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ECOSYSTEMS

Spatial and Temporal Variation of Large Wood in a Coastal River

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ABSTRACT

Large wood (LW) is a critical habitat-forming feature in rivers, but our understanding of its spatial and temporal dynamics remains incomplete due to its historical removal from waterways. Few studies have the necessary spatial and temporal extent and resolution to assess wood dynamics over long time periods or in response to flood disturbance. We used an exceptional dataset from 65 km of a free-flowing coastal river in Oregon, USA, to characterize LW dynamics over a 12-year period (1989–2000). Our objectives were to assess the spatial dynamics of LW over multiple spatial scales and characterize changes in these patterns in response to a major flood in November 1996. Higher LW densities were found in the tributaries, and higher temporal variation of density existed in the main stem. Within years and among reaches, LW density varied by 2 to 3 orders of magnitude across the river. Patterns of LW accumulation across the river were not comparably different when considered at spatial resolutions < 6 km. A large flood in 1996 homogenized the wood distribution across the system, particularly at fine spatial scales (that is, 1.5–0.1 km scales), but considerable heterogeneity was reestablished within 2–3 years post disturbance. At the habitat unit scale, LW tended to accumulate in locations with narrow channel widths, and to a lesser extent, in shallow reaches. These data highlight the dynamic nature of the natural wood regime in coastal rivers that is produced by continuous recruitment and transport through the system.

Key words: large wood; spatial dynamics; spatial scale.

HIGHLIGHTS

- Wood density varied by up to 3 orders of magnitude among reaches in a river draining an intact watershed, with higher and more stable densities in tributaries than the main stem.
- A major flood in 1996 had a system-level effect that homogenized the spatial distribution of wood. This was most apparent at fine spatial resolutions.
- The high spatial variation in LW density quickly recovered after the major flood, indicating a dynamic river system.

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INTRODUCTION

The natural wood regime is crucial, along with hydrologic flows and sediment processing, for structuring the physical and biological attributes of aquatic ecosystems (Wohl and others 2019a). Wood regulates many geomorphic conditions and processes in the river corridor such as the transport and deposition of sediments (Gurnell 2013; Montgomery and others 2003; Wohl and Scott 2017), organic matter, and nutrients (Wohl and Beckman 2014), and streambed composition and stability (Buffington and Montgomery 1999; Díez and others 2000). It also influences floodplain and channel form (Wohl and others 2019a) and provides habitat for fishes (Beechie and Sibley, 2011; Fausch and Northcote 1992; Reeves and others 1993) and other aquatic organisms (Benke and Wallace 2010).

Spatial and temporal variability is a critical feature of the natural wood regime (Wohl and others 2019a). Variability originates from two sources: wood recruitment and channel and network geomorphic features. Spatially, the potential of stream reaches to transport or store wood depends on local geomorphic features (Wohl and Jaeger 2009; Galia and others 2022), channel-floodplain connectivity (Wohl and others 2018, 2019a), and the flow regime (Kramer and Wohl 2017; Ruiz-Villanueva and others 2016), especially floods (Millington and Sear 2007; Wohl and others 2019b). The size of wood relative to bankfull width or other physical stream attributes also influences transport and deposition (Lienkaemper and Swanson 1987). Additionally, variation in the sources of wood can contribute to the patchiness of wood density. Wood may enter the stream network chronically via stand mortality (Benda and Sias 2003), and episodically via landslides (Reeves and others 2003) and floods. This results in periods of low input punctuated by large inputs associated with major disturbance events (Kramer and Wohl 2017).

The intricate and stochastic interaction of wood input and channel morphology and geomorphic features makes it challenging to quantify the spatial distribution and dynamics of wood which characterize the natural wood regime. Long-term data sets collected at relatively large extents are critical to understanding the distribution and abundance of wood in river networks (Lininger and Hilton 2021; Torgersen and others 2022), in part, because of the inherent spatial and temporal variability. However, most studies of wood in stream systems are done at small spatial scales, 10^1–10^2 m, over a period of a few years (for example, Nakamura and Swanson 1993). While such studies provide important insights into short-term aspects of the natural wood regime, the lack of long-term observations of large wood abundance and distribution across stream networks has hampered our ability to advance our understanding of a natural wood regime (Swanson and others 2021) and to integrate it within management and restoration efforts.

Fausch and others (2002) and Carbonneau and others (2012) underscored the need to move beyond the focus on selected stream reaches to collecting spatially continuous data over large extents to more accurately represent the heterogeneity of biological and physical attributes of river networks. In this study, we use a dataset representing a census (complete count) of LW over 65 continuous km of a free-flowing coastal river in Oregon to characterize wood dynamics over 8 years in a 12-year period. Our objectives were twofold: (1) assess the spatial dynamics of LW over multiple spatial scales and (2) characterize the temporal variation of these patterns in response to an extreme flood disturbance. This dataset offers a unique insight into the patch dynamics of habitat conditions, increasing understanding of the implications of disturbance on wood dynamics in rivers.

METHODS

Study Area

The Elk River Basin is in southern coastal Oregon, near Port Orford (42°5′N latitude and 124°3′W longitude) (Figure 1), within the traditional territories of the Tolowa Dee-ni′ Nation, who refer to the Elk River watershed as K′vms-me′ Tr′ee-ghii -li ~ (E. Partee, Tolowa Dee-ni′ Nation, personal communication). It is approximately 240 km^2 in area with headwaters in the Copper-Salmon Wilderness Areas (Figure 1) in the Klamath Mountains physiographic province and flows freely to the Pacific Ocean. The main stem of the Elk River is a 6th order channel, and the tributaries we studied are either 3rd- or 4th-order channels (Strahler 1957). Average annual precipitation is 260 cm with a temperate maritime climate and moderate year-round temperatures; maximum elevation is 1138 m (Maguire 2001; USFS 1998).

The geology in the coastal lowlands consists of Quaternary marine and non-marine terrace deposits, with soils that are deep, silty clay loams to sandy loams (Maguire 2001). In the upper basin, the geology is a mixture of highly fractured rock point sandstone and siltstone, shales of the Galice Formation, graywacke, granite, diorite, serpentine, and ultramafic rock (Maguire 2001; USFS 1998),

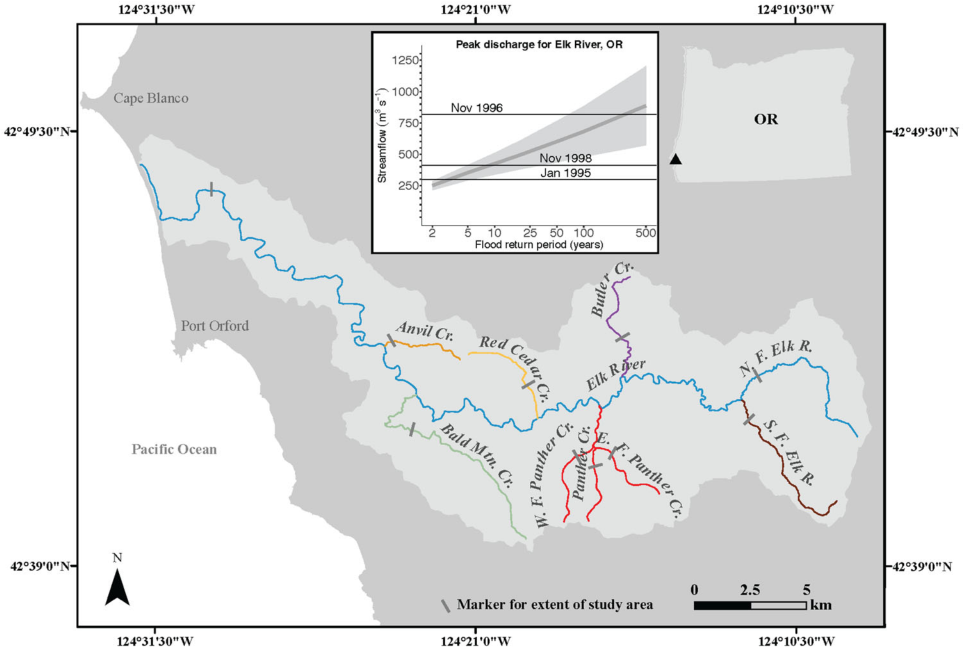

Figure 1. Map of the study area and an inset figure of flood recurrence in the Elk River, OR. The maximum extent of spatially continuous habitat data analyzed is indicated by the gray bars placed perpendicular to the streamline. This includes the main stem and 6 tributaries. The inset figure of flood recurrence includes 3 horizontal lines for 2 small flood events in 1995 and 1998 and an extreme flood event in 1996 with a greater than 75-year flood recurrence. The light gray band in the inset figure indicates 95% confidence intervals of flood magnitude, and the dark gray line is the mean.

and the soils in the upper basin consist of silt loam to gravelly loam (Maguire 2001). Ongoing uplift creates a steeped terrain with gorges throughout (USFS 1998).

Forest composition in the Elk River watershed includes early seral to an old-growth forest with a predominant habitat of mature hemlock/Douglas-fir temperate forest (Burnett and Reeves 2006). Primary tree species are Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), Port Orford cedar (*Chamaecyparis lawsoniana*), tanoak (*Notholithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and California bay laurel (*Umbellularia californica*). In the riparian areas, western red cedar (*Thuja plicata*), big leaf maple (*Acer macrophyllum*), and red alder (*Alnus rubra*) are common (Burnett and Reeves 2006).

Land ownership and management varies across the basin. The portion below Bald Mountain Creek (Figure 1), about 23% of the total area, is privately owned (Maguire 2001). The vast majority of the upper basin, 76% of the total area, is managed by the U.S. Forest Service (USFS 1998). The U.S. Bureau of Land Management manages 1% of the area. Timber harvest occurred on about 20% of the federal lands from 1938 to 1998 (USFS 1998), and much of this area is currently designated wilderness and late-successional reserves through the Northwest Forest Plan (USFS 1998). The Elk River is designated a National Wild and Scenic River and State Scenic Waterway. Under Section 303(d) of the Clean Water Act, the main stem Elk River is listed as water quality limited for summer water temperatures (USFS 1998).

The upper basin provides spawning and rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha)*, coho (*O. kisutch*), coastal cutthroat trout (*O. clarkii clarkii*), and winter-run steelhead (*O. mykiss*). In addition, a small population of chum salmon (*O. keta*) has been observed in the lower main stem (Burnett 2001).

Stream Habitat and Wood Surveys

Every channel unit along 40–47 km of the main stem Elk River and 17 km of fish-bearing tributaries (Anvil Cr., Bald Mountain Cr., Butler Cr., Panther Cr. including east and west forks, Red Cedar Cr., and the South Fork Elk River; Figure 1) were sampled from 1985 to 2001 using the visually based estimation method of Hankin and Reeves (1988). Surveys were conducted during summer low flow between late July and mid-August for approximately 3 weeks per survey. For this paper, we used the 8 years when surveys covered the maximum distance on the main stem of Elk River (47 km) that ran from the top upper limit of fish distribution downstream to the head of tidal influence. These years were 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000.

Channel units in the main stem Elk River and tributaries, classified as pools, riffles, glides, rapids, cascades, or steps according to the criteria of Bisson and others (1982), were sampled to the upper end of fish distribution, which was determined as the point where snorkelers did not observe fish for eight consecutive habitat units. Flow variation and other factors resulted in different endpoints of the surveys and sampled stream lengths from year to year.

In addition to the classification of the habitat units, the number of pieces of LW (length ≥ 3.0 m and a diameter ≥ 0.3 m) that had at least 50% of its length located in the bank full zone (that is, the area of the stream channel up to the regular high-water mark) was counted in every unit. This minimum size is larger than the minimum size used in recent studies, ≥ 10 cm diameter, and 1 m length (see examples cited in Wohl and others 2023). In small aggregations all pieces were counted. In larger aggregations where counting every piece of wood was not possible, the dimensions of the aggregate were measured, and the number of wood pieces was estimated.

Data Analysis

Linear referencing methods were used in ArcGIS 10.4 to georeference each channel unit on digital hydrography in a geographical information system (GIS; Environmental Systems Research Institute 2003, 2014). Cumulative channel unit lengths along the main stem were calibrated and positioned between known geographic locations, including tributary junctions, bridges, and other flagged locations which were noted in the original surveys. In stream reaches with split channels, only channels that had more than 10% of the estimated stream flow were used. Habitat data were georeferenced to hydrography in U.S. Geological Survey (USGS) topographic quadrangles (USGS 2019) for earlier years (1988–1996) and to the National Hydrography Dataset (USGS 2019) for later years (1997–2000).

We characterized the flood regime of the Elk River to explore the relationship between the intensity of flood disturbance and the spatial and temporal distribution of LW. Based on systematic and historical records, the peak discharge of 818 $m^3 s^{-1}$ in November 1996 had an estimated return period of > 75 years (Cooper 2005; USGS 2016; USFS 1998; Figure 1). To assess flood magnitude, we used the regression-based MOVE method (Hirsch 1982; Vogel and Stedinger 1985) and the Streamflow Record Extension Facilitator (Granato 2009) to augment missing streamflow records for USGS stream gage 14327250 (Elk River above Anvil Cr.) from 1988 to 1993, 1994, and 1999. This method required long-term continuous flow from a nearby gaging station; USGS stream gage 14325000 (S. F. Coquille R. at Powers, OR) was used. For the remainder of the paper, the November 1996 flood is referred to as the '1996 flood.'

We normalized the spatial and temporal patterns of LW density using pieces per km, and coefficient of variation (CV) was used to characterize the spatial variation in LW density within and temporal variation at sites among years. Wood density and variation were assessed at multiple spatial scales. A reach scale of 0.4 km was used to map the mean density (pieces of LW km^{-1}), and CV of the mean density of LW across 8 years within individual reaches throughout the entire surveyed steam network (that is, the main stem and tributaries). We selected the 0.4-km scale for visualizing wood density because this was the finest resolution that could be displayed cartographically at the stream network scale. To explore longitudinal patterns of LW pieces at multiple spatial scales, we focused on the main stem and binned the data at 5 different spatial scales (resolutions): 24, 6, 1.5, 0.4, and 0.1 km, according to the methods of Welty and others (2015) using R (RStudio Team 2019). The spatial CV of LW distribution in the main stem Elk River was calculated for each of 5 spatial scales to create a gridded heat map using the R package ggplot2. The annual peak mean discharge was derived for each water year in the heat map from the augmented annual mean daily discharge (Table 1).

Linear mixed models were used to quantify the effects of geomorphic attributes of the river channel on LW distribution in the main stem and tributaries. At the channel unit scale (that is, the scale at which the data were collected), we analyzed the influence of wetted width, channel mean depth, and distance from the ocean on LW density (Table 2).

Linear mixed effects regressions were used to quantify relationships between LW density and river geomorphic features using the lme4 package (Bates and others 2015) in R (RStudio Team, 2019). Performance of competing models (Table 3) was assessed with Akaike's information criterion (AIC) according to standard methods (Burnham and Anderson 2004), and the slope and standard error (SE) of model coefficients were calculated to quantify relationships between LW density and geomorphic conditions. Density of LW, channel

Table 1. Drainage Area, Range of Surveyed Length, and Range of Mean Channel Wetted Width of 6 Tributaries and the Elk River, OR

Subbasin	Abbreviation	Drainage area (km^2)	Surveyed length (km)	Mean channel wetted width (m)
Elk River (main)	ER	222.0	44.4–49.6	1.8–40.3
Anvil Cr.	AN	6.9	0.5–0.6	1.5–10.6
Bald Mtn. Cr.	BM	27.5	5.1–6.3	1.6–16.3
Butler Cr.	BU	17.7	2.1–2.7	1.5–11.1
Panther Cr.	PA	36.0	4.8–5.6	1.4–15.5
Red Cedar Cr.	RC	7.4	2.0–2.4	1.0–10.7
S. F. Elk R.	SF	20.0	1.3–1.6	2.0–10.3

Survey years were 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000.

Table 2. Total Counts (Number of Pieces), Mean Density (Pieces km^{-1}), and Coefficient of Variation (CV) of Large Wood in the Mainstem and 6 Tributaries in the Elk River, OR

Subbasin	1989	1990	1992	1994	1996	1997	1998	Mean density	CV
Elk River[1]	1661	799	1302	1028	1241	832	940	22.4	0.32
Anvil Cr.	ND[2]	ND[2]	34	41	52	31	52	73.0	0.25
Bald Mtn. Cr.	1343	671	ND[2]	720	1162	338	493	121.3	0.57
Butler Cr.	177	98	56	58	70	58	49	30.9	0.52
Panther Cr.[3]	507	184	793	242	212	190	204	58.8	0.68
Red Cedar Cr.	285	233	197	226	169	47	173	88.0	0.36
S. F. Elk R.	138	142	147	135	157	17	117	86.4	0.37

[1] The Elk River includes the main stem and the North Fork of Elk River.
[2] ND = no data.
[3] Panther Cr. includes the east and west forks.

width, and channel depth were $\log_{10}$ transformed to normalize variances, and distance from the ocean to a channel unit was assessed in linear space. Year of each survey was considered as a random effect in all models.

RESULTS

Temporal Patterns of Wood Abundance

Among years, the overall density of LW was higher and generally more variable in the tributaries, except in Anvil Creek, compared to the main stem Elk River (Figure 2). Annual mean density of LW in tributaries was 1.4–5.5 times higher than the mean LW density in the main stem Elk River, ranging from 31 pieces km^{-1} in Butler Creek to 121 pieces km^{-1} in Bald Mountain Creek. The coefficient of variation in wood density among years was 0.32 in the main stem Elk River compared to a range of 0.25 (Anvil Creek) to 0.68 (Panther Creek) in the tributaries.

There was a decline of varying degrees in LW density across the river system in 1997 in response to the 1996 flood (Figure 2). A 30% decrease in LW density occurred in the main stem Elk River, while in the tributaries LW density decreased from 12% in Panther Creek to 89% in the South Fork (Figure 2). Initial signs of post-flood recovery were apparent in the increase in LW abundance from 1997 to 1998 in the main stem ER and the tributaries, except in Butler Creek (Figure 2). Most notably, there were fourfold and eightfold increases in LW density from 1997 to 1998 in Red Cedar Creek and the South Fork, respectively, and a 110% increase in LW density in the main stem ER.

The density of LW also varied within a particular stream over the years studied. The highest mean LW density was observed at the reach scale in the uppermost reaches of the main stem Elk River and the lower reaches of 5 tributaries among the 8 years of study (Figure 3a). In the Elk River main stem, reaches with high mean LW density (> 56 pieces km^{-1}) were located at the confluence with the South Fork and upstream from this confluence (Figure 3a). There were no reaches immediately downstream of the confluence with the South Fork in the Elk River that compared to the hot spots in the tributaries with reaches that had high mean LW density (> 56 pieces km^{-1}; Figure 3a). The upper reaches of the tributaries all had high mean LW

Table 3. Alternative Competing Models to Explain the Spatial Variation in LW Density at the Channel Unit Scale Across the Elk River

Model	k	AIC	△ AIC	Intercept	Width	Depth	Distance	Model rank
1	3	− 61,682.97	272.32	0.010 (0.001)	–	–	–	7
2	4	− 61,955.29	0	0.024 (0.001)	− 0.016 (0.001)	–	–	1
3	4	− 61,742.49	212.8	0.013 (0.001)	–	− 0.026 (0.003)	–	5
4	4	− 61,663.30	291.99	0.007 (0.001)	–	–	9.02×10^{-8} (2.28×10^{-8})	8
5	5	− 61,950.90	4.39	0.024 (0.001)	− 0.015 (0.001)	− 0.009 (0.003)	–	2
6	5	− 61,924.26	31.03	0.026 (0.002)	− 0.016 (0.001)	–	-4.94×10^{-8} (2.41×10^{-8})	3
7	5	− 61,712.05	243.24	0.011 (0.001)	–	− 0.024 (0.003)	5.14×10^{-8} (2.33×10^{-8})	6
8	6	− 61,921.17	34.12	0.027 (0.002)	− 0.016 (0.001)	− 0.010 (0.003)	-5.68×10^{-8} (2.42×10^{-8})	4

	Model
1	Wood ~ (1|Year)
2	Wood ~ Width + (1|Year)
3	Wood ~ Depth + (1|Year)
4	Wood ~ Distance + (1|Year)
5	Wood ~ Width + Depth + (1|Year)
6	Wood ~ Width + Distance + (1|Year)
7	Wood ~ Depth + Distance + (1|Year)
8	Wood ~ Width + Depth + Distance + (1|Year)

Models were specified with mixed effects, with year as a random effect and various combinations of channel wetted width, channel depth, and distance from the ocean as fixed effects. Models were ranked from best to worst according to AIC. The number of parameters in each model is specified by k. Coefficients for the slopes and intercepts (and their standard errors) are also given.

density except the main fork Panther Creek and Butler Creek (Figure 3a). Red Cedar and the South Fork had the greatest proportion of high mean LW density reaches (Figure 3a).

Temporal variability within reaches was assessed for individual stream locations among years. There were more reaches with a relatively high CV of LW density (CV > 1.52) downstream of Panther Creek in the main stem ER (Figure 3b). LW tended to be more stable within individual reaches within the Elk River tributaries, and no reaches had relatively high wood density CV (Figure 3b). LW density was less variable (CV < 0.57) in Anvil Creek and Red Cedar Creek compared to the reaches in other tributaries (Figure 3b).

At the reach scale, LW density was highly variable among years in the main stem Elk River and a few stream sections of the tributaries (Figure 4). In any given year, densities of LW frequently varied by 2 orders of magnitude in adjacent 0.4-km reaches. Among years in the same location, densities of LW varied widely by as much as 2–3 orders of magnitude. In the lower main stem, LW densities were highest in 1989 and relatively low in subsequent years (Figure 4a). In the reaches between Red Cedar Creek and Panther Creek, LW densities were highest in 1992 and variable in the other years (Figure 4b).

Longitudinal Patterns in the Main Stem at Multiple Scales

Across most spatial resolutions considered, little evidence existed for scale dependence in the patterns of LW accumulation in the main stem Elk River (Figure 5); the general patterns of LW density observed at the 6-km scale were also evident at finer spatial scales (0.1–1.5 km). For example, distinct aggregations of LW at rkm 42 and 48 in 1989 at the 6-km scale were also apparent at finer spatial scales (Figure 5). Similarly, in the upper main stem, an exceptionally high density of LW was observed in 1994 at the 6-km and finer spatial scales (Figure 5). At the coarsest scale (24 km) in 1989, a different pattern emerged in which LW

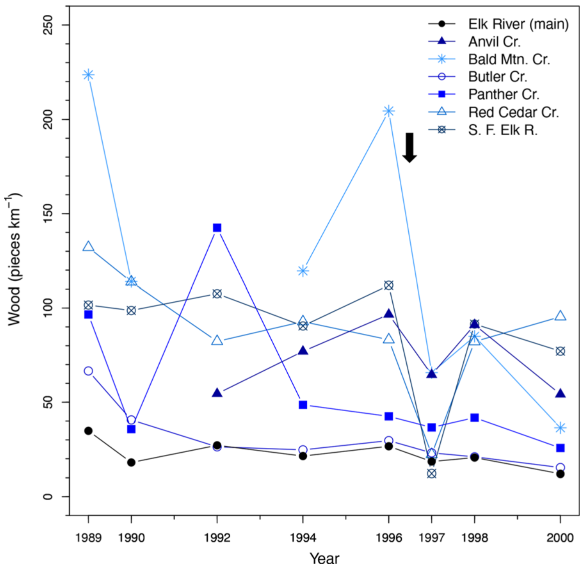

Figure 2. Time series of LW density (pieces km^{-1}) in the 6 tributaries and the Elk River in 1989, 1990, 1992, 1994, 1996, 1997, 1998, and 2000. The tributaries are in blue. The Elk River (main) includes the main stem and the N. F. Elk River. Panther Cr. includes both the east and west forks. Bald Mountain Cr. was not sampled in 1992, and Anvil Cr. was not sampled in 1989 and 1990. The black arrow marks the extreme flood event in winter of 1996.

density was higher in the lower main stem (0–24 km) compared to the distribution of LW in other years at 24 km (Figure 5).

There were two general patterns of LW density in the main stem Elk River. First, LW density was high in the downstream- and upstream-most reaches; this was most apparent at the 6-km scale in 1989, 1997, and 2000 (Figure 5). In other years, high LW density was observed in the upstream-most reaches of the main stem, and low LW density was observed in the lower main stem (for example, 1990 and 1994 at 6 km and 1.5 km; Figure 5). A stark contrast was shown in the spatial pattern of high LW density with more patchiness before the 1996 flood and low LW density after the 1996 flood, particularly at finer spatial scales (0.1–0.4 km; Figure 5).

High levels of spatial variation were particularly evident at fine spatial scales in most years of the study in the main stem Elk River (Figure 6). The CV of LW density distinctly increased when evaluated at the 0.1 km scale from 1989 to 1994. Furthermore, the two highest LW aggregations in any given year were observed in 1994 in two channel units alone, which accounted for 30% of LW in the river that year (Figure 6, Appendix A). The 1996 flood homogenized the spatial variation in LW as shown by the distinct decrease in CV among reaches when considered at the finest scales. In 1–2 years, CV had increased, and the heterogeneity in LW density returned to pre-disturbance levels (Figure 6).

Channel Geomorphic Associations with Wood Accumulation

Fine-scale variation of LW density was significantly associated with basic geomorphic characteristics of the river channel (Figure 7). Despite wide variation in LW density among channel units, there was a significant negative association between LW and the wetted width of channel units (Figure 7a). While there was a tendency for higher wood accumulation in the tributaries, this effect was accounted for by a continuous negative relationship between channel width and average wood density. A model that included distance from the ocean was distinctly poorer (ΔAIC $>$ 31) than a model with only wetted width as the independent variable (Table 3). The density of LW tended to be higher in shallow channel units (Figure 7b), and a model with both channel width and depth was not as parsimonious as the model with only channel width as the key geomorphic variable affecting local wood density (ΔAIC $>$ 4; Table 3).

DISCUSSION

The spatial distribution and density of LW in the Elk River and its tributaries were highly variable over the course of this study, with overall variability and density generally higher in tributaries than the main stem. The coefficients of variation, among years, of wood density in the tributaries studied ranged from 0.25 to 0.68, suggesting that wood, or at least a large fraction of it, was mobile and not stable. Other studies have reported movements of 30% (Kramer and Wohl 2017) to 50% or more (Lienkaemper and Swanson 1987; Dixon and Sear 2014), which are comparable to our findings. This pattern of variability is also similar to that found by Picco and others (2021) over 13 years in a 22 km reach of a stream in the Andes Mountains of Chile and suggested by Wohl and others (2019a) for the natural wood regime. This finding supports the emerging conceptual basis of aquatic ecosystem science that is shifting away from an equilibrium perspective to one that recognizes dynamic non-equilibrium conditions and natural variability (Naiman and others 1992; Wallington and others, 2005).

The natural wood regime of a given river system depends on the physical features and disturbance

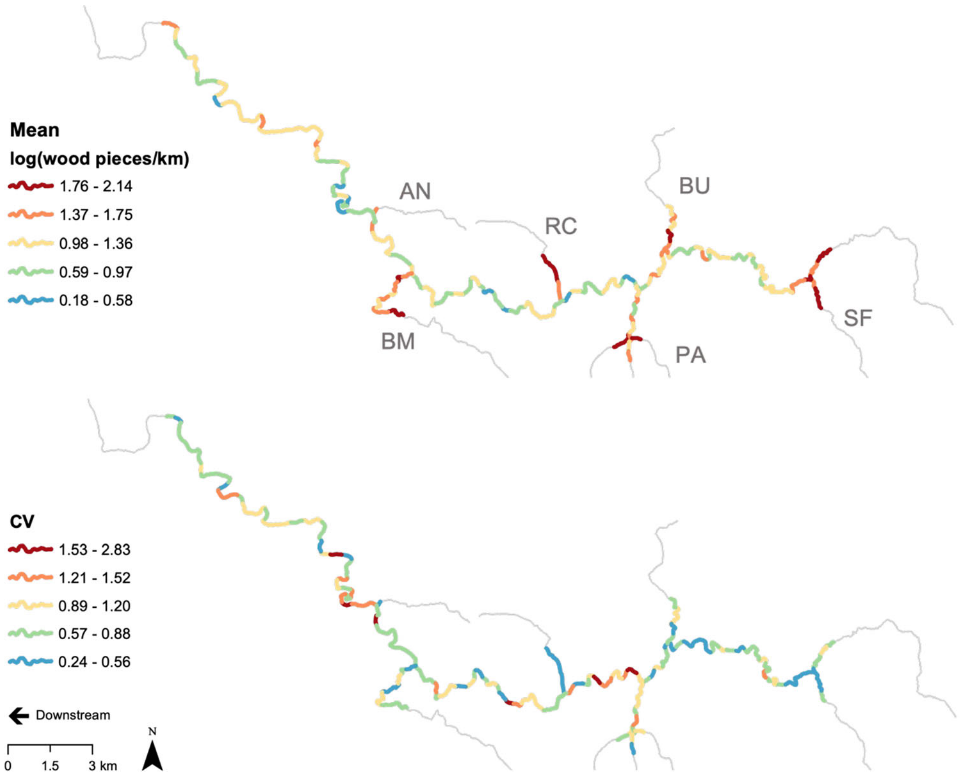

Figure 3. Log_{10} of the number of pieces km^{-1} in 0.4 km bins summarized by (**A**) mean of the log and (**B**) coefficient of variation (CV) in the Elk River and 6 tributaries across 8 years of study. Categories in the legend are at equal intervals for mean and CV. The category for the highest CV has a large interval due to an outlier with a value of 2.83. Note difference in scales with Figure 4.

regime of the river network (Wohl and others 2019a). The area of Elk River considered in this study is composed primarily of constrained and alluviated canyons (Burnett 2001). The strong (negative) effect of wetted channel width on the density of wood in reaches demonstrates that constrained reaches tend to trap LW, at least temporarily, and are the key geomorphic features affecting the spatial distribution of wood across the riverscape. This effect is likely produced by large 'key pieces' of LW producing the foundation of what becomes a debris jam as smaller pieces accumulate around such obstructions. However, it is important to note that our results show clearly that such debris jams are ephemeral and their locations vary substantially among years.

The high variability of wood abundance also suggests that the residence time of a large proportion of the wood in Elk River was relatively short. Previous studies in the Pacific Northwest suggest that residence time can vary from 12 years for larger streams, and 83 years for smaller streams (Lienkaemper and Swanson 1987). One potential reason for the amount of movement found and short residence time in this study is that we considered the entirety of the population of wood (minimum length of 3 m and diameter of 0.3 m) and not just larger pieces, over a large area. Most pieces were smaller than the width of the active channel, which would make them highly mobile (Lienkaemper and Swanson, 1987; Keim and others 2000), even at flows below flood levels (Kramer and Wohl 2017). Smaller pieces of wood are more mobile than larger ones because they move on the rising and falling limb of the hydrograph and not just on the ascending limb as happens for larger pieces (MacVicar and Piégay 2012; Ravazzolo and others, 2015). As a result, wood movement in the Elk River and its tributaries was more extensive annually than suggested by Kramer and Wohl (2017). Large wood is characterized by long periods of relative stability punctuated by brief times of movement. The extent of movement may have been even higher had we defined large wood with the standard used currently (minimum length 1 m and diameter 0.1 m). Mobile wood is ecologically important to periodically disturb floodplains (Collins and others 2012; Osei and others 2015) and provide habitat for microorganisms and macroinvertebrates (Harmon and others 1986). The varia-

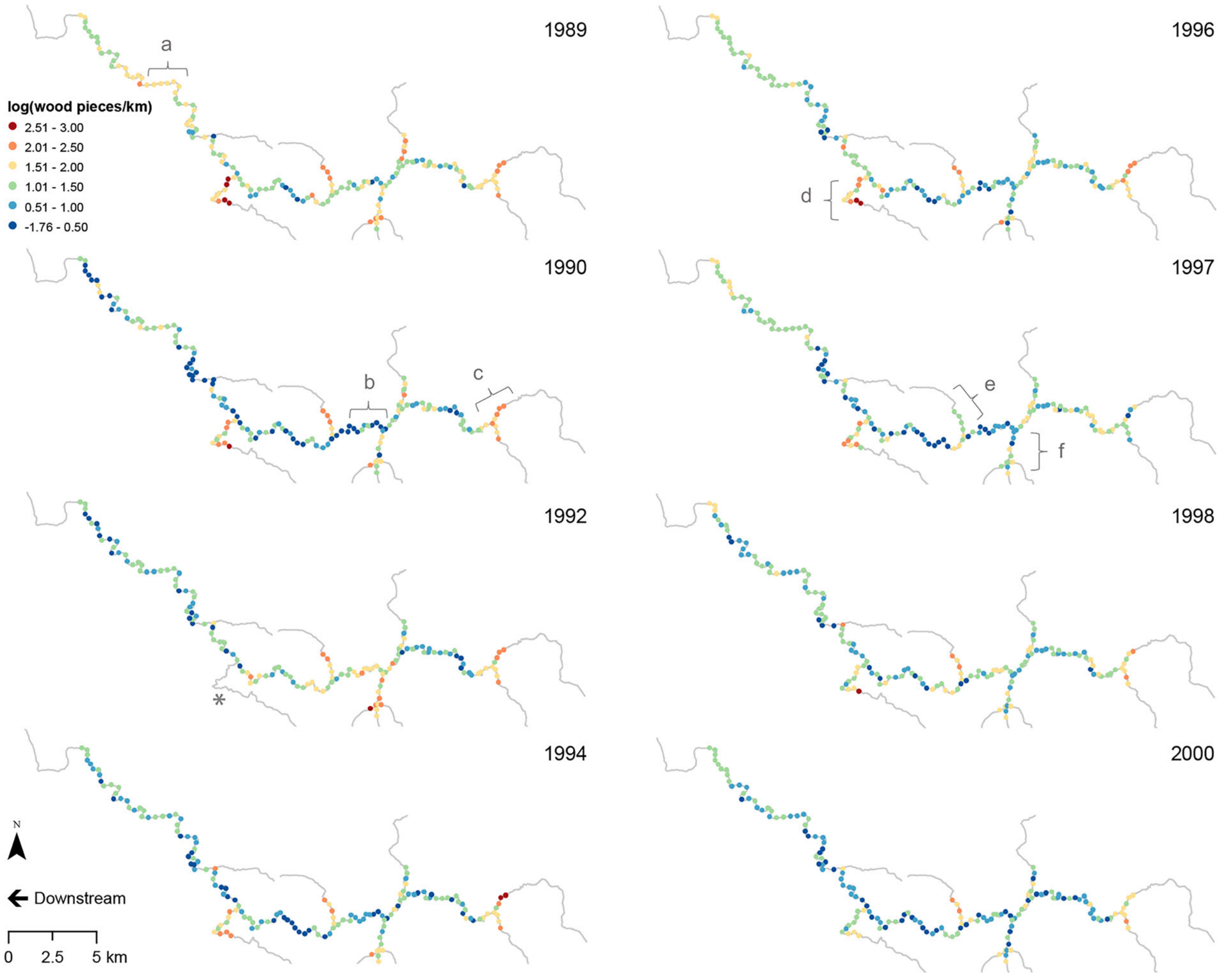

Figure 4. Spatial patterns of wood density in the Elk River and 6 tributaries across 8 years of study. Densities are calculated for 0.4-km bins and $\log_{10}$ transformed. The asterisk symbol '*' indicates a tributary that was not sampled during a given year. The category for the lowest LW density has a large interval due to 15 values < 0 that were spread across the 8 years. Note difference in scales from Figure 3.

tion in the density of large wood also suggests that there may be a shifting mosaic of conditions that could influence the spatial distribution of fish production across rivers (Brennan and others 2019).

Wood density was higher in the upper reaches of the Elk River, which was primarily in a confined channel, than in the lower reaches, which are unconfined—consistent with the finding of Wohl and Jaeger (2009) and Wohl and Cadol (2011). This pattern differs from Fox and Bolton (2007) who found that bankfull width, which increases going downstream, was the best predictor of wood density. A potential explanation for these differing results is that the capacity for wood transport increases with basin area (Hassen and others 2005; Wohl and Jaeger 2009; Iskin and Wohl 2021). Additionally, we considered all sizes of wood and not just larger pieces. Smaller sizes are more mobile over a greater range of flows than larger ones (MacVicar and Piégay 2012; Ravazzolo and others, 2015) and are likely transported through the lower section of the study area rather than being deposited on the floodplain.

Wood abundance declined in the main stem Elk River and most of the tributaries following the 75-year flood and had not yet recovered to pre-flood levels three years later. The geomorphology of the study may have exerted a strong influence on recovery. Storm events that result in floods may recruit wood to channels by directly killing trees or through the occurrence of landslides. Unconstrained reaches (wide valleys and low gradient floodplains) are stream reaches where recruitment of trees may be greatest during floods (Acker and others 2003). Such reaches are scarce on the Elk River main stem and tributaries. The exceptions

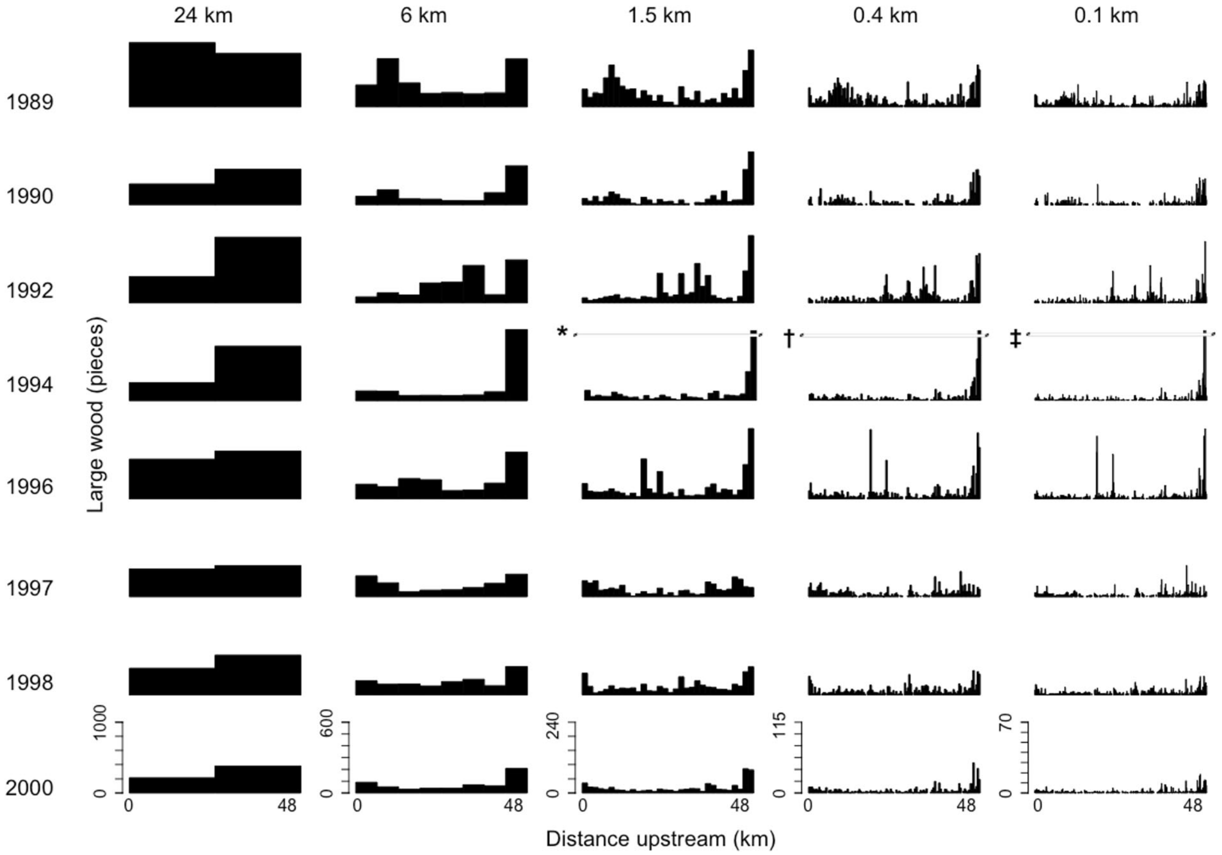

Figure 5. Longitudinal patterns of large wood counts in the Elk River binned at 5 spatial scales (24, 6, 1.5, 0.4, and 0.1 km) across 8 years. The x-axis indicates the distance upstream from the lowermost point of the survey to the uppermost point in the N. F. Elk River (see Figure 1). In 1994, maximum y-values are 466 (1.5 km scale) (*), 224 (0.4 km) (†), and 194 (0.1 km) (‡).

were Cedar Creek and Anvil Creek, which were unconstrained in much of the stream channel sampled. Here, the amount of wood actually increased after the flood but declined within a few years, suggesting that the newly recruited pieces were likely in the smaller range. Landslides may contribute substantial amount of wood to streams (Reeves and others, 2003a, b). However, landslides that reach fish-bearing streams in the Elk River Basin are extremely rare (McHugh 1986). Wood delivery to stream channels in Elk River and its tributaries is likely primarily from individual tree mortality, suggesting that it may take a rather long period for wood levels to return to pre-flood levels.

The range of variability is dependent on the extent (the area over which data are collected) and the resolution (the smallest feature discernable in observations) (Torgersen and others 2022; Wiens 1989). The amount of variability in the density of wood in the main stem of Elk River was greater at smaller scales (< 1.5 km resolution) than at larger scales (> 6 km), being highest at the finest scale (0.1 km). Old-growth ecosystems in coastal Oregon exhibit similar pattern of variability with scales, with the largest variation at the smallest scale (Wimberly and others 2000). Many monitoring programs of wood and other features of aquatic ecosystems are done at small spatial scales (< 1 km) and consider a single (Kershner and others 2004) or several (Reeves and others, 2003a, b) short reaches. This potentially introduces large variation in the amount of wood, making discerning statistically defensible trends difficult. Such programs could embrace the results of this study and consider modifying the size and number of sampling sites.

We provide a deeper understanding of the interannual variability of LW at the watershed scale. Results from this study support the contention of Carbonneau and others (2012) and Wohl and others (2023) that an accurate detection of patterns requires high-resolution data collected over a large areal and temporal extent and is essential to identifying patterns and relationships in

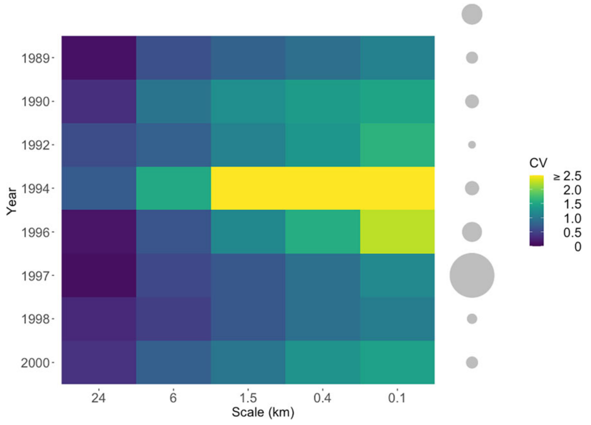

Figure 6. Coefficient of variation (CV) of large wood counts in the Elk River at 5 different spatial scales across 8 years. The Elk River includes the main stem and the N. F. Elk River. The range of CV (0–3.6) was truncated at 2.5 for visual differentiation. Flood magnitude is represented by gray circles positioned according to when they occurred. The diameter of the circles is proportional to the annual peak mean discharge in the water year (Oct. 1-Sept. 30) of occurrence. For example, the top circle represents the water year 1988. The 1996 flood occurred in the water year 1997. The smallest circle represents a discharge of 60.7 m^3s^{-1} in 1992, and the largest circle is 402 $m^3s.^{-1}$ in 1997.

river ecosystems. Long-term studies can reveal interannual patterns and provide a context for interpreting the results from any one year that are missed in short-term studies of wood dynamics in rivers. Transferability of fish habitat models and results to other years may be limited by the failure to account for interannual variation. Documenting and understanding temporal variability can also aid in designing programs to monitor trends and increase the effectiveness of conservation strategies.

Our results show that much of the heterogeneity in large wood distributions in rivers is expressed at relatively fine spatial resolutions, and that this scale of heterogeneity is most sensitive to disturbance associated with large floods. Recovery of wood heterogeneity may take several years following major disturbance events, assuming that watershed processes that recruit wood to the river are functioning. The dynamic nature of wood distributions in the Elk River emphasizes the critical importance of maintaining the biological and physical processes that recruit wood to rivers and allow for their movement once they are part of the river system in conservation and restoration activities. Such an emphasis shifts activities away from a narrow focus

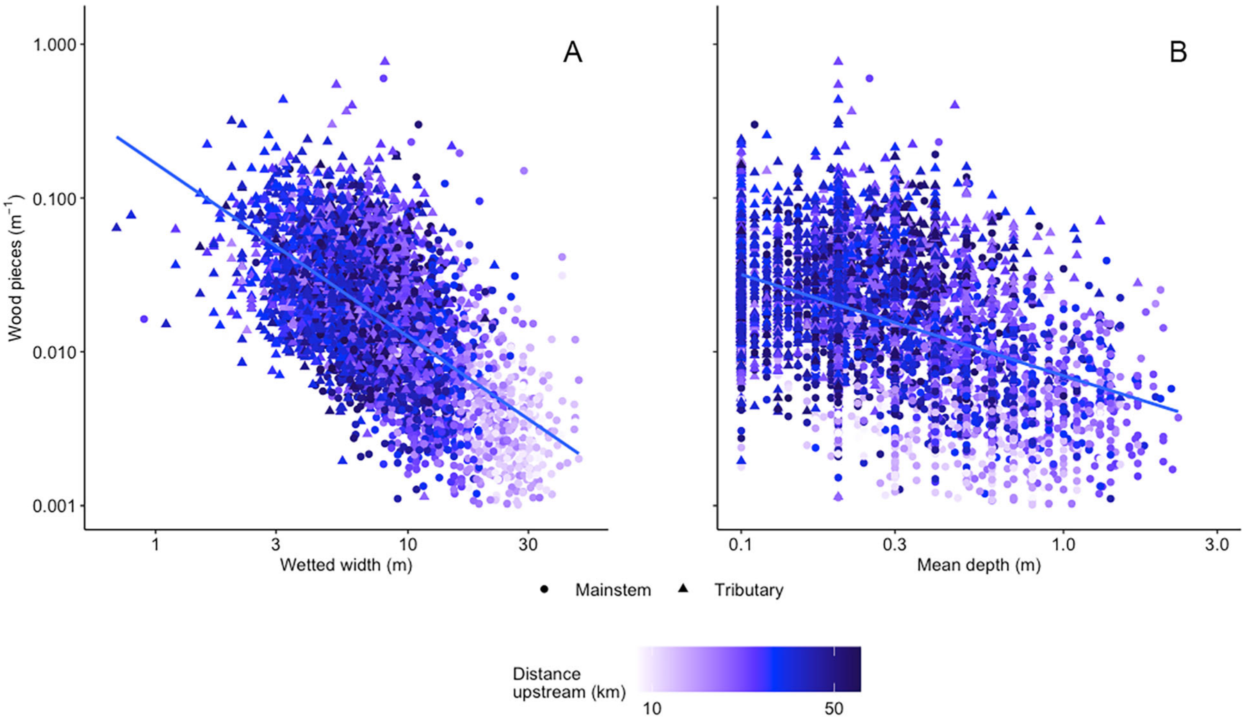

Figure 7. Relationship between the density of LW observed in individual channel units and the associated wetted width (**a**) and channel depth (**b**). Both axes are $\log_{10}$ transformed. All data across all years of the study are shown here. Dots are colored according to the distance from ocean of individual channel units. Triangles are used to show sites in tributaries and circles for sites in the main stem.

on the dynamics of wood in the river itself, to a broader focus on the integrated watershed-river system that accounts for the processes that affect wood delivery from the watershed and accumulation and transport through the river system.

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DATA AVAILABILITY

Data are not publicly available; contact the corresponding author and the University of Washington for further information.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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