, as well as field observations of in-channel wood being only slightly decayed and showing abundant signs of transport (broken branches, abrasion marks, etc.), we infer that wood load distributions measured here reflect the effects of recent (on the order of a few years) floods and wood recruitment events, with minimal legacy effects from older floods or wood recruitment events. The timescales listed above cover these recent floods and recruitment events for each site and time examined. The only exception is the Tolt 2009 observation, which almost entirely reflects effects of the January 2009 flood. For that observation, however, the most recent pre-flood aerial imagery available was from 2007.

2.2 Field Observations

Assessing wood equilibrium requires measurements of wood load, retention capacity and supply that appropriately reflect the wood regime processes of interest (here, the recruitment, transport, and retention of primarily large logs). To design metrics of wood retention capacity and wood recruitment that appropriately reflected those processes, we had to understand the nature of those processes in the study rivers through field observation. This informed how we measured wood retention capacity (section 2.4) and wood recruitment (section 2.5).

We walked, boated, and swam the wood-mobile areas of each study reach during low flows, noting how wood was retained (i.e., in shallow zones, bifurcated channels, vegetated bars, etc.) and how wood appeared to be getting to the river (i.e., whether streamside forests were being eroded, tributaries were delivering substantial quantities of wood, active landslides were scouring mature or just nascent forest, etc.). We also installed a timelapse camera and visited several sites around Snoqualmie Falls from October 21 to 25, 2019, during a flood

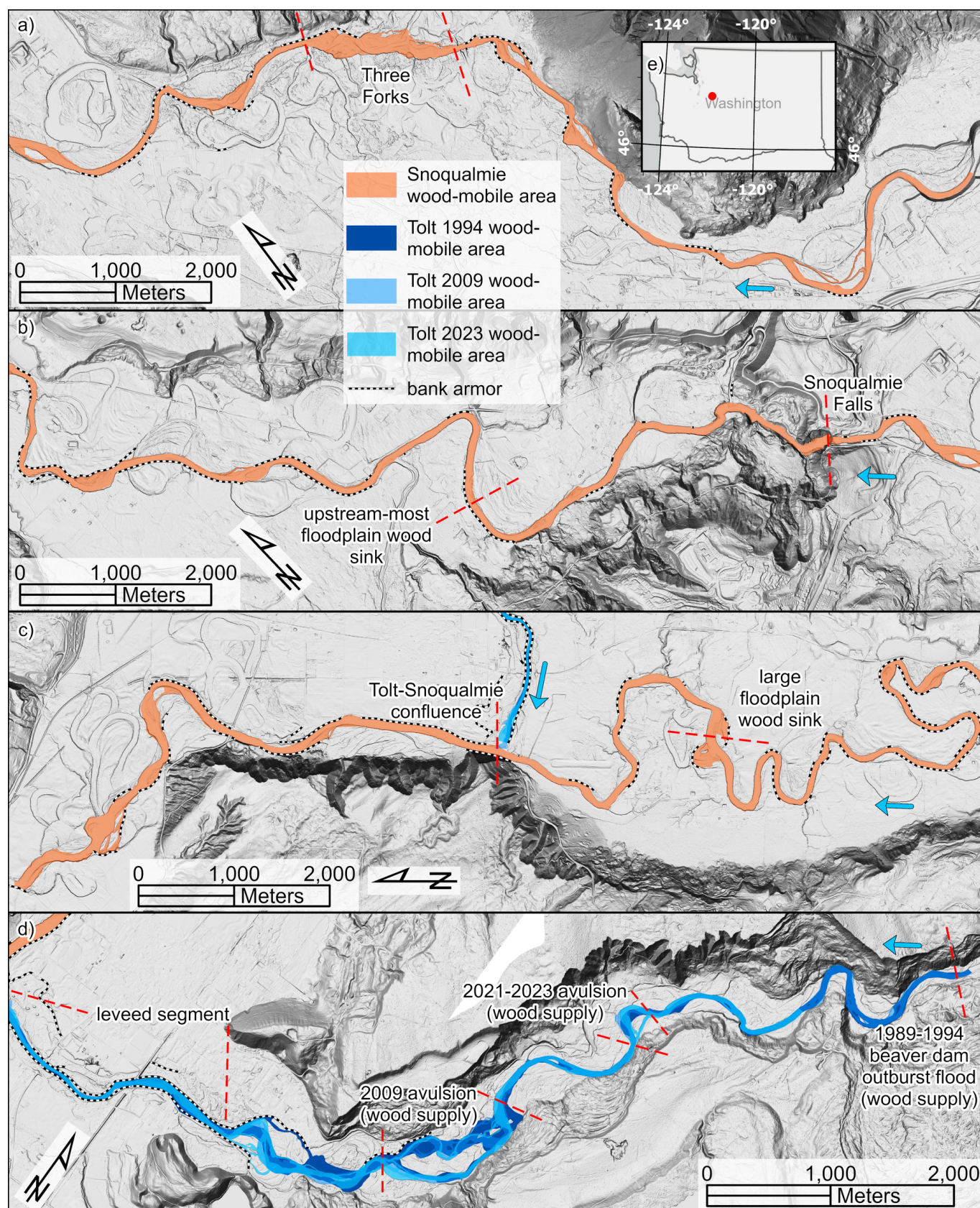


Figure 2 Map of the study rivers, showing the wood-mobile area and notable landmarks for the Snoqualmie (a, b, c, from upstream to downstream), and Tolt (c, d, from downstream to upstream), with inset showing site location in Washington State, USA (e). Blue arrows show flow direction. Basemap shows 2021 topography. See text for explanation of wood-mobile area and variability between those areas for the Tolt.

that transported a substantial amount of wood. These field observations and timelapse data also allowed us to verify our interpretation of remote sensing data and directly observe wood transport and retention.

2.3 Wood Load

We measured wood load in GIS by delineating a multi-part polygon covering all wood within the wood-mobile area visible in 0.08 to 0.3 m resolution aerial imagery.

Field observations indicated that wood jams tended to be of consistent height and were typically only slightly taller than individual wood pieces, indicating that it would be safe to assume that areal wood load measurements accurately represent relative differences in wood retention amongst reaches. We measured in aerial imagery all visible large wood (> 10 cm diameter and 1 m length), including any smaller wood that was part of a large wood accumulation, but excluding wood that was placed artificially. Artificially placed wood was recognizable in the field from excavator tooth marks and anchoring materials (e.g., chain, rock ballast, etc.), and we verified artificially placed wood locations with local land management agencies. We also delineated polygons covering the portions of the wood-mobile area that were unmappable due to being obscured by tree canopy.

We computed normalized wood load for each reach as the proportion of the mappable wood-mobile area (i.e., total wood-mobile area minus the unmappable area) covered by wood, which should correct for missing data from unmappable areas assuming that unmappable areas retained wood at densities similar to mappable areas (this appeared true based on qualitative field observations).

2.4 Wood Retention Capacity

Wood retention capacity is the capability of a reach to retain wood. Unlike sediment, wood can leave a reach (i.e., fail to be retained) via both downstream transport and decay. When the primary wood depletion process is transport during floods, wood retention capacity is the inverse of wood transport capacity. When the primary wood depletion process is wood decay, then wood retention capacity is a measure of the factors resisting decay. The importance of transport versus decay as a wood depletion process occurs along a continuum that varies with time and space. Wood retention capacity is difficult to measure in an absolute sense, so we use a relative measure here. We sought an indicator that would reflect the relative magnitude of the dominant mechanisms by which wood is retained for a given wood process domain over a given timescale and magnitude of flooding that has set the observed wood load distribution of interest. For the sites studied here, the dominant process of wood depletion is transport during floods, and thus we use a measure of wood retention capacity that reflects the inverse of transport capacity.

In the moderately large rivers studied here, channels are generally wider than log length and deeper than log diameter, allowing buoyant wood to float and move downstream in sporadic contact with the bed during even moderately high flows. Flume and modeling work indicates that wood is trapped either when friction between logs and channel boundaries overcomes downstream hydraulic force (i.e., when flow becomes shallow or wood is dragged along banks; Ruiz-Villanueva et al., 2020) or when it racks on an upstream-facing surface exposed to wood flux (Okitsu et al., 2021). This matches field observations of wood retention correlating with the abundance of large roughness elements, shallow flow areas such as bars, bifurcated channels,

and heterogenous flow patterns such as eddies (Galia and Máčka, 2023; Marshall et al., 2024; Picco et al., 2020; Scott and Wohl, 2018; Wyżga and Zawiejska, 2005; Yuan et al., 2024).

From this, we estimate that wood retention capacity is highest when there are abundant obstructions that can rack wood such as vegetated islands, shallow flow surfaces such as bars, and diversity in channel landforms. All these characteristics tend to correlate with the average total width of the wood-mobile area (i.e., the combined width of all channels and low, nascent floodplains), which has been empirically found to predict wood retention following a flood (Piton et al., 2024). Consequently, we use that metric here.

2.5 Wood Supply

We calculated the average width of the wood-mobile area by dividing the total area of each wood-mobile area reach by its along-valley length (derived from the centerline described in section 2.1.1). We assume due to the relatively short length of the studied portions of each river that flood flow characteristics, which may also influence retention capacity (i.e., during higher flows, retention capacity may overall be lower for a given wood-mobile area average width), did not vary longitudinally. Given both this assumption about longitudinal flow consistency and the fact that this metric is only a proxy for the many factors that influence wood retention, we treat it solely as a relative measure of retention capacity comparable among reaches within each study segment and time period analyzed, but not between them.

We sought to explain the longitudinal distribution of wood load as a function of both wood retention capacity and the spatial distribution of wood supply, specifically focusing on local wood supply (i.e., recruitment directly into a reach). We qualified the spatial distribution of wood recruitment as a binary variable for each reach of the wood-mobile area by reviewing aerial imagery at the time of and in the time period preceding each observation (see section 2.1.2). During field observations, we recorded four mechanisms by which wood was recruited to the wood-mobile area of the study rivers: 1) recent channel migration into streamside forest, 2) the presence of tributaries that showed evidence of wood transport (e.g., transport jams), 3) recent landslides or debris flows that scoured forested hillslope and connected to the channel, or 4) recent tree fall directly into the channel (e.g., from blowdown or falling snags). We denoted each reach as having a local wood supply only if aerial imagery examination revealed the presence of any of these four mechanisms. We did not differentiate the magnitude of wood supply for each reach, other than in noting when local wood supply was particularly large (e.g., a large debris flow or unusually large amount of channel migration into streamside forest); we simply noted as an attribute of the wood-mobile area polygon whether each reach had at least one local wood supply mechanism.

2.6 Statistical Analysis and Evaluation of Equilibrium State

We used a combination of correlation analysis and visual examination of longitudinal profile trends in the relationship between wood load, retention capacity, and supply to infer the equilibrium state of the study rivers. Our primary test of whether a river segment (i.e., multiple river reaches) was in wood equilibrium (H1) was whether reaches that lacked local wood supply displayed a significant, positive, monotonic correlation (i.e., both variables increasing consistently in relation to one another without respect to linearity) between wood retention capacity and wood load. That would indicate that as wood retention capacity increased, wood load increased in a way that reflected no evident limitation of wood supply.

We conservatively exclude from this correlation analysis reaches with local wood supply because wood load in those reaches may simply reflect such local wood supply, and not the inter-reach scale patterns in wood supply that define wood equilibrium over a longer river segment. That is, local wood supply can confound interpretation of whether cumulative wood supply is sufficient to sustain wood equilibrium over the longer spatial scales we were interested in.

This method of inferring wood equilibrium limits the minimum spatial scale of our analysis. It must be applied over enough reaches to achieve a sufficiently large sample size and wood retention capacity variability to achieve sufficient statistical power to robustly evaluate the correlation between wood load and retention capacity. While the actual number of reaches required to achieve these criteria will depend on the variability in that correlation, in practice, this limits us to evaluating river segments that are comprised of at least on the order of 10 reaches. Only in cases with many reaches of no local wood supply, a wide range of wood retention capacity, and low variability in the relationship between wood load and retention capacity could we evaluate a shorter river segment with this statistical methodology.

While this method of detecting wood supply limitation versus wood equilibrium requires a relatively large spatial scale, wood transport limitation can be detected on a much smaller scale — as small as a single reach — provided that reach is situated within a larger analyzed segment. This is because transport limitation can be inferred simply by looking for outliers from the overall correlation between wood retention capacity and supply. Reaches with particularly high wood load relative to their retention capacity can be inferred to be transport limited, provided that the relationship between wood load and retention capacity is well-established by a number of other reaches.

We performed statistical analysis using the R statistical package (R Core Team, 2023) and the tidyverse package (Wickham et al., 2019) in RStudio (Posit Team, 2025). We tested univariate correlations between wood load and retention capacity using a Spearman correlation coefficient (ρ , where -1 indicates a perfectly monotonic negative correlation, 0 indicates no correlation, and 1 indicates a perfectly monotonic positive correlation)

and inferred significance by visually interpreting data and examining p values and 95% confidence intervals (CI) on ρ . We tested for differences between sample groups using Wilcoxon rank sum tests and interpretation of boxplots and 95% CI on median values.

3 Results

3.1 Snoqualmie

The median wood load in the downstream segment of the Snoqualmie was considerably lower than the upstream segment: the median proportion of wood-mobile area covered by wood is 0.001 downstream of Snoqualmie Falls, significantly lower than the 0.007 value upstream ($p = 0.0071$). While we originally thought that Snoqualmie Falls may pulverize logs falling over it sufficiently to limit the supply of large wood downstream of the falls, we observed both locally high wood load and large logs in transport just downstream of Snoqualmie Falls during a flood in October 2019 (e.g., Figure 3).

The Snoqualmie exhibits multiple floodplain wood sinks that may effectively remove wood from the wood-mobile area (i.e., the channel). We noticed that May 28, 2009, aerial imagery revealed multiple large wood jams and rafts deposited during a large flood in January 2009 in open, unforested portions of the floodplain downstream of Snoqualmie Falls in the lower 25.5 km of the study segment (Figure 4). The wood raft shown in Figure 4a was at least 1.9 ha in area (likely greater, assuming some wood is obscured by vegetation, which overgrew much of this raft in subsequent years), an area larger than 10% of the reaches on the Snoqualmie. Note that the extensive outer bank armor on the Snoqualmie (Figure 2) limits channel migration and floodplain wood removal is common, so wood deposited in these floodplain sinks has little chance of making it back to the channel. These observations led us to think that the driver of lower wood loads in the downstream portion of the Snoqualmie was not pulverization by Snoqualmie Falls, but instead removal of wood from the wood-mobile area (i.e., channel) to these floodplain wood sinks, which could effectively cut off downstream supply.

3.1.1 Snoqualmie Wood Equilibrium Results

We tested H2 by examining the wood equilibrium state of the Snoqualmie both upstream and downstream of floodplain wood sinks. Upstream of the floodplain wood sinks, we found a significant, positive, monotonic correlation between wood load and retention capacity for reaches without local wood supply ($\rho = 0.66$, 95% CI from 0.34 to 0.84, $p = 0.0005$, $n = 25$; Figure 5b). In contrast, downstream of floodplain wood sinks, we found no such significant correlation for reaches without local wood supply ($\rho = 0.036$, 95% CI from -0.27 to 0.34, $p = 0.8189$, $n = 44$; Figure 5a).

The longitudinal profile of wood load for reaches upstream of floodplain wood sinks reveals that reaches both with and without local wood supply can retain high

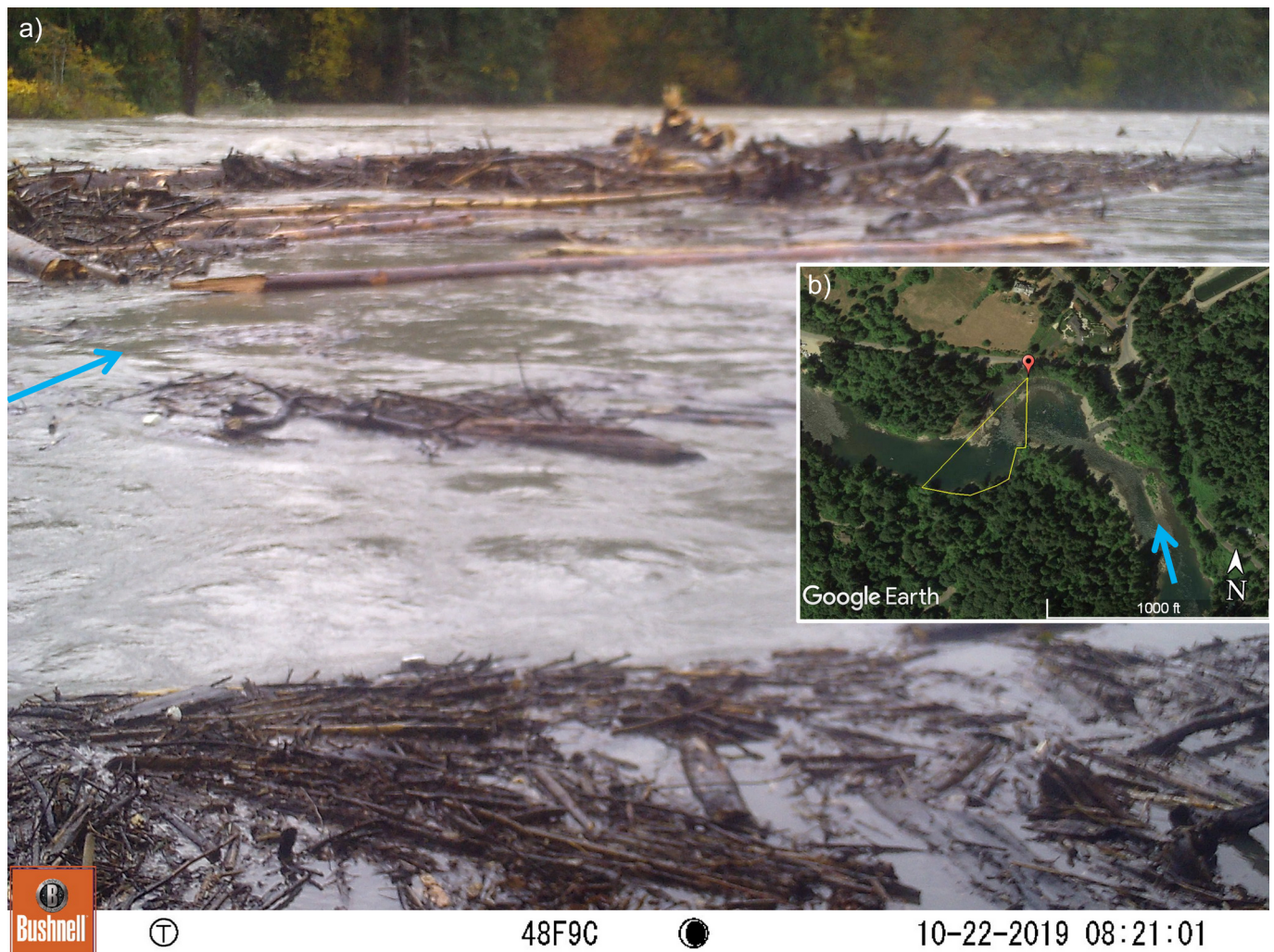


Figure 3 Image from a timelapse camera placed on the right bank of the Snoqualmie 1.3 km downstream of Snoqualmie Falls (a). Inset (b) shows location of camera (red) and approximate field of view (yellow). Blue arrows indicate flow direction. Flow at this time was 1,220 cms at the Snoqualmie River near Snoqualmie, WA USGS gage (12144500).

quantities of wood commensurate with their retention capacity (Figure 5c). The Three Forks reach a potential wood trap (i.e., it has a high wood retention capacity and could conceivably cut off upstream supply to downstream reaches) but is also a notable source of wood supply from tributaries and ongoing bank erosion into streamside forest, which could offset its trapping effects on downstream wood flux. Indeed, when we split our sample into reaches without local wood supply downstream and upstream of Three Forks, we found that both still show a likely positive correlation between wood load and wood retention capacity (for reaches downstream, $\rho = 0.44$, 95% CI from -0.09 to 0.77, $p = 0.0913$, $n = 16$; for reaches upstream, $\rho = 0.88$, 95% CI from 0.51 to 0.98, $p = 0.0031$, $n = 9$).

Moving downstream into the segment with floodplain wood sinks, wood load drops with only a few outlier reaches (Figure 5c). Wood load tends to be low across a range of retention capacity. High wood loads only occur immediately downstream of or at sites of high local wood supply. These high wood load reaches are located in a subsegment at 17.2–22.2 km from the downstream boundary of the study segment and have experienced the greatest recent bank erosion into streamside forest among reaches in this segment. However, the correla-

tion between wood load and retention capacity is not significant for reaches in this subsegment without local wood supply ($\rho = 0.50$, 95% CI from -0.59 to 0.87, $p = 0.4976$, $n = 7$) or even when considering all reaches in that subsegment ($\rho = 0.46$, 95% CI from -0.21 to 0.84, $p = 0.1543$, $n = 11$). Even downstream of the Tolt, which could plausibly be a substantial source of wood, there is no significant correlation between wood load and retention capacity for reaches without local wood supply ($\rho = 0.44$, 95% CI from -0.24 to 0.83, $p = 0.1825$, $n = 11$). While that subsegment downstream of the Tolt does display a significant, positive correlation between wood load and retention capacity when all reaches are considered ($\rho = 0.59$, 95% CI from 0.13 to 0.84, $p = 0.0152$, $n = 17$), this may be driven primarily by reaches with local wood supply, which are common in this subsegment due to an abundance of ongoing bank erosion into streamside forest.

3.1.2 Snoqualmie Wood Equilibrium Discussion

Based on the relationship between wood load and retention capacity and its marked change from upstream to downstream of observed floodplain wood sinks, we conclude that the wood equilibrium state of the Sno-



Figure 4 Aerial imagery from May 28, 2009 showing large wood rafts (outlined in orange) in the floodplain of the Snoqualmie approximately 10.7 km (a) and 25.5 km (b) upstream of the downstream end of the study segment. Blue arrows indicate flow direction. Panel a shows the “large floodplain wood sink” labeled in Figure 2 and Figure 5. Panel b shows the “upstream-most floodplain wood sink” labeled in Figure 2.

qualmie is strongly regulated by those sinks. Upstream of the floodplain wood sinks, the Snoqualmie River is in a state of wood equilibrium, supporting H1, as evidenced by the strong, positive, monotonic correlation between wood load and retention capacity for reaches that lack local wood supply. That is, wood load is limited only by wood retention capacity, and not by wood supply. This condition describes even reaches upstream of Three Forks, which is likely the largest single source of wood in the studied segment. That implies that there must be sufficient wood flux from the upper basin of the Middle Fork Snoqualmie to supply wood to those upper reaches. Further, even downstream of Three Forks, which could act as a wood trap, reaches are likely still in a state of wood equilibrium, suggesting sufficient supply persists downstream of Three Forks and that it is not depriving those reaches of wood supply.

In contrast, in the downstream segment with flood-

plain wood sinks, where wood can be removed from the wood-mobile area and sequestered on the floodplain as it is transported overbank, the Snoqualmie is in a wood supply-limited state, as evidenced by the lack of correlation between wood load and retention capacity. This supports H2 by demonstrating that wood equilibrium state can vary longitudinally due to changes in wood supply driven by wood transport dynamics. While the subsegment from 17.2–22.2 km and the subsegment downstream of the Tolt may be in a state of wood equilibrium due to notable local sources of wood supply, the spatial extent of that potential equilibrium is too small to quantitatively evaluate with our methodology.

We conclude that floodplain wood sinks on the Snoqualmie limit wood supply by limiting the transport distance of wood. That is, wood moving in the channel during floods is likely transported overbank where flow can pass onto the floodplain without encountering stream-

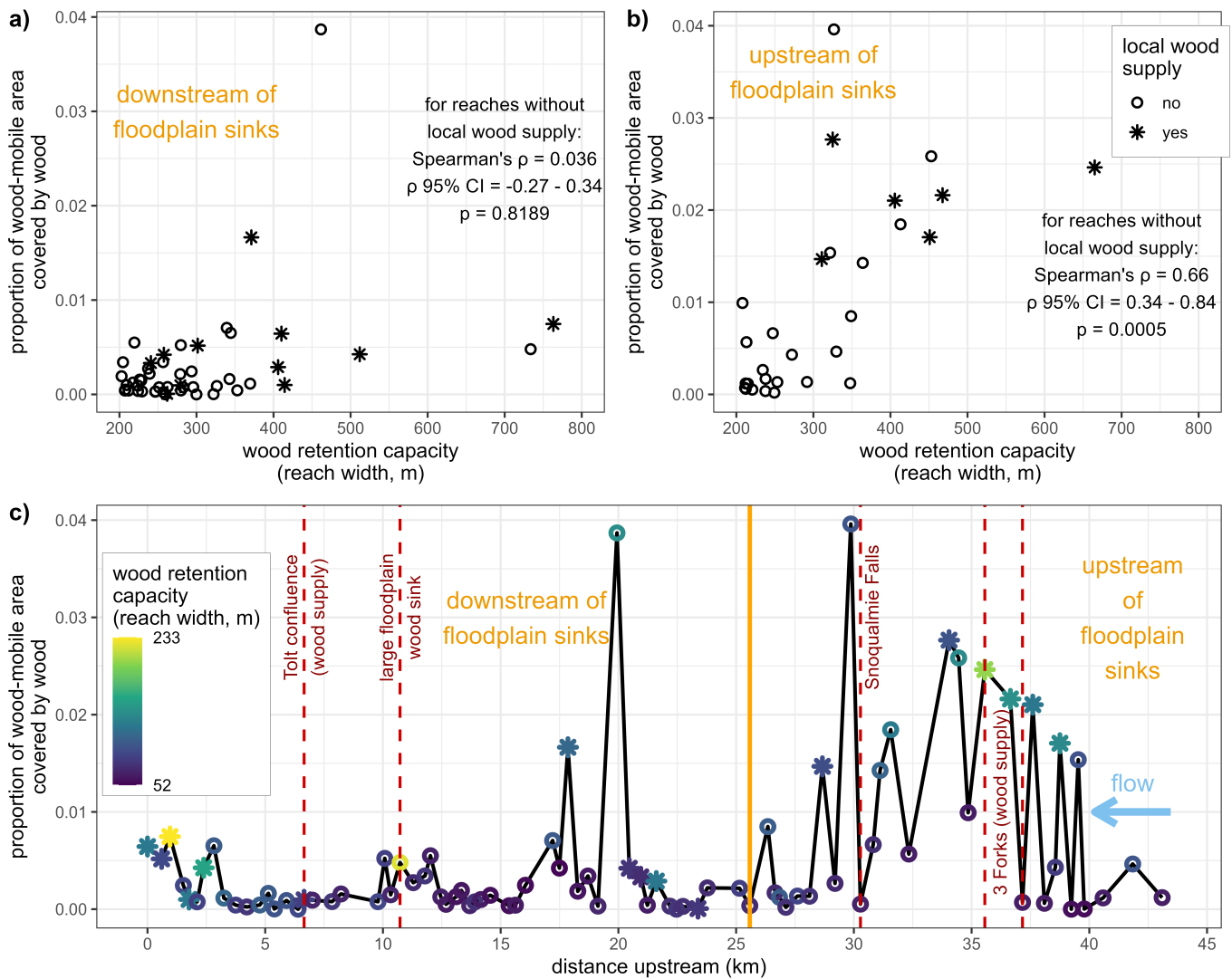


Figure 5 Relationship between wood load and wood retention capacity for the segment downstream of floodplain sinks (a) and upstream of floodplain sinks (b) and wood load as a longitudinal profile (c) for the Snoqualmie River. Points, which represent reaches, are symbolized by whether they have local wood supply.

side vegetation that could keep it in the channel. Once wood enters these open patches of floodplain, it racks against vegetation far from the channel (e.g., Figure 4) and is either removed artificially or sequestered on the floodplain by vegetation growth and a lack of subsequent bank erosion, which is rare along most of the Snoqualmie due to the extensive bank armor along outer bends (Figure 2). This means that wood in transport in the channel is only likely to travel as far as the next floodplain wood sink, thus limiting upstream wood supply to any given reach to wood recruited downstream of the nearest floodplain wood sink.

3.2 Tolt

3.2.1 Tolt 1994 Wood Equilibrium Results

The Tolt in 1994 exhibited a significant, positive, monotonic correlation between wood load and retention capacity for reaches without local wood supply ($\rho = 0.57$, 95% CI from 0.20 to 0.79, $p = 0.0039$, $n = 24$; Figure 6a). This is likely due to two major sources of wood: 1) a 3.7-ha beaver pond drained in what we interpret to be a beaver dam outburst flood, recruiting a 0.6 ha swath

of forest from a hillslope into the Tolt between 1989 and 1994 (Figure 7), and 2) substantial channel migration from 3–5 km upstream of the Snoqualmie confluence that recruited wood from streamside forests. Examining the longitudinal profile (Figure 6b), it appears that the wood supplied from the beaver dam outburst flood and any wood from farther upstream accumulated on mid-channel bars in the low retention capacity reaches downstream of the outburst flood, much of which subsequently mobilized as of the next available aerial image in 1998 (Figure 8).

3.2.2 Tolt 2009 Wood Equilibrium Results

In 2009, we found no significant correlation between wood load and retention capacity for reaches without local wood supply ($\rho = 0.33$, 95% CI from -0.12 to 0.67, $p = 0.137$, $n = 22$; Figure 9a). This lack of correlation still holds when we exclude the confluence reach, which exhibited abnormally high wood load ($\rho = 0.24$, 95% CI from -0.22 to 0.62, $p = 0.2908$, $n = 21$). With the exception of the confluence reach, high wood retention occurred only in reaches with local wood supply.

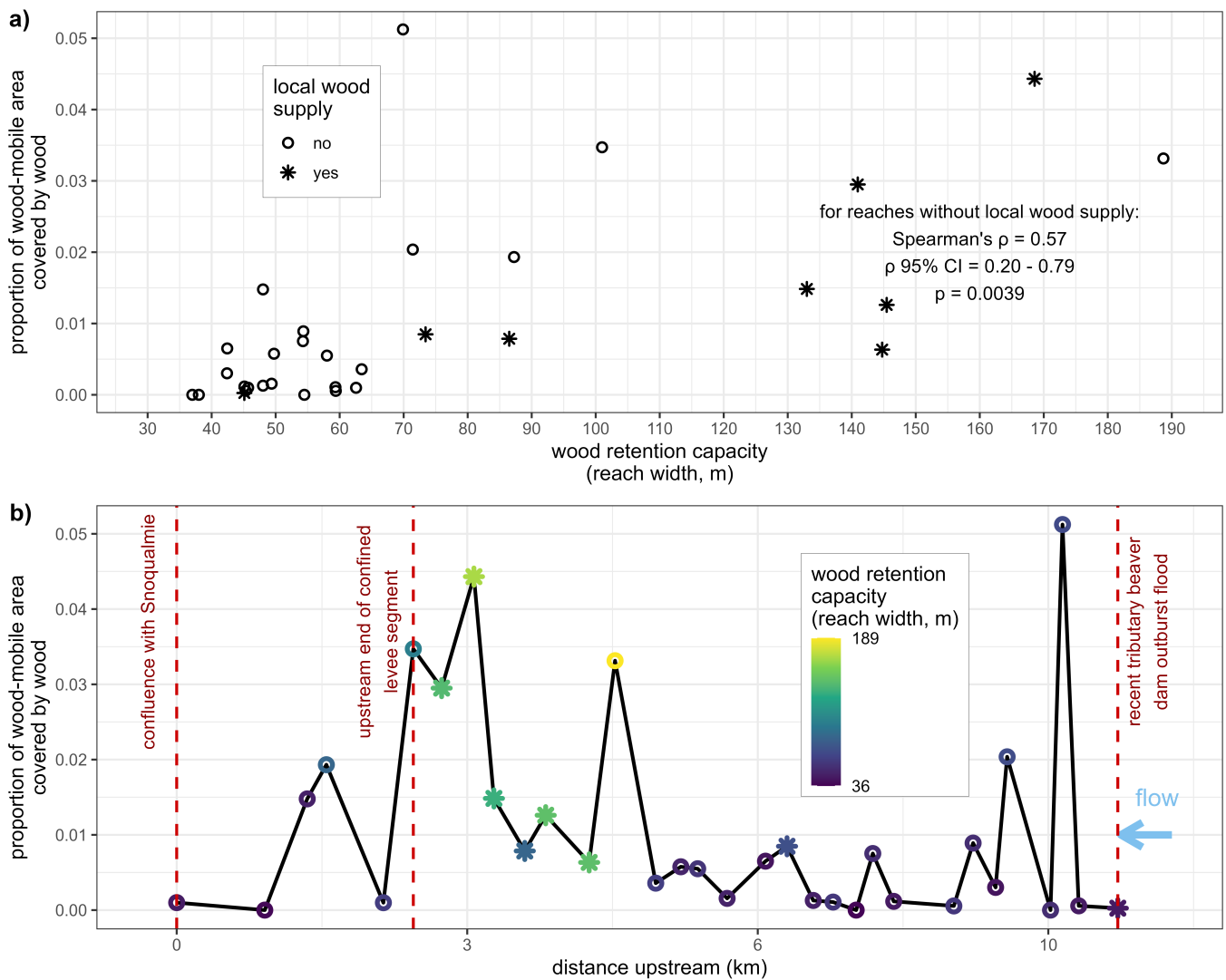


Figure 6 Relationship between wood load and wood retention capacity (a) and wood load as a longitudinal profile (b) for the Tolt River in 1994. Points, representing reaches, are symbolized by whether they have local wood supply.

A large avulsion in January 2009 supplied a substantial amount of wood to the lower 4.5 km of the Tolt (Figure 9b) by recruiting 1.7 ha of streamside forest. While some of that wood was likely trapped just downstream, it appears that enough made it to and through the low retention capacity segment of the Tolt near the confluence to form a 0.75 ha wood raft (Figure 10a). The upper 2/3 of that wood raft was removed during a levee set-back project later in 2009 (Todd Hurley, personal communication, 2025), although the remaining lower 1/3 had almost entirely mobilized by 2012, the next available aerial image (Figure 10b). Upstream of that avulsion, which includes most of the study segment, wood load remained low even in reaches with high retention capacity.

3.2.3 Tolt 2023 Wood Equilibrium Results

In 2023, the Tolt again displayed a strong, positive, monotonic correlation between wood load and retention capacity ($\rho = 0.73$, 95% CI from 0.47 to 0.88, $p < 0.0001$, $n = 26$; Figure 11a). This may have been driven by a substantial avulsion that occurred between 2019 and 2021 in the upper portion of the study segment

combined with bank erosion into streamside forest further downstream (Figure 11b). Around that avulsion, wood load was abnormally high in 2023 relative to other reaches of similar retention capacity. By 2023, the channel appeared to be actively migrating around the large wood jam that had formed after the avulsion (Figure 12), although we noticed during our 2024 field observations that another avulsion formed a channel through the center of the wood jam, mobilizing a portion of it.

3.2.4 Tolt Wood Equilibrium Discussion

Wood equilibrium state on the Tolt varied over time, from equilibrium in 1994 to supply-limited conditions in 2009 and finally back to equilibrium in 2023. The presence of wood equilibrium supports H1, and the variability of equilibrium state over time supports H3.

In 1994, wood equilibrium across much of the study segment was indicated by wood load positively correlating with retention capacity for reaches without local wood supply. This was likely driven by wood supply from the beaver dam outburst flood and substantial channel migration further downstream. The only notable deviation from equilibrium was the reach just

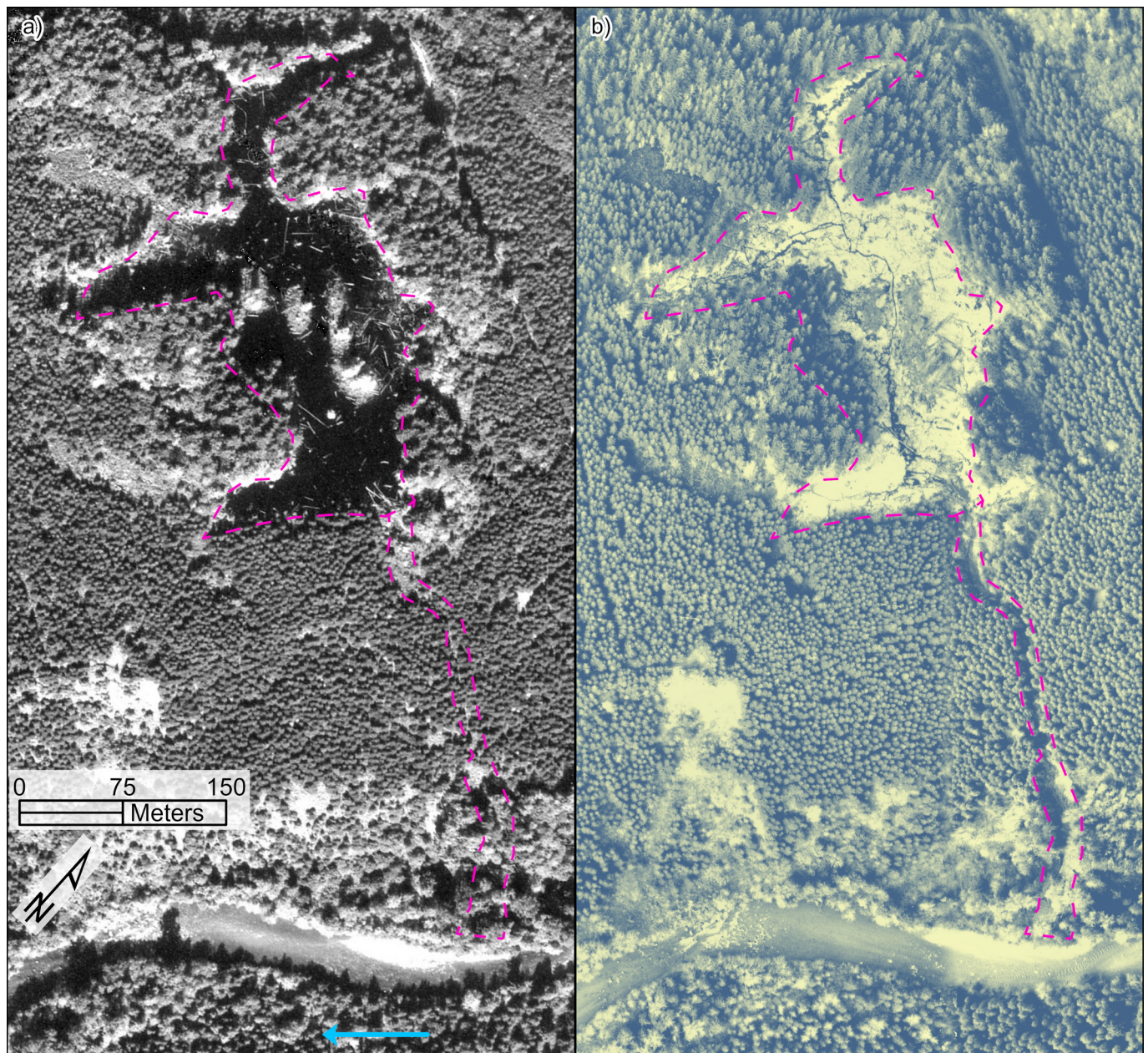


Figure 7 Aerial imagery from 1989 (a) and 1994 (b) showing the beaver pond and the debris flow scar resulting from its drainage (outlined in pink dashed line). Blue arrow indicates flow direction.

downstream of the beaver dam outburst flood, which exhibited transport-limited conditions. That is, it exhibited wood load greater than retention capacity would predict based on other reaches in the study segment, which took the form of a single large, bar-apex jam that was short-lived adjustment mode *a* in Figure 1).

In 2009, a primarily supply-limited state was indicated by the lack of correlation between wood load and retention capacity for reaches without local wood supply. We suspect that the large avulsion around 4.5 km upstream of the confluence may have created wood equilibrium conditions downstream of that avulsion. However, we failed to quantitatively demonstrate equilibrium conditions there because reaches without local wood supply had low variability in wood retention capacity, limiting our ability to test for a correlation between wood load and retention capacity. Thus, while we are confident in the supply-limited conditions up-

stream of the avulsion, we are uncertain downstream. The wood raft in the confluence reach of the Tolt likely represented a transport-limited condition, which was resolved by transport of the portion of the raft not already removed by humans (Figure 10, adjustment mode *a* in Figure 1).

In 2023, the Tolt largely returned to wood equilibrium conditions, likely due to substantial wood supply in the upstream portion of the study segment (adjustment mode *d* in Figure 1). Again, though, transport-limited conditions may have developed in the reach that received much of the wood from the 2019–2021 avulsion. It appears that this transport-limited condition may be resolving itself via channel migration around the retained wood (Figure 12). Burial of the jam in nascent floodplain would reduce the wood load within the wood-mobile area, possibly returning the reach to wood equilibrium (adjustment mode *a* in Figure 1). Alternatively,

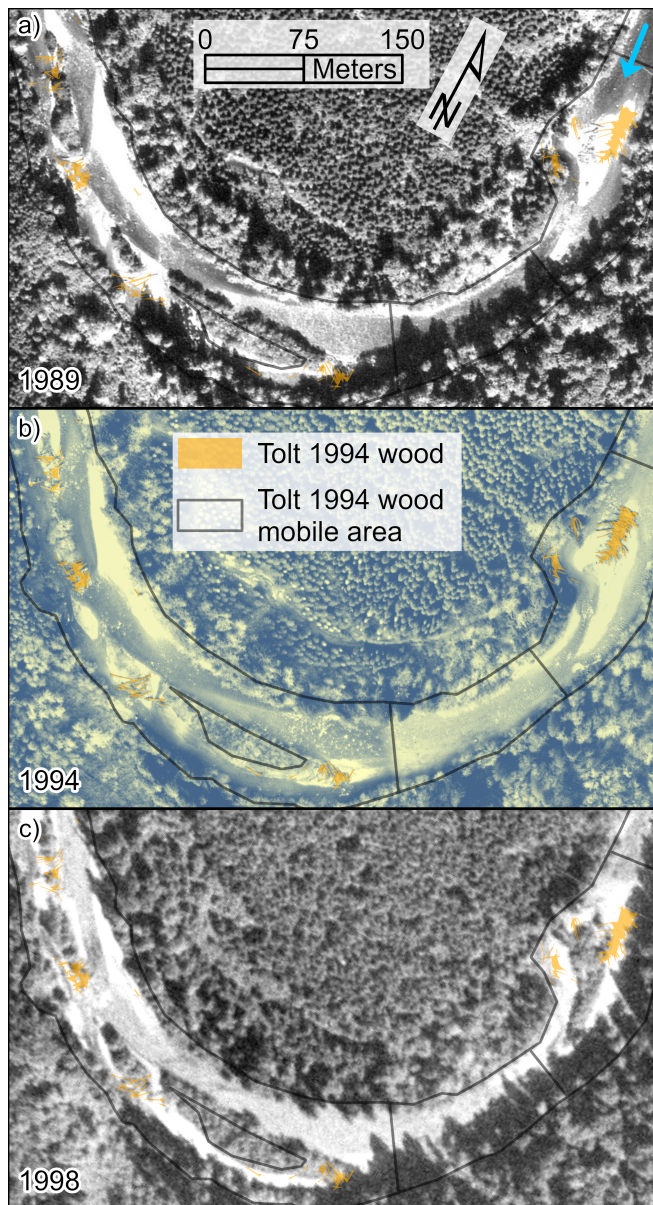


Figure 8 Aerial imagery from 1989 (a), 1994 (b), and 1998 (c) showing the reaches 9.2–10 km upstream from the Snoqualmie confluence. Blue arrow indicates flow direction.

channel migration may be widening the reach and increasing its retention capacity to accommodate the high wood load (adjustment mode *b* in Figure 1).

Wood equilibrium on the lower 10 km of the Tolt seems to require well-distributed wood recruitment along the study segment, which may explain high wood loads in the study segment, despite the historical legacy of a loss of wood supply from the upper watershed. Within the lower 10 km of the Tolt, wood can come from either hillslope erosion or fluvial erosion of streamside forests, but wood equilibrium is limited to reaches downstream of major wood sources (e.g., the beaver dam outburst in 1994 or channel migration into streamside forest in 2023). When reaches are deprived of these nearby sources of wood, they transition to a supply-limited state, as exhibited in the upper portion of the study segment in 2009.

Wood equilibrium variability and the local nature of the wood recruitment driving that variability sup-

port the idea of a strong link between the wood regime and geomorphic condition and evolution (Collins et al., 2012; Scott and Wohl, 2018). Comparing wood retention in 1994 and 2023 to that in 2009 shows that avulsion and floodplain reworking not only generate wood supply, but also the geomorphic spatial heterogeneity and wood retention capacity needed to trap wood (Scott and Wohl, 2018) and prevent wood export to the Snoqualmie. In 2009, most wood supply was likely just upstream of the single-thread, low retention capacity, leveed reach of the Tolt, and thus most wood was simply exported to the Tolt-Snoqualmie confluence without being retained. In 1994 and 2023, however, wood supply was upstream of numerous multi-thread reaches experiencing active avulsions, which allowed wood equilibrium to develop as supplied wood was retained in these heterogeneous reaches. The maintenance of such heterogeneous reaches via avulsion is thought to in turn depend at least in part on wood (Collins and Montgomery, 2002; Marshall et al., 2024; Scott, 2024; Wohl, 2011). Along the Tolt, there appears to be a sufficiently wide valley bottom to provide enough time for streamside forests to mature before the floodplain is fully reworked by channel migration. This provides a substantial source of wood supply and suggests a floodplain large wood cycle (Collins et al., 2012) that is at least sufficient to sustain periods of wood equilibrium and continued avulsion.

3.3 Utility of the Wood Equilibrium Concept for Riverine Wood Management

A key objective of many river restoration efforts is to increase riverine wood function in driving the geomorphic, hydraulic, and biogeochemical processes that create and sustain riverine ecosystems (Grabowski et al., 2019; Ockelford et al., 2024; Roni et al., 2015). A key difficulty of wood reintroduction is that wood is a transient component of the riverscape (Wohl et al., 2023); wood load must be sustained from upstream and local wood supply to maintain wood function as wood decays, breaks, and mobilizes downstream. Even when riverine wood is securely anchored in place, it tends to lose half its mass to decay alone in two decades (Andersen et al., 2016; Sass, 2009; Scherer, 2004; Spänhoff and Meyer, 2004) if it does not physically break down (Merten et al., 2013) or decay even sooner (e.g., in tropical environments; Wohl et al., 2009). Thus, to plan for wood transience, **a crucial question that riverine wood management must answer is: Will there be sufficient local and upstream wood supply to sustain the desired wood load, and thus wood function, engendered by wood placement?** The answer to that question sets key expectations for monitoring and adaptive management — if wood loads will not be sustained over time by fluvial processes, then artificial wood replenishment will be necessary to sustain desired wood load and function.

A wood equilibrium assessment provides a low-cost way of answering this question that avoids often infeasible direct measurements of wood supply (e.g., via multi-year video monitoring of wood flux; Ruiz-Villanueva et al., 2024). The wood equilibrium concept is in this way similar to the Capacity-Supply Ratio (CSR) con-

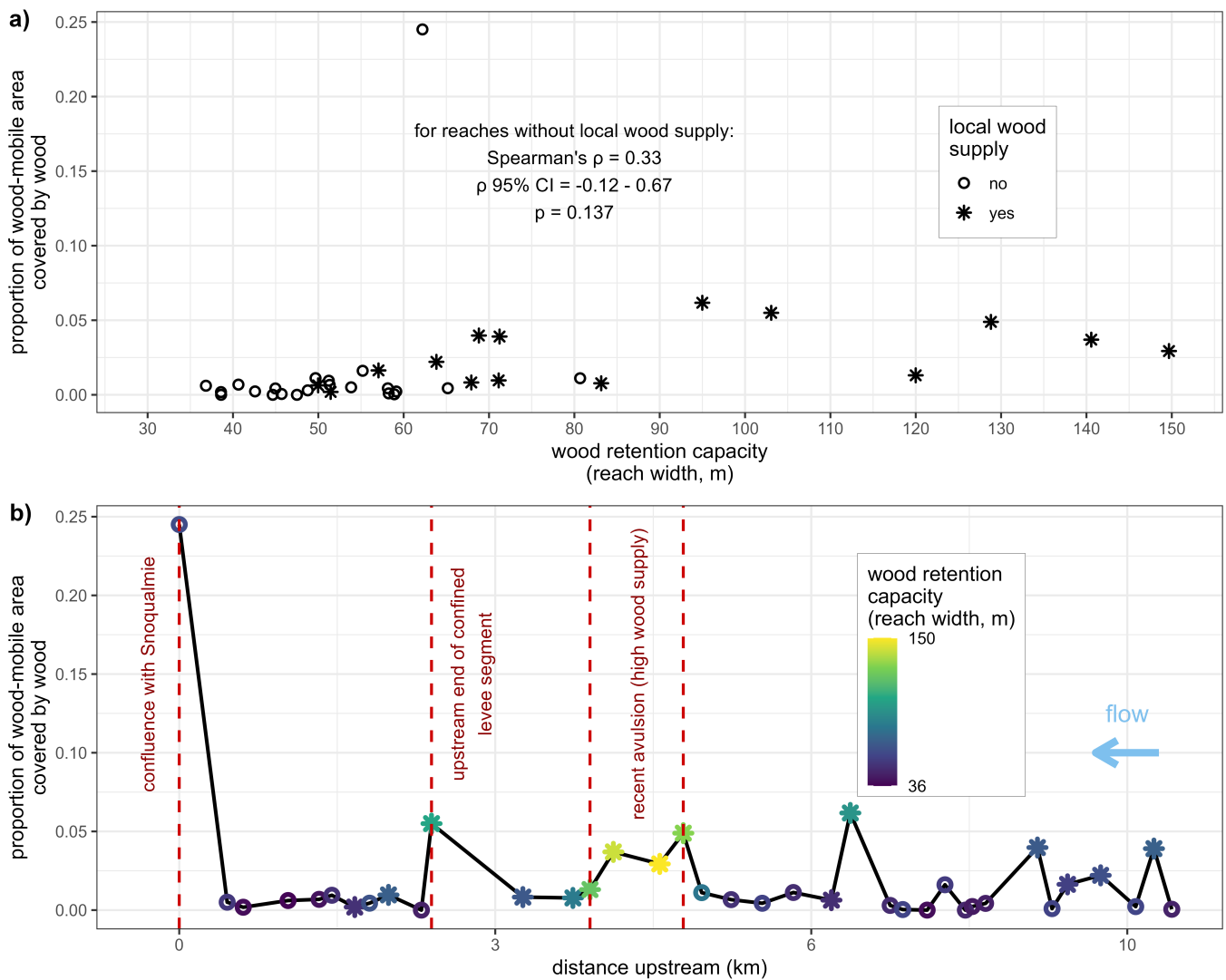


Figure 9 Relationship between wood load and wood retention capacity (a) and wood load as a longitudinal profile (b) for the Tolt River in 2009.

cept for evaluating the need for sediment management (Stroth et al., 2017), in that equilibrium state directly indicates the ratio between wood supply and wood load, as opposed to attempting to quantify wood supply precisely.

The results of the wood equilibrium assessments presented here can provide guidance for wood management efforts. On the Snoqualmie, a wood reintroduction effort downstream of the floodplain wood sinks would likely need either a local supply of wood or periodic wood reintroduction to sustain a wood load greater than the low quantity generally present there. Wood reintroduction upstream of the floodplain wood sinks may be sustained from upstream supply alone, although an analysis of wood equilibrium state over a longer time period, as on the Tolt, would be helpful to inform whether wood supply along the upper Snoqualmie is consistent over time. On the Tolt, wood placement commensurate with retention capacity in the downstream-most leveed reaches is likely to be sustainable given that there usually is upstream wood supply to that location, although artificial replenishment to sustain wood load could be required during lulls in upstream channel migration. While retention capacity is generally low in

those leveed reaches, an increase in retention capacity, for instance, by reconnecting channels currently disconnected by levees, could enable the sustainable placement of higher wood loads.

3.4 Assessing Wood Equilibrium in Other Settings

The wood equilibrium concept can also be applied to cases unlike those presented here, although assessing wood equilibrium in other wood process domains or for other classes of wood (e.g., small wood) may require a change in methodology and framing.

The key factors that determine wood equilibrium assessment methods and framing are: 1) the objective of the assessment, including the portion of the river-scape and sizes of wood that are of interest, 2) the mechanism by which wood tends to be depleted from the area of interest over the timescale of interest (i.e., decay versus downstream transport), and 3) the mechanisms by which wood can be supplied to the area of interest (e.g., local point-source recruitment versus accumulation of transported wood from upstream). River size may also determine the feasibility of various data collection methods (e.g., remote sensing-based versus ground



Figure 10 2009 aerial image showing the extent (highlighted in orange with black outline) of the wood raft that formed at the Tolt-Snoqualmie confluence following the January 2009 flood (a) and the same area in 2012 (b). Blue arrow indicates flow direction.

surveys).

A wood equilibrium assessment is primarily defined by how one measures and interprets the relationship between wood load and retention capacity. Wood load can be characterized by a limited set of potential metrics (e.g., wood volume, area, piece count, etc.), and the choice of metric is unlikely to substantially affect assessments of wood equilibrium. In contrast, wood retention capacity can be characterized by a much larger set of potential metrics (e.g., braid index, geomorphic spatial heterogeneity, even metrics reflecting the potential for wood retention itself to enable further wood retention; [Scott and Wohl, 2018](#)), and the choice of metric is critical to interpreting wood equilibrium state. Different objectives and wood process domains may also justify different interpretive methods than used here (i.e., the univariate correlation analysis described in section 2.6). If retention capacity was more complex than in the rivers studied here, multivariate analysis may be required, with retention capacity being determined as the combination of many metrics.

For example, in smaller streams with less frequent large wood transport, the focus of wood equilibrium assessment may shift to towards smaller wood (e.g., [Wohl and Scamardo, 2022](#)). Understanding small wood

dynamics can be crucial to understanding patterns of wood jam porosity ([Livers et al., 2020](#); [Manners et al., 2007](#)) and thus explaining variability in wood function, particularly in small streams or secondary channels that may not transport large wood ([Scott, 2024](#); [Sear et al., 2010](#); [Wohl and Scamardo, 2022](#)). A small wood equilibrium assessment may focus more on large wood jams, living riparian vegetation, or confinement as determinants of retention capacity ([Guiney and Lininger, 2022](#); [Scott and Wohl, 2018](#)) and sources of small wood supply (e.g., streamside shrubs, areas of canopy overhanging the stream, streamside floodplain deposits of small wood) that might not be as relevant for an assessment of large wood. Commensurately, it may require analysis over different spatial and temporal scales, reflecting the more frequent but possibly short-distance transport of small wood. It could also be informative to separately assess wood equilibrium for large wood over a long timescale and small wood over a shorter timescale that reflects its more rapid cycling through the riverscape.

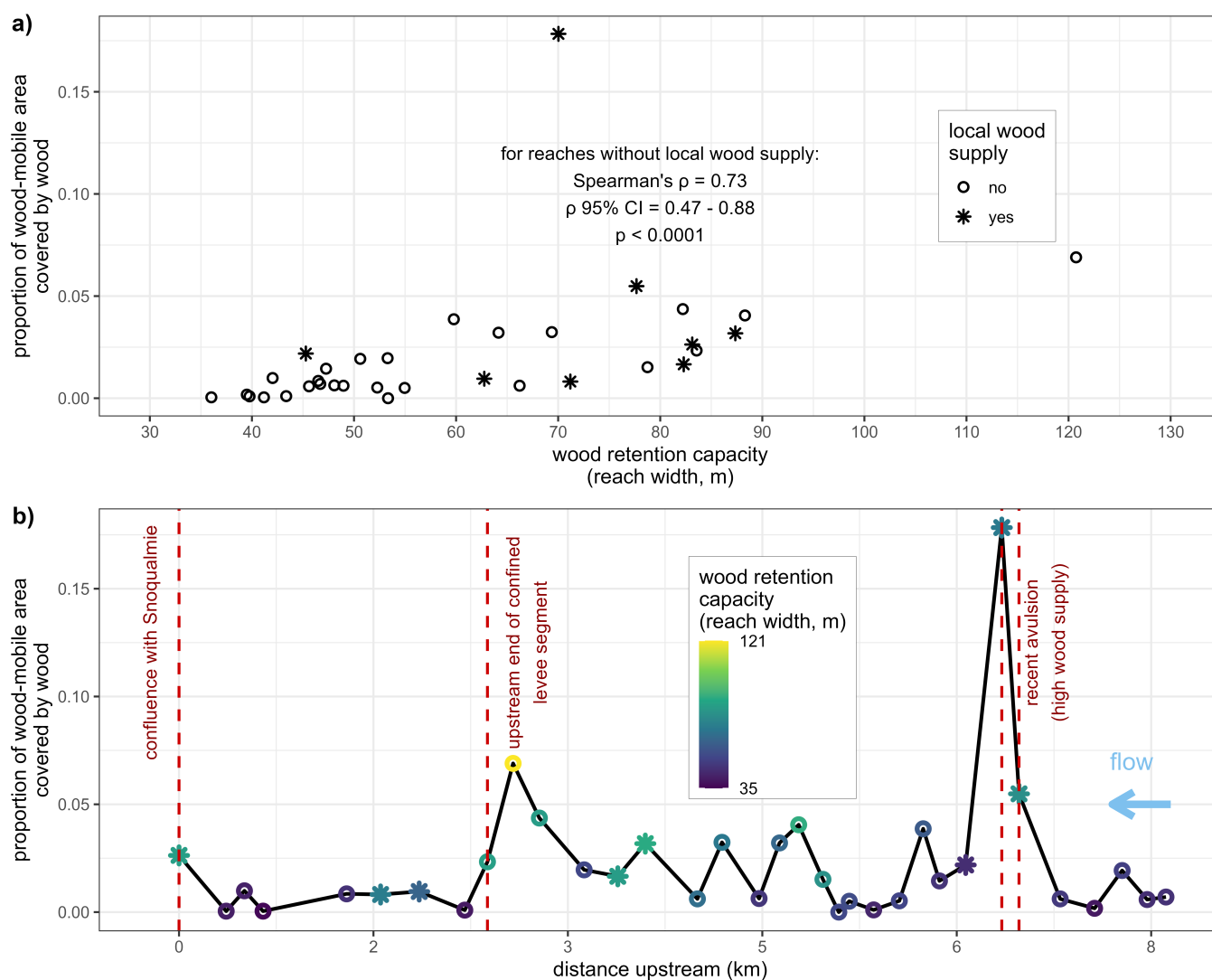


Figure 11 Relationship between wood load and wood retention capacity (a) and wood load as a longitudinal profile (b) for the Tolt River in 2023.



Figure 12 Aerial imagery from 2021 (a) and 2023 (b) showing the large wood jam that formed due to the avulsion that occurred between 2019 and 2021 approximately 6.8 km upstream of the Snoqualmie confluence.

Wood equilibrium assessment could also focus on floodplain environments, which might produce insights into the wood regime over much longer timescales or help test hypotheses regarding the influence of vegetation and channel development on wood supply to, transport through, and retention within floodplains (e.g., Lininger et al., 2021). There, decay may be the primary wood depletion mechanism, requiring wood retention capacity to reflect inhibitors of decay (in which case, “depletion-limited” may be a more accurate term than “transport-limited”). Wood supply may also vary depending on floodplain forest characteristics, which may regulate whether floodplain wood is derived locally or from upstream (Guiney and Lininger, 2022; Wohl, 2019).

4 Conclusions

Here, we formalize the wood equilibrium concept: that if a river has sufficient wood supply to fill its wood retention capacity, it will be in a state of wood equilibrium characterized by wood load that is commensurate with wood retention capacity. Conversely, with too much or too little wood supply for its retention capacity, a river can be in a state of wood transport limitation or supply limitation, respectively. We show through application of this concept that it can explain wood load patterns in relation to wood supply and retention capacity (the inverse of transport capacity). On the Snoqualmie, wood equilibrium assessment revealed that floodplain wood sinks can regulate wood transport distance and thus induce a longitudinal change in equilibrium state. On the Tolt, assessment revealed the conditions necessary for wood supply and the variability of that supply over time, which in turn induces temporal variability in equilibrium state. Wood equilibrium assessment crucially serves as a semi-quantitative way of relating and holistically assessing the three core components that define the wood regime: wood recruitment, transport, and retention (Wohl et al., 2019).

The wood equilibrium concept generally, and especially the methods used to assess it here, present a relatively low-cost way of assessing the sustainability of river restoration that relies on artificially placed wood or, more generally, river stewardship in river ecosystems that depend on wood. Wood equilibrium assessment can describe the spatial and temporal patterns of the processes that recruit, move, and retain wood in rivers. That information can guide wood reintroduction, for example, by enabling estimates of how much wood might be sustainable given upstream supply. Or, it could help set expectations for long-term management by identifying persistent supply-limited conditions that may require repeat wood supplementation.

While we were able to adequately assess wood equilibrium here, important knowledge gaps remain:

1. While we captured geomorphic influences on wood retention capacity, direct feedbacks between wood load and wood retention capacity remain unconstrained (i.e., retaining wood can enable even more wood retention on that wood; Lininger and Hilton, 2022; Scott and Wohl, 2018).
2. The nature of the wood equilibrium curve remains elusive. Constraining its degree of non-linearity and the factors that might induce threshold behavior (e.g., changes in the direction of influence of factors that control retention capacity; Malakoff et al., 2025) or more generally influence its shape would greatly improve efforts to judge wood equilibrium, especially over finer spatiotemporal scales and in systems with more complex wood regimes.
3. Finally, our methods, while applicable to in-channel wood retention of moderately large, migrating rivers, would likely be inappropriate to quantify floodplain or small stream wood equilibrium state, which may integrate different timescales of wood regime processes or be more difficult to measure using remote sensing data. More flexible and adaptable methods, perhaps better integrating a combination of remotely sensed and field data, would help to expand wood equilibrium assessment to a wider range of environments. The addition of measurements of wood supply magnitude could also aid in assessing wood equilibrium over smaller spatial scales.

Author Contribution Statements

D.S. conceptualized the research, designed methodology, acquired funding, performed analysis, and wrote and edited the manuscript. E.W. conceptualized the research, acquired funding, and edited the manuscript. All authors have endorsed the manuscript’s final version for publication.

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Land Recognition

This work was completed within areas of cultural significance to the Tulalip, Snoqualmie, Cayuse, Umatilla, and Walla Walla People.

Data and Codes Availability

All data used in the analyses presented here are available in the Dryad repository (<https://doi.org/10.5061/dryad.n8pk0p38t>).

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Conflict of Interest Disclosure

The authors have no competing interests

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The authors declare that no artificial intelligence tool was used to assist in or generate any part of the contents in this manuscript.

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