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Unravelling the frequency and magnitude of large wood mobility and transport distance across 11 low-order streams over multiple years

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Abstract

Large wood (LW) entrainment and transport observations of naturally occurring wood in rivers are critical for understanding wood dynamics. However, they remain limited and sparse, primarily originating from single-site studies. As a result, broader spatial or temporal variability of wood dynamics may not be adequately captured. We compiled a database of tracked, natural pieces of wood from 11 low-order and relatively steep streams in the Chilean Andes, Swiss Alps, United Kingdom and United States. From decades to single-year studies, we gathered 59,739 observations of tracked wood, which all include at least a recorded length and transport distance. River characteristics varied according to channel width, less than 5 m to wider than 15 m, and gradient, between < 0.02 and > 0.04 m/m. The meta-analysis enabled us to calculate probabilities and identify general patterns. Wood mobilization varied significantly interannually, reflecting the complex interplay between flood events and wood storage. Overall, a small proportion of tagged wood moved during study periods, primarily during events associated with return periods exceeding 10 years. Most mobile pieces travelled less than 1 km, and longer distances had relatively low probabilities, typically occurring during high-magnitude flood events associated with return periods over 10 years. Results showed that large wood mobility in rivers is generally infrequent and highly variable, influenced by a combination of wood characteristics, river size and flood magnitude. Understanding variability can help inform risk-based flood hazard planning, river management and river restoration projects implementing large wood. Future studies should expand upon the current dataset.

KEYWORDS
displacement distance, entrainment, initial conditions, instream wood, mobility by wood flux

1 | INTRODUCTION

Large wood contributes to the ecological and physical integrity of rivers (Verdonschot & Verdonschot, 2024; Wohl, 2024). Although less frequently studied than stationary wood, mobile wood (i.e., wood pieces that are actively being transported by the flow; Wohl et al., 2023) similarly plays a crucial role. However, in the context of river management, attention has been given primarily to artificially stabilizing wood, potentially overlooking the ecological value of its mobility (Wohl et al., 2023). Lack of research on mobility is evident in the scarcity of monitoring sites where wood mobility is being tracked (Ruiz-Villanueva et al., 2024), which limits our understanding of wood dynamics in rivers.

Drawing an analogy with flow and sediment regimes, quantifying the wood regime requires estimation of fluxes or transport rates, physical factors governing wood movement within a river section, initiation or entrainment and the wood transport distance. However, while sediment transport monitoring dates back to the 19th century (Kondolf & Piégay, 2003; Rickenmann et al., 2017), monitoring wood transport in rivers began in the second half of the 20th century and remains underdeveloped.

Under what conditions does wood begin to move? Which types of wood are more likely to be mobilized? And how far can wood be transported within river systems? These questions are fundamental for the study of wood mobility. Scientists have tried to answer them, and significant progress has been made in the past years, expanding the observations of wood mobility across time and space. Table 1 summarizes these efforts by synthesizing studies over the past three decades for which wood in rivers was traced or tracked and mobility was characterized and assessed. These studies employed a varied array of techniques, including periodic surveys, tags with unique IDs or trackers like radio frequency transmitters (Jochner et al., 2015; MacVicar et al., 2009; Schenk et al., 2014; Wyżga et al., 2017), and in a few cases, GPS or smart sensors were also used (Ravazzolo et al., 2015; Spreitzer et al., 2022, 2024). Remote sensing and drones were also used (Finch et al., 2025; Hortobágyi et al., 2024; MacVicar et al., 2009), but in all cases field surveys were performed. Wood dynamics also have been quantified with time lapse cameras or video cameras (e.g., Boivin, Buffin-Bélanger, & Piégay, 2017; Ghaffarian et al., 2021; Kramer & Wohl, 2014; MacVicar et al., 2009), however, these studies usually focused on quantifying wood fluxes rather than wood piece mobility; therefore, we do not include them in the table. Monitoring periods ranged from 1 month to 50 years across a variety of stream types including headwater, gravel-bed, low-gradient and wandering piedmont systems. The reviewed studies of naturally occurring instream wood recorded annual mobility between 0% and 95%, with displacement distances reaching a maximum of 125 km.

This interannual variability of wood mobility, where more wood is observed to move more likely in some years than in others and in some rivers than in others, highlights the need for analysing both the frequency and magnitude of these transport events. Similar analyses have long been applied in hydrology, often using the concept of return period or recurrence interval. However, this concept has not yet been developed or applied to wood transport in river systems. By compiling studies that include multiple years of wood tracking observations (Table 1), we established magnitude-frequency relationships for wood transport events. This approach allows us to quantify how often wood movement occurs and how much wood is typically mobilized, providing a foundation for developing recurrence intervals like those used in hydrology. In addition to evaluating magnitude-frequency relationships, we partitioned the datasets into channel width classes and gradient classes to investigate whether similarities and differences in wood mobility exist among these classes, as identifying such patterns constitutes one of the primary objectives of this study. Through this synthesis, we seek to bring a more systematic and predictive understanding of wood mobility in river systems.

2 | MATERIAL AND METHODS

2.1 | Sites selection and data

The 11 rivers involved regular field surveys of naturally occurring wood that had identification tags installed on them so their location could be tracked over time. The rivers, generally lower in order with small catchment sizes, are: one river from the United Kingdom — Highland Water (Dixon & Sear, 2014); two from Switzerland — Spöl and Avançon de Nant (Aarnink, 2025; Finch et al., 2025); four from Chile — Pichún, Vuelta de la Zorra, Tres Arroyos and El Toro (Iroumé et al., 2018); and four from the United States — Poplar Creek, Mack Creek, North Fork (NF) Caspar Creek and South Fork (SF) Caspar Creek (Figure S1; Daniels, 2006; Gregory et al., 2024; Lininger & Hilton, 2022). Low gradient rivers with broadleaved-dominated forests comprise two of the eleven rivers: Poplar Creek and Highland Water. The remaining nine rivers are in mountain environments with moderate to high gradients, predominantly coniferous forest stands and some broadleaved trees: Spöl, Avançon de Nant, Pichún, Vuelta de la Zorra, Tres Arroyos, El Toro, Mack Creek, NF Caspar and SF Caspar Creek. Detailed descriptions of each study site can be found within the respective publications, but we have included Table 1 to list relevant values for the 11 rivers as well as other wood-related tracking studies.

Most studies limited observations to pieces of wood at least 1 m in length and 10 cm in diameter, but Lininger & Hilton (2022) opted for a 2 m and 20 cm threshold due to wood pieces being abundant and on average very large within the region. Identification tags, in the forms of small metal or plastic plaques (Aarnink, 2025; Daniels, 2006; Dixon & Sear, 2014; Finch et al., 2025; Gregory et al., 2024; Iroumé et al., 2018; Lininger & Hilton, 2022), and, at times, radio-frequency identification tags were installed within the wood pieces (Aarnink, 2025) so the pieces could be identified during a subsequent survey to determine any change in location. Estimates of storage and potential pieces that could move were limited to the active channel and wood extended partially into the channel perimeter (Aarnink, 2025; Daniels, 2006; Finch et al., 2025; Iroumé et al., 2018; Lininger & Hilton, 2022) or additionally included wood in the floodplain (Dixon & Sear, 2014; Gregory et al., 2024).

The total duration and frequency of surveys varied among studies and can be seen in Figure 1c. The study with the longest duration, 24 years, was on Mack Creek, Oregon, USA, by Gregory et al. (2024), which surveyed annually from 1985 to 2008, apart from 1987 and resulted in 22 observations of wood mobility and transport. The second longest study, conducted by Lininger and Hilton (2022), examined the North and South Forks of Caspar Creek, California, USA, from 1998 to 2018. Spanning 20 years, the study followed an approximately biannual survey schedule, resulting in nine observations. Poplar Creek in Illinois, USA, lasted only part of a single year in 2000 with three survey events and two observations (Daniels, 2006). The four Chilean rivers were surveyed by Iroumé et al. (2018) annually, each with a slightly different duration, and two years were missed on Tres Arroyos. Durations, from longest to shortest, for the Chilean rivers are Tres Arroyos, Vuelta de Zorra, El Toro and Pichún, which spanned from 2005 to 2016 (12 years and nine observations), 2008 to 2014 (7 years and six observations), 2008 to 2013 (6 years and five observations) and 2008 to 2010 (3 years and two observations),

TABLE 1 Review of wood-tracing or tracking studies, updated from Ruiz-Villanueva et al. (2024), including their location, river characteristics (channel width and gradient) and wood surveys information (duration, number of tagged pieces, mobility and observed transport distance). In grey we highlighted the studies considered in this work.

Reference	Country	River	Survey length (km)	Mean channel width (m)	Channel gradient (m·m−1)	Drainage area (km2)	Tagged pieces	Natural or introduced wood	Time monitored (months)	Annual mobility (proportion of mobile wood pieces in %)	Mean transport distance (m)	Maximum transport distance (km)	Qmax (m3 s−1)
Benke & Wallace, 1990	USA	Ogeechee and tributaries	Transects-based	33–1,340	0.0002	-	290	Natural	20	17–84%	11,090	101	350
Berg et al., 1998	USA	6 streams in California's central Sierra Nevada	1.00 per stream (6.00)	2.1–12.7	0.02–0.08	-	1700	Natural	36	0.8–31%	215.5	-	-
Jacobson et al., 1999	South Africa	Kuiseb	90.0–260.0	<20- > 130	0.003–0.006	2,490–14,700	2,105	Natural	Flood event	34%	13–32	125	159
Keim et al., 2000	USA	3 streams in Oregon Coast Range	0.45, 0.58, 0.70	6.5	0.01	11.2	45–124	Not natural	36	32–56%	203	0.7	-
Haga et al., 2002	Japan	Oyabu Creek	5.5	9	0.04	5.3	63	Not natural	9	92%	840	4	14.4
van der Nat et al., 2003	Italy	Tagliamento	1.5, 2.5	≤1,000, 800	0.01	2,580	165 'plots' of $100m^2$	Natural	19	25–95%	13,000	51	-
Daniels, 2006	USA	Poplar Creek	0.6	15	0.001	56	140	Natural	5	52%	80	0.32	15
Millington & Sear, 2007	UK	Highland Water	2.05 then 2.46	4.5	0.01	9.5	324	Not natural	36	86–100%	209. 5	1.2	2.6
Warren & Kraft, 2008	USA	Rocky Branch	0.40	8	0.06	7.4	112	Natural	36	25%	5	0.3	356
MacVicar et al., 2009	USA	Sacramento	240.0	360	0.025–0.05	28,057	25	Natural	72	0–68%	7,475	35	2,550
MacVicar et al., 2009	France	Ain	0.80 and 22.0	80–130	0.15	3,630	-	Natural	13	-	-	-	930
Iroumé et al., 2010	Chile	Vuelta de Zorra	1.56	11	0.04	5.8	484	Natural	11	13%	117	0.5	1.45
Dixon & Sear, 2014	UK	Highland Water	0.75 of ~10	4.5	0.01	9.2	162	Natural	32	50–62%	256	5.6	36.8
Schenk et al., 2014	USA	Roanoke	143.0	85	0.002	-	290	Natural	36	16%	1,190	101.1	600
Schenk et al., 2014	USA	Roanoke	143.0	85.5	0.002	-	54	Natural	Flood event	-	1,330	72.1	600
Jochner et al., 2015	Switzerland	Erlenbach	0.32	3.7	0.18	0.7	236	Not natural	6	-	10	-	1.25

(Continues)

TABLE 1 (Continued)

Reference	Country	River	Survey length (km)	Mean channel width (m)	Channel gradient (m·m−1)	Drainage area (km2)	Tagged pieces	Natural or introduced wood	Time monitored (months)	Annual mobility (proportion of mobile wood pieces in %)	Mean transport distance (m)	Maximum transport distance (km)	Qmax (m3 s−1)
Lucía et al., 2015	Italy	Rienz	na	3.5	0.01	630	238	Not natural		-	500		
Ravazzolo et al., 2015	Italy	Tagliamento	~18.0	800	0.003	-	113	Not natural	17	28–34%	6,555	51.1	-
Wyżga et al., 2017	Poland	Czarny Dunajec	~16.0	25–180	0.008	134	30	Not natural	Flood event	-	6,815	14.6	130
Iroumé et al., 2018	Chile	El Toro	2.19	13	0.05	17.8	181	Natural	60	2–13%	236	2.2	-
Iroumé et al., 2018	Chile	Pichún	1.00	5	0.1	4.3	79	Natural	96	5–17%	69	0.98	-
Iroumé et al., 2018	Chile	Tres Arroyos	2.07	10	0.1	9	536	Natural	96	1–10%	133	2	-
Iroumé et al., 2018	Chile	Vuelta de Zorra	1.56	11	0.04	5.6	403	Natural	96	1–9%	179	1.5	-
Bosio et al., 2021	USA	State Creek	0.24	2.2	0.01	24	25	Not natural	168	8%	3	30	0.12
Bosio et al., 2021	USA	Shane Creek	0.24	2.4	0.01	45.5	25	Not natural	168	3%	1	14	0.16
Bosio et al., 2021	USA	Walton Creek	0.24	2.1	0.01	35.7	25	Not natural	168	13%	8	28	0.20
Lininger & Hilton, 2022	USA	North Fork Caspar Creek	1.84	5.5	0.02	4.8	1,356	Natural	240 (Bi-annual)	2–8%	41	0.22	-
Lininger & Hilton, 2022	USA	South Fork Caspar Creek	1.91	5	0.015	4.2	518	Natural	240 (Bi-annual)	1–8%	80	0.64	-
Gregory et al., 2024	USA	Mack Creek	1.00	11.4	0.09	5.8	2,972	Natural	288	0.3–13%	92	0.52	-
Hortobágyi et al., 2024	France	Allier	12.0	60	0.003	12,430	220	Natural	24	38–86%	7,877	33	568
Aarnink, 2025	Switzerland	Avançon de Nant	3.60	22.7	0.1	13.4	870	Natural	36	3–27%	184	2.7	-
Finch et al., 2025	Switzerland	Spöl	1.60	27.5	0.02	49	1,393	Natural	After floods for 5 years	6–36%	281	1.5	40

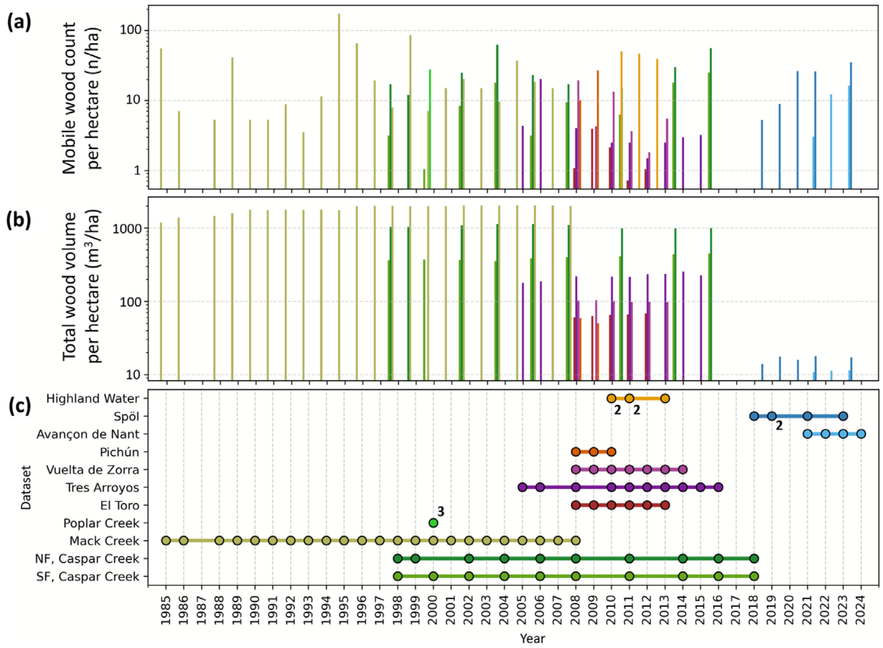

FIGURE 1 Bar graphs show the a) count of mobilized wood pieces normalized by hectare and b) total wood volume surveyed per year, river or site, and normalized by hectare; c) timeline of the study periods with field survey events denoted by markers. Numerical values adjacent to markers represent the frequency of surveys within the given year, if more than one was performed. Colours are the same as in Figure S1.

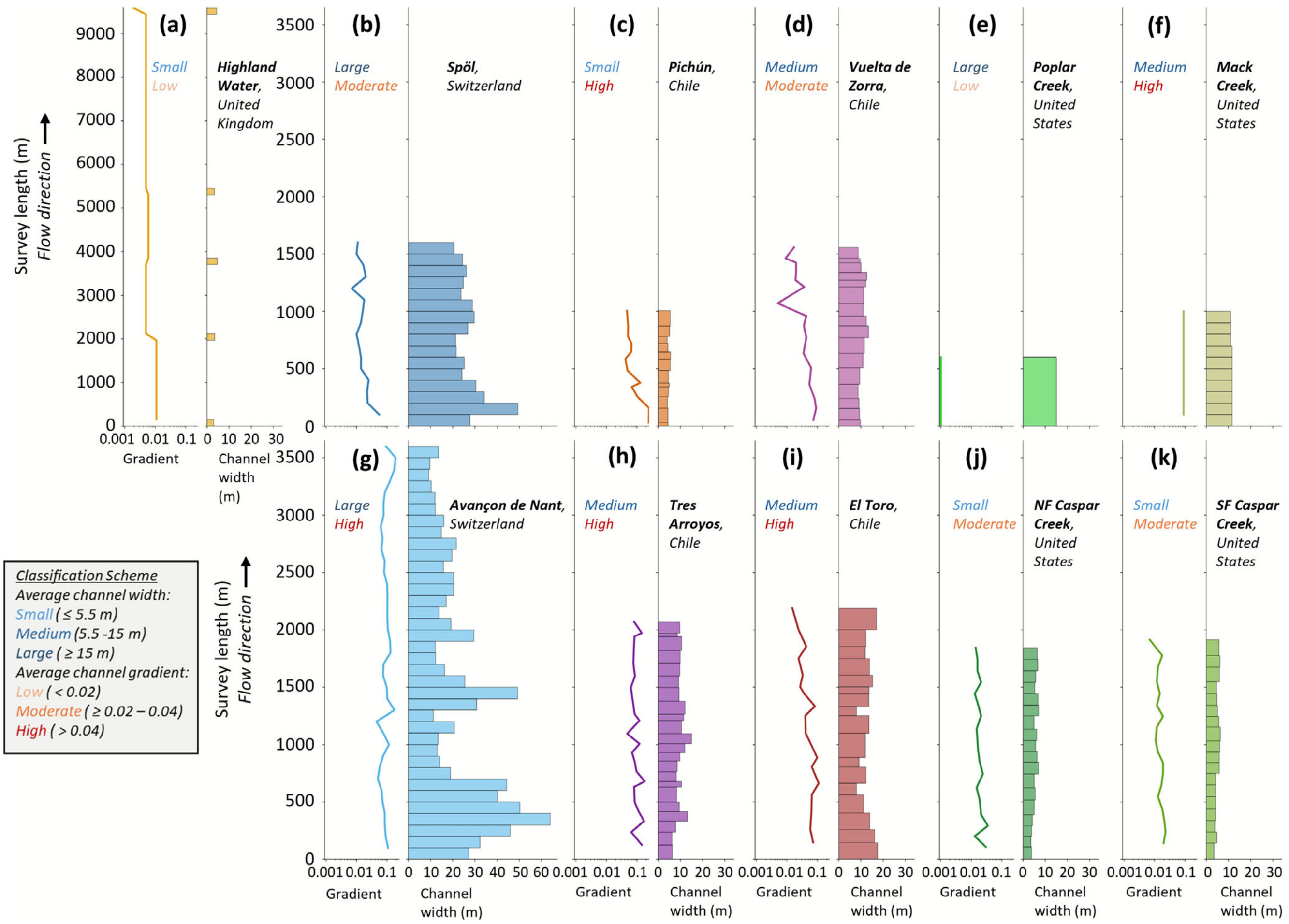

FIGURE 2 Legend on next page.

respectively. Wood was surveyed annually on the Avançon de Nant from 2021 to 2024 — 4 years and three observations (Aarnink, 2025). The Spöl River, a unique study site where experimental floods' effects on wood mobility were captured, was surveyed from 2018 to 2023 for 6 years and five observations (Finch et al., 2025). Highland Water was surveyed by Dixon & Sear (2014) from 2010 to 2013 for 4 years and four observations. The basis of these studies details wood storage volumes, Figure 1b, and wood mobility through time, Figure 1a.

In terms of flood magnitude and frequency, Mack Creek experienced a flood event with a 41-year recurrence interval in 1996 (Gregory et al., 2024) and includes a hydrograph of the daily maximum discharge. Daniels (2006) also included a mean daily discharge hydrograph. Dixon & Sear (2014) refers specifically to two floods in 2012–2013 but also includes a hydrograph during the survey period. Vuelta de Zorra had 9 bankfull events in a single winter of 2009 (Iroumé et al., 2010). Otherwise, Iroumé et al. (2018) recorded the maximum height of flow in comparison to bankfull for each year and river. Lininger and Hilton (2022) express the frequency of greater than one-year floods. Aarnink (2025) approximated the influence of high flows during the survey period based on a stream gauge. Finch et al. (2025) include hydrographs of each of the surveyed floods.

Channel reaches are illustrated in Figure 2, for the 11 rivers, which depicts the observed channel width and gradient along the longitudinal distance of the surveyed area (see Table S1 for exact reach values). Methods for segmentation of the studied areas varied, and details are explained in the data pre-processing methods section of this study. Based on average channel width or gradient, classifications of the 11 rivers were performed. Three channel width classes were defined as relatively large (greater than or equal to 15 m), medium (greater than 5.5 and less than 15 m) and small (less than or equal to 5.5 m). Based on the channel width classification scheme, three rivers were classified as relatively large: the Spöl, Avançon de Nant and Poplar Creek; four rivers were classified as medium: Vuelta de la Zorra, Tres Arroyos, El Toro and Mack Creek; and four rivers were classified as small: Highland Water, Pichún, NF Caspar Creek and SF Caspar Creek. The three channel gradient classes defined were: steep (greater than 0.04 m/m), moderate (greater than or equal to 0.02 but less than or equal to 0.04 m/m) and gentle (less than 0.02 m/m). Based on the channel gradient classification scheme, five channels were classified as steep: Pichún, Mack Creek, Avançon de Nant, Tres Arroyos and El Toro; four channels were classified as moderate: Spöl, Vuelta de la Zorra, NF Caspar Creek and SF Caspar Creek; and two channels were classified as low gradients: Highland Water and Poplar Creek. It should be noted that most of the catchment sizes were small (maximum 56 km^2) and rather steep.

In addition to channel width and gradient classes, individual wood piece lengths were compared to channel reach widths (Lw/Cw), when available, to assign each piece to one of three ratio classes: Lw/Cw < 0.5, Lw/Cw ≥ 0.5 or Lw/Cw ≥ 1.0—an adaptation of Gurnell et al.'s (2002) channel descriptions based on Lw/Cw relationships.

Access for NF and SF Caspar Creek, Mack Creek and Spöl datasets was available online (Aarnink, 2025; Finch et al., 2025; Finch & Ruiz-Villanueva, 2024; Gregory et al., 2024; Hilton et al., 2022; Lininger & Hilton, 2022). The data from Poplar Creek and Highland Water was manually extracted from figures within the published articles (Daniels, 2006; Dixon & Sear, 2014). Due to the graphical extraction, some information was missing; for example, the individual wood pieces' diameters (only the lengths were able to be determined); therefore, the ability to accurately compute values such as the overall percentage of mobile to non-mobile wood pieces reported in their respective studies was not possible. Avançon de Nant was made available by Aarnink (2025). Chilean data was provided by Iroumé et al. (2018).

2.2 | Data pre-processing

Data homogenization was required when combining different studies as slight variations in their recordings were observed. Agreement between studies in terms of 1) criteria that distinguish pieces to have moved or not moved, 2) categories of wood's initial conditions such as orientation and decay and 3) channel reach segmentation methods needed pre-processing.

Regarding motion, some studies did not describe any criteria which wood must satisfy to qualify as having moved (Dixon & Sear, 2014; Iroumé et al., 2018). Others mention a 10-cm threshold to qualify as movement (Daniels, 2006), a 30-cm threshold to require additional verification from aerial or ground imagery (e.g., Lininger & Hilton, 2022), or that their transect-grid format of 10-m relative to the normal size of mobile pieces was sufficiently accurate (Gregory et al., 2024). Aarnink (2025) and Finch et al. (2025) included a criterion for movement observations based on the measured change in distance and the length of the wood piece, which had to be greater than two times the length of the wood. This constraint reduces any possible errors in assuming entrainment related to potential minor offsets that occur during the record of the wood piece's location or for rotations of wood that did not become fully entrained. The distance to twice the wood piece length criterion was applied to all datasets for consistency. If a piece failed the movement criterion, the piece was determined to have not moved, even if it was considered moved in the original study.

Regarding wood's characteristics before motion, here defined as the wood's initial conditions, they were described according to five variables: the wood piece was part of a jam or accumulation (yes or no), presence of roots (yes or no), orientation with respect to the flow (three classes), decay (three classes) and burial (yes, or no). Table 2 describes the studies for which this information was available.

The state of decay included three decay classes (Aarnink, 2025; Finch & Ruiz-Villanueva, 2024; Iroumé et al., 2018) or five decay classes (Gregory et al., 2024). The five decay classes used by Gregory et al. (2024) to describe wood pieces were distilled to three in the following manner: 1 – fresh, 2 – intermediate, 3 and 4 – decayed. Gregory et al. (2024) did not report any wood pieces to be of class 5, as they were likely unable to hold a tag. The three decay classes used in our research—fresh, intermediate and decayed—are based on structural and visual indicators, following the classification approach of Ruiz-Villanueva et al. (2016b). Fresh wood retains most of its original structure, including bark, branches and leaves; intermediate wood shows early signs of decay and partial bark loss; and decayed wood is heavily decomposed with no bark remaining.

Regarding wood orientation, Lininger and Hilton (2022) and Gregory et al. (2024) had recorded the angle in degrees while the other studies (Aarnink, 2025; Finch et al., 2025; Iroumé et al., 2018) used three classes: parallel, oblique and perpendicular to describe wood's longest axis relative to the channel or flow direction. To homogenize the data, three classes of orientation were defined: 0 to 30° – parallel, 30 to 60° – oblique and 60 to 90° – perpendicular.

Jam association was a unique condition that we did not pre-process in any dataset. However, differences between studies should be acknowledged: some defined the minimum requirement as two pieces in contact (Aarnink, 2025; Finch et al., 2025; Iroumé et al., 2018), while others required three (Gregory et al., 2024; Lininger & Hilton, 2022).

TABLE 2 List of the 11 rivers used in this work. Shading themes for the rivers are a continuation of the colour schemes applied in Figures 1 and 2. Olive green shading denotes relevant variables for movement and reach analysis. Light grey shading is for the initial conditions analysed. Dark grey demonstrates where data was unavailable.

Source	River, country	Moved pieces	noMove pieces	notFound pieces	Reach location and variables	Jam	Roots	Orientation	Decay	Buried
Dixon & Sear, 2014	**Highland Water, UK**	X, lengths	X, lengths	-	-	-	-	-	-	-
Finch et al., 2025	**Spöl, Switzerland**	X	X	X	X	X	X	X	X	X
Aarnink, 2025	**Avançon de Nant, Switzerland**	X	X	X	X	X	X	X	X	X
Iroumé et al., 2018	**Pichún, Chile**	X	X	X	X	X	X	X	X	-
Iroumé et al., 2018	**Vuelta de Zorra, Chile**	X	X	X	X	X	X	X	X	-
Iroumé et al., 2018	**Tres Arroyos, Chile**	X	X	X	X	-	-	-	-	-
Iroumé et al., 2018	**El Toro, Chile**	X	X	X	X	X	X	X	X	-
Daniels, 2006	**Poplar Creek, USA**	X, lengths	-	-	-	-	-	-	-	-
Gregory et al., 2024	**Mack Creek, USA**	X	X	X	X	X	X	X	X	-
Lininger & Hilton, 2022	**NF, Caspar Creek, USA**	X	X	X	X	after 2008	X	X	-	X
Lininger & Hilton, 2022	**SF, Caspar Creek, USA**	X	X	X	X	after 2008	X	X	-	X

To account for the presence of roots and a burial state, the data provided did not require any preprocessing.

Studied rivers were segmented according to standard intervals of approximately 100-m (Aarnink, 2025; Finch et al., 2025; Lininger & Hilton, 2022), uniformity of slope, channel width or wood abundance (Iroumé et al., 2018), being representative of the various types of geomorphological planforms found across the studied system (Dixon & Sear, 2014) or two unique reaches defined as old-growth and new-growth related to logging practices (Gregory et al., 2024). The only pre-processing on the channel reach segmentations was performed on Mack Creek for Gregory et al. (2024) to create approximately 100-m sections from their described old and new-growth reaches, similarly to their calculations of wood abundance per 100 m conducted in their study. The approximate channel width (m), length (m), area (ha) and gradient (m/m) are known for all studies, but the locations of wood pieces were not known to us for Daniels (2006) and Dixon & Sear (2014) due to data retrieval.

2.3 | Wood entrainment and mobility analysis

Entrainment describes the initial motion of wood or its transition from a state of rest to movement due to hydraulic forces. Pieces which have been determined to have moved are called Moved wood, while stationary wood or those that were determined to not have moved are called noMove. The determination of wood's movement defines its entrainment class or wood subset: Moved or noMove.

Entrainment analysis requires at least the Moved and noMove wood distributions to be known (see Table 2 for data availability per study). Proportions (and percentages) of wood counts and volumes for moved and not moved wood were explored. If the proportion of Moved to noMove wood could not be determined during data compilation, we used the reported average movement values from the respective study; this was the case for Highland Water and Poplar Creek. When applicable, initial conditions such as the presence of roots, inclusion in a jam, burial, orientation and state of decay were used to evaluate entrainment to recognize relative influences on movement probability. Distributions of wood piece dimensions (length, width and diameter) can be compared according to their determined entrainment value, as well, to reflect any unique properties per movement and/or initial conditions. Fisher's tests were applied to determine if the proportion of wood pieces that moved versus those that did not move significantly differed across conditions.

Wood dimension ratio (DR) is used here to describe the total length of the wood piece divided by the diameter of the wood piece, both in meters. DR is a dimensionless ratio that is tied to the size of the wood piece. Given the minimum requirements for wood size in these tracking studies are 1 m by 10 cm or 2 m by 20 cm, the DR value for the minimum wood size is 10. Values less than 10 represent blockier wood pieces, and values greater than 10 represent elongated wood pieces in relation to their diameter, as shown in Figure S2. DR was used to compare mobility among datasets. Histograms, plots and statistical tests were done in Python using pandas (McKinney et al., 2010), matplotlib.pyplot (Hunter, 2007), numpy (Harris et al., 2020), unicodedata and scipy.stats (Virtanen et al., 2020): norm, lognorm, skew, mannwhitneyu and ks_2samp.

An additional class for wood, called here as notFound, describes wood pieces that were not found again following being tagged during an earlier survey. These pieces cannot be found for a multitude of reasons as discussed in Finch et al. (2025), which include obscuration in accumulations/jams or within sediment bars, loss or removal of identification tags and possible exportation from the system via transport out from the studied reach. NotFound wood is an ambiguous case when it comes to data handling because of uncertainty. Therefore, notFound wood is not always included in the analysis, but should be a recognized class since these occurrences do describe some change. Boxplots and statistics of Moved, noMove and notFound wood were constructed in Python using pandas, seaborn (Waskom, 2021), matplotlib.pyplot, matplotlib.colors and matplotlib.ticker. ScalarFormatter. Table 2 shows for which studies notFound wood was available.

Wood that could not be located during one survey may reappear during a later survey. At times, the wood remains in the same location and, due to natural phenomena like obscuration in a jam or burial, the wood piece was missed in a survey but re-found in a later survey. In this case, the piece of wood has its entrainment class changed from notFound to noMove, and the wood piece is not written in for the year it had skipped. Alternatively, the wood piece has been transported downstream by the time it is re-found. In this case, wood pieces have been termed Timelag, as used in previous studies (Finch et al., 2025). Timelag wood describes pieces that have been transported a distance, but, due to being missed during an intervening survey, we cannot assign the transported distance to a particular year.

Since each wood piece's location is known for many studies apart from Daniels (2006) and Dixon & Sear (2014), we can relate wood values such as volume (m^3) and counts (n) to channel reach characteristics like spatial area (hectare, ha) and longitudinal distance (km) to construct variables like the wood load per reach (m^3/ha), wood load or frequency per reach (m^3/km) and proportion of moved wood (m^3/m^3 or n/n) per reach and survey. Scatterplots of these variables and function fits were performed in Python.

2.4 | Transport distance analysis

The change in wood's location from one survey to the next can represent a transport, displacement or travelled distance if the change occurred in the downstream direction and was greater than two times the length of the wood piece, as explained earlier. Depending on the study, transport distances were computed based on the difference between the initial and sequential surveys: measured distance along the river (Daniels, 2006; Iroumé et al., 2018; Lininger & Hilton, 2022), distance along the transect-grid (Gregory et al., 2024), distance between the start and end point of a log's GPS points (Dixon & Sear, 2014), or values derived from the distance to the outlet (Aarnink, 2025; Finch et al., 2025). Wood that did not move or did not satisfy the distance criterion was given transport distances of zero (0). The notFound subset, or wood which was not found again after having been tagged, could be handled as censored data and given distances of at least equal to the distance to the end of survey or omitted from the analysis. NotFound wood is included in some transport distance distributions as censored data, and these occurrences will be explicitly stated.

Cumulative distribution functions (CDF) for uncensored and censored data were performed in R with the survminer and surviver packages (Therneau, 2020).

2.5 | Frequency and magnitude analysis

Two approaches were used to compute probabilities and perform a frequency analysis of wood mobility and transport distances: 1) the Weibull formula for empirically estimating the return period of an event and 2) general extreme value distribution (GEV) fitting (Katz, Parlange, & Naveau, 2002). The two approaches are designed to characterize and model extreme values, helping to contextualize the frequency of both known and future events. The maximum transport distance, based on the 90th percentile, and the sum of the mobilized wood volume were computed per dataset, then divided by the total spatial area of the river reaches.

The Weibull formula and GEV methods were applied to both datasets separately. Python was used for return periods (numpy and scipy.stats.linregress) and GEV fitting (scipy.stats.genextreme, scipy.optimize.minimize).

3 | RESULTS

3.1 | Wood entrainment and mobility conditions

Wood mobilization on the 11 rivers varies annually (Figure 3) in comparison to the overall mobility ratio (Figure S3). This reflects wood mobility's mixed responses to flow events, differences in wood availability/conditions, and is a function of the maximum proportion of wood that moves. For wood volume, the Spöl, Avançon de Nant and El Toro have the greatest ranges of wood mobility observed during their study periods, with differences between their maximum and minimum for wood volumes mobilized of 22%, 11% and 11%, respectively. The other five rivers varied within a range of 3%, and NF Caspar Creek with a value of 2%, which equated to small rivers varying only from 2 to 3%. The Spöl and Avançon de Nant, two relatively large-sized rivers with moderate and high gradients, constitute two of the three rivers with the greatest range of wood movements observed. Therefore, relatively large and medium-sized rivers had ranges of approximately 11% to 22% and 3% to 11%, respectively. Moderate and high gradient rivers had ranges of approximately 2% to 22% and 3% to 11%.

Count-based wood movements retained Spöl and Avançon de Nant as two large rivers with the greatest range of values, 30% and 24%, respectively. Relatively large rivers experienced ranges of count-based wood movements from 24 to 30%, medium rivers from 8% to 13% and small rivers from 7% to 12%. In terms of gradient classifications, moderate gradient rivers ranged from 8% to 30%, and high gradient rivers ranged from 7% to 24%.

Distributions of the dimensions (i.e., length, diameter, volume) of entrained wood pieces are often statistically different for wood that moved, did not move or was not found as well as when compared to wood of different river width or gradient classifications. See Figure 4 for boxplots and Figure S4 for statistical test results. Overall and per entrainment class (Moved, noMove, notFound), wood in small rivers appears to be characteristically longer, wider and larger in volume than other river classes, which could be slightly inflated by NF and SF Caspar Creek's threshold of 2-m and 20-cm diameter. Nonetheless, length, diameter and volume decrease as river size increases ($p < 0.05$; Figure S4), but the exception is Moved wood for medium

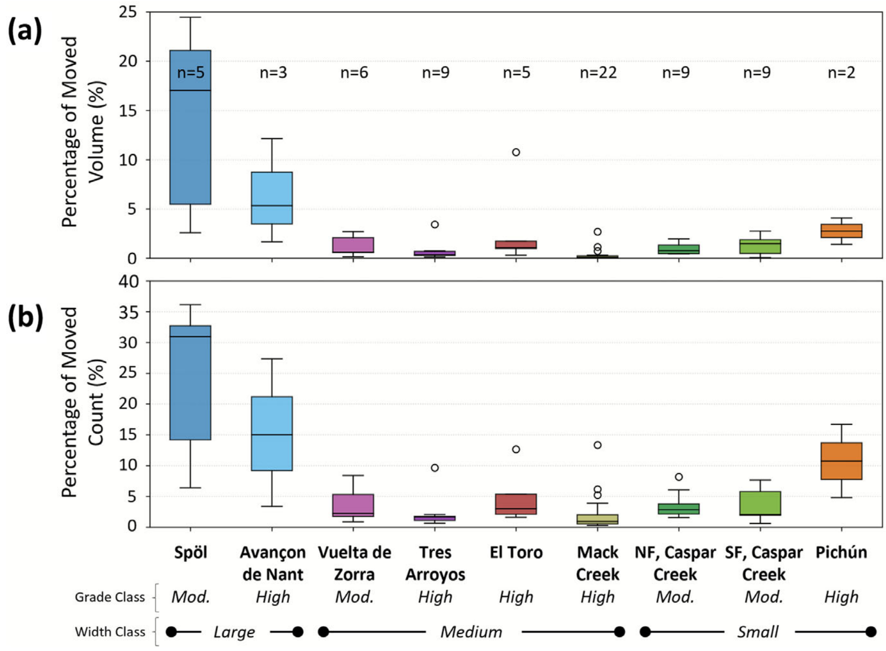

FIGURE 3 Boxplots of observed annual percent movements by a) volumes and b) counts per dataset. Values are computed based on moved wood compared to the sum of Moved and noMove wood per dataset-year (n = years of observations). Boxplots are ordered first by channel width classification and, within each width class (width class), by gradient class (grade class).

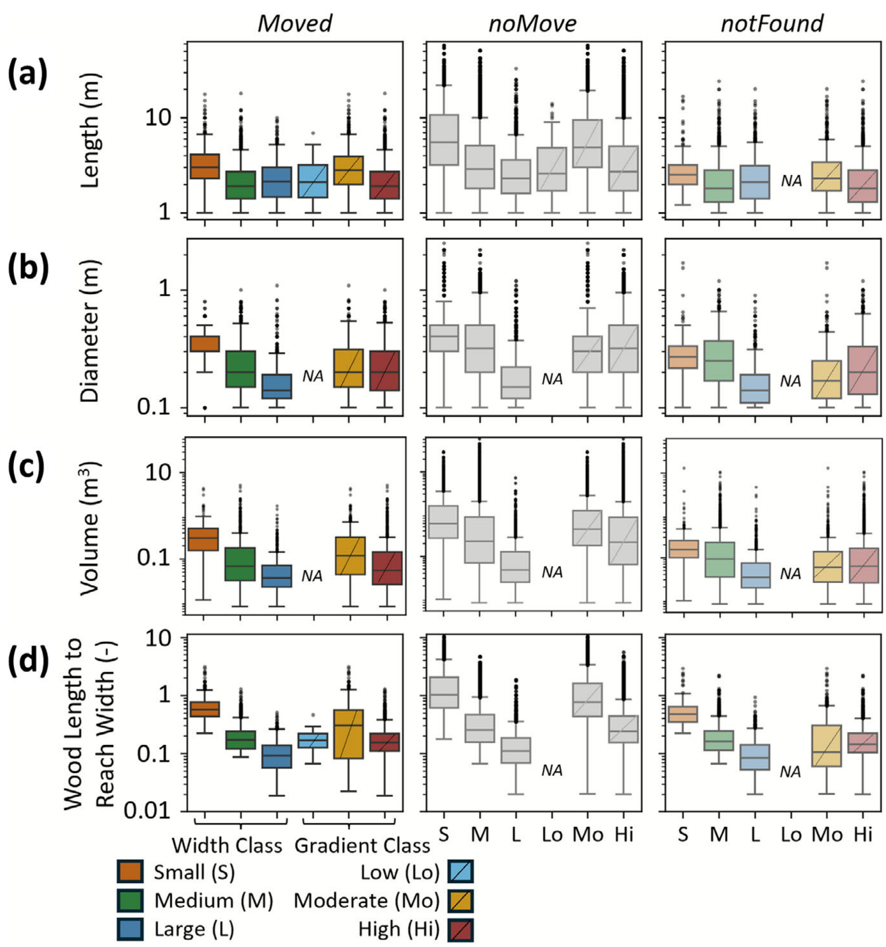

FIGURE 4 Boxplots of a) length, b) diameter, c) volume and d) wood length to reach width ratio for width and gradient river classes per Moved, noMove and notFound entrainment status. Due to data availability, some distributions cannot be constructed. Sample counts, maximum, minimum, mean, standard deviation and median are in table S2, and statistical test results are included in Figure S4.

and relatively large rivers in which large has slightly greater median and mean values for length ($p < 0.05$; Figure S4). Observations were limited for the low gradient class, but the lengths of Moved and noMove subsets indicate high and low gradient classes to have more similar distributions ($n = 63$ for low class; $p > 0.05$; Figure S4) to each other while moderate gradients, on average, have longer pieces with greater volumes compared to other gradient classes ($p < 0.05$; Figure S4). In addition, diameters were similar for moderate and high gradient channels ($p > 0.05$; Figure S4), so the primary difference is the length of wood pieces for these gradient classes ($p < 0.05$; Figure S4).

Of the 59,739 surveyed wood pieces, just 3.2% were observed to have moved. Mobile wood pieces were predominantly shorter than the reach channel width: 1837 of 1887 (97%) mobilized pieces had lengths less than the reach channel width based on the entire dataset. Relatively large rivers never observed wood pieces in transport longer than the reach channel width. Medium rivers had sparse occurrences of pieces longer than the reach channel width being mobilized: 4 of 892 (0.4%). Small rivers had the highest percentage of wood in motion with lengths greater than the reach channel width: 46 to 399 (12%). However, 99.4% of surveyed wood in relatively large rivers was shorter than their reach width, 93% for medium rivers and 52% for small rivers.

Based on wood piece length to channel width ratio classes, 4% of 38,151 wood pieces less than half the channel width moved, 2% of 9,689 wood pieces equal to or greater than half the channel width moved, and 0.7% of 7,679 wood pieces equal to or greater than the channel width moved (see supporting information Figure S5 for histograms of counts of each class per dataset). Based on Fisher's tests, the proportions of Moved vs. noMove differed significantly among all ratio classes ($p < 0.05$).

Proportions of wood's initial conditions (jam, burial, roots, decay and orientation) reported by entrainment class (Moved, noMove) can indicate unique differences in wood mobility. Relative proportions of movement have already been described for each study (Figure S3) and per year for each study (Figure 3), which can be given an additional level of complexity by sorting them according to wood's assigned initial conditions, see Figures S5 and 5. Figure S6 demonstrates the proportions of Moved and noMove wood by river and all the rivers combined. Figure 5 demonstrates a similar partitioning of data as in Figure S6 based on the initial conditions but as proportions for channel width and gradient classes.

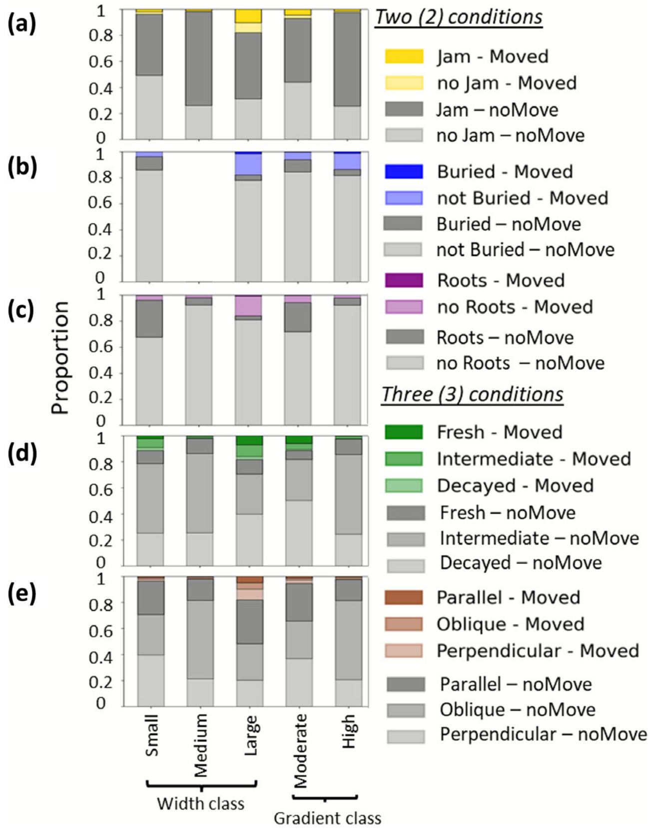

FIGURE 5 Count-based proportional bar plots for initial conditions per river class: a) jams, b) burial, c) roots, d) decay and e) orientation for channel width and gradient classes. Coloured proportions represent mobile wood, and greyscale represents non-mobile wood. Values are based on all observations combined per river classification. All relevant counts and associated volumes can be seen in the supporting information in table S3.

Proportions of wood in jams vary greatly in the individual rivers' datasets, with Pichún and El Toro having well less than 50% in jams compared to the others, which have half or more of their wood in jams. Based on classified datasets, small rivers have less wood in jams than medium and relatively large rivers, while high gradient rivers have more wood in jams than moderate gradient. Jam-associated pieces showed slightly higher movement proportions in El Toro (<1%), NF Caspar Creek (<1%) and SF Caspar Creek, but slightly lower movement proportions in Avançon de Nant, Mack Creek, Pichún (<1%) and Spöl. However, these differences may reflect varying abundances of wood jams among rivers rather than a true effect of jam association. Movement probability, based on Fisher's tests, was not significant ($p > 0.05$) for the small river class, relatively large river class, Spöl, Pichún, El Toro and NF Caspar.

Movement of buried wood was more frequent in the Spöl and Avançon de Nant than for wood that was reported to not be buried. In contrast, NF and SF Caspar Creek observed burial reduced movement probability. Criteria for burial, such as partially buried, may be related to these varied results, but related causes are discussed in more detail later in the discussion. These differences are also reflected in the relatively large (Spöl and Avançon de Nant) and small river classes (NF and SF Caspar Creek), respectively. According to Fisher's tests, all the datasets had statistically significant ($p < 0.05$) differences in the proportions of Moved vs. noMove pieces between buried and unburied wood.

Roots uniformly reduced movement probability (Spöl < 1%) with exception for Pichún, which observed a greater likelihood of movement of 14%. However, Pichún only had 4 recordings of wood with roots against 131 pieces without roots. Roots' proportion of Moved vs. noMove, according to Fisher's tests, was not significant ($p > 0.05$) only for the relatively large river class, Spöl, Avançon de Nant, Pichún and Vuelta de Zorra.

Fresh and intermediate wood was more likely to move than decayed wood in all rivers except for Vuelta de la Zorra; Mack Creek had a difference of less than 1%. Fresh wood in comparison to intermediate decay class showed mixed responses among rivers; fresh wood was more frequently moving than intermediate in El Toro, Mack Creek (< 1%) and Pichún. Intermediate was more frequent than fresh wood in Avançon de Nant and Spöl. Decay's influence on movement probability, according to Fisher's tests, was significant ($p < 0.05$) for fresh to decayed wood for medium rivers, high gradient rivers, Spöl and Mack Creek. Fresh to intermediately decayed wood's proportion of Moved vs. noMove was also significant ($p < 0.05$) for the relatively large river class. In addition, intermediate to decayed wood proportion of Moved vs. noMove was significant ($p < 0.05$) for the medium river class, relatively large river class, high gradient river class, Spöl, Avançon de Nant, Vuelta de Zorra and Mack Creek.

Orientation of wood pieces was generally well-distributed with no one orientation being proportionally larger, although Mack Creek had a high frequency of oblique wood compared to other rivers. Regarding motion, parallel oriented wood was always observed to move more frequently than oblique wood (less than 1% difference for Mack Creek and Vuelta de Zorra). Movement probability for parallel-oriented wood was significantly different from the other orientations across nearly all datasets and within width and gradient classes (Fisher's Exact Test, $p < 0.05$), except for the following comparisons, which were not statistically significant: Large – perpendicular, Nant – oblique, Pichún – both orientations, Vuelta de Zorra – perpendicular, El Toro – both orientations, SF Caspar Creek – both orientations. Wood orientated perpendicularly to the channel moved more often than parallel in the Avançon de Nant and El Toro. Oblique orientation when compared to perpendicular wood had a mixed response among rivers. Oblique pieces were more likely to move than perpendicular ones in Mack Creek (<1%), NF and SF Caspar Creek and Pichún. Conversely, perpendicular orientation was associated with a greater likelihood of movement compared to oblique in Avançon de Nant, El Toro, Spöl and Vuelta de Zorra. Movement probability for oblique to perpendicular oriented wood was not significantly different ($p > 0.05$) for the following comparisons: Medium, Moderate, Spöl, Avançon de Nant, Pichún, El Toro, Mack Creek, SF Caspar Creek.

Channel reaches, defined by original research groups or by us at 100-m intervals, were related to wood volumes or loads for constructing relationships between wood volume or loads and wood mobility (Figure 6). Mobile wood volume increased as wood storage in the reaches was greater in the nine rivers. These trends were consistent for individual rivers and classified datasets, although relatively large rivers have generally lower storage volumes when compared to medium and small rivers; medium rivers have the greatest amounts of wood in storage. Rivers in the high and moderate gradient classes

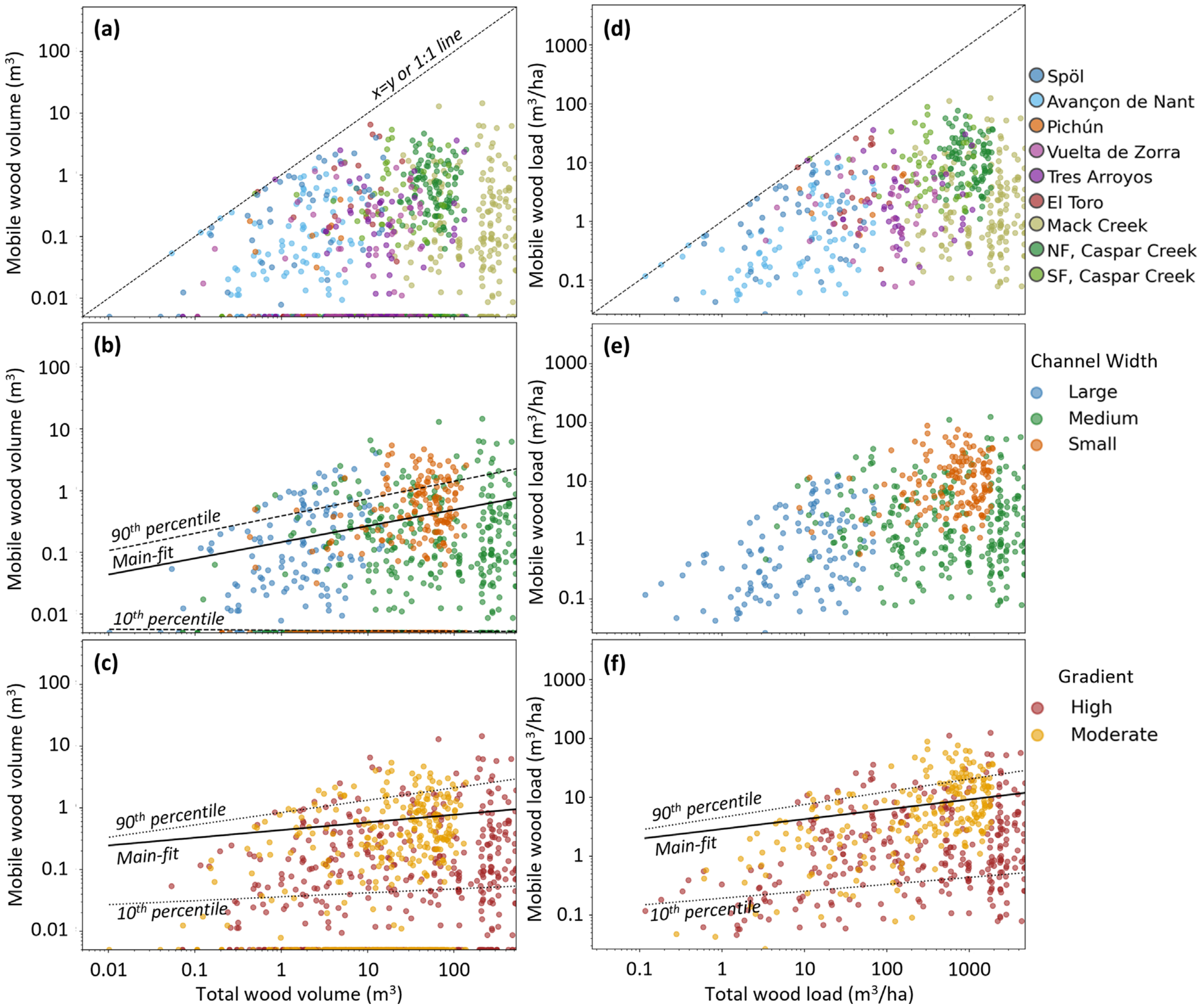

FIGURE 6 Scatter plots of mobile wood volume (m^3) and total wood volume (m^3) for a) individual rivers, b) channel width classifications and c) channel gradient classifications. Panels d, e and f are those classifications, respectively, but by wood load (m^3/ha). Each point represents a reach per event per dataset. For wood volume panels (a-c), reaches in which wood was present but no pieces were observed to move were assigned an arbitrary low value of 0.005 m^3 for plotting on the log scale (n = 588; n_total = 1,076). These zero-movement cases appear along the lower edge of each plot. The dashed line in panel a represents mobile wood volume equaling total wood volume. In panel b, the 90th- and 10th-percentile power-law fits are shown as dashed lines, and the main fit is shown as a solid line, and they include the zero (0.005 m^3) values in the fit. The power-law coefficients (a, b) for the main, 10th-percentile, and 90th-percentile fits were (0.15, 0.26; $R^2 = 0.03$), (0.005, −0.008) and (0.39, 0.28), respectively. Panel c excludes the zero values during fitting, and power-law coefficients for the main, 10th-percentile, and 90th-percentile fits were (0.43, 0.12; $R^2 = 0.02$), (0.04, 0.06) and (0.83, 0.20). Panel f includes the main, 10th-percentile, and 90th-percentile power-law fits based on wood load, which were (2.88, 0.17; $R^2 = 0.04$), (0.19, 0.12) and (4.56, 0.22). The relationship for low gradient rivers could not be computed due to data availability.

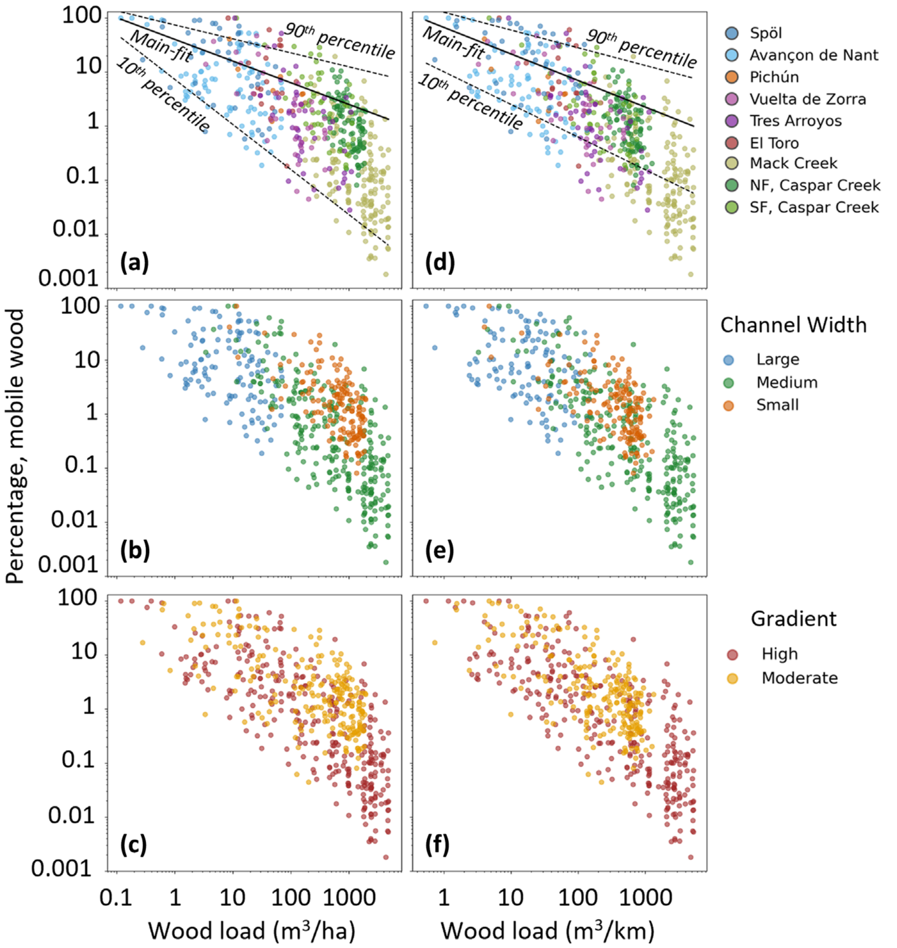

FIGURE 7 Scatter plots of the percentage of mobile wood pieces by wood load in m^3/ha and m^3/km per dataset and reach. Left-hand panels represent the percentage of mobile wood volume to total wood load by reach area (m^3/ha) for a) individual rivers, b) channel width classifications and c) channel gradient classifications. d) Individual rivers, e) channel width and f) gradient classifications, right-hand panels, are expressed in terms of wood load by reach length (m^3/km). The solid line in panel a is a power-law equation fit to all the data. The upper and lower-dashed lines are confidence intervals computed at the 90th and 10th percentiles. For wood load by hectare (panel a), the power-law coefficients (a, b) for the main, 10th-percentile, and 90th-percentile fits were (0.40, −0.40; $R^2 = 0.39$), (0.07, −0.83) and (0.75, −0.26), respectively. For wood load by length (panel d), the power-law coefficients (a, b) for the main, 10th-percentile, and 90th-percentile fits were (0.67, −0.49; $R^2 = 0.39$), (0.101, −0.60) and (1.27, −0.33), respectively. The relationship for low gradient rivers could not be computed due to data availability.

share a similar range of storage values, with high gradients having greater amounts of storage, and both classes demonstrate the same general trend of increasing storage resulting in more wood movement. Mobilized wood volumes, excluding no movement occurrences, were statistically different among channel width and gradient classifications based on pairwise Mann–Whitney U (MW-U) and Kolmogorov–Smirnov (KS) tests with the exception for the KS test comparing relatively large and medium rivers (p value of 0.08).

Known channel areas (ha) and segment lengths (km) have been used to estimate wood load storage (m^3/ha and m^3/m) relative to channel reach dimensions (see Figure 7). Despite similar absolute values, there is a clear negative correlation between wood storage and movement: as wood storage increases, the proportion of moved wood decreases. This relationship holds whether using area or length, but using channel width to calculate wood load by area (m^3/ha) results in a more continuous range of values compared to length-based values (m^3/km). MW-U and KS tests indicate statistically significant differences in wood-movement proportions, both with and without zero-movement cases, for all classes except one: when zero values are included, moderate and high gradient classes do not differ (MW-U $p = 0.27$).

The wood dimension ratio (DR) differed between mobile and non-mobile wood pieces (Figure S7 for histograms and Figure S8 for bell curves). Distributions were nearly all right-skewed, with only the Moved wood distribution for El Toro being a normal distribution. NF and SF Caspar Creek appeared particularly limited to DR values well under 50 for movement to have occurred, which is a relatively limited fraction of their overall dataset, and their respective noMove distributions are significantly different from the Moved. The general trend was for noMove wood to have greater average DR values and standard deviations than for Moved wood; see Table S4. Moved wood average DR values across rivers ranged from values of 9–23 (standard deviations of 7–22). NoMove wood DR values across rivers ranged from values of 11–32 (standard deviations of 9–29). Median values were always less than mean values for all entrainment classes (Moved, noMove) and datasets.

DR values for mobile wood in small, medium and relatively large rivers (Figure 8a-e) have median values of 9.3, 9.0 and 13.6 and mean values of 12.2 (std = 9.4), 11.4 (std = 8.5) and 16.7 (std = 11.1). Moderate and high gradient rivers have median values of 11.6 and 9.6 and mean values of 15.2 (std = 11.3) and 12 (std = 8.5; Figure 8d and e). In comparison to non-mobile wood, high gradient rivers are the only class to have a smaller median value for its related non-mobile wood than for its mobile wood: 9.3 to 9.6. Otherwise, even for high gradient channels, the mean value for non-mobile wood is always larger than for mobile wood and with larger standard deviations, see Table S4. Moved (mobile) wood was the only subset of wood to not demonstrate statistical significance when comparing DR distributions across river classifications based on MW-U and KS tests (Figure S9).

3.2 | The distance travelled by the wood

Transport distances based on all 1887 records of wood movement from the 11 rivers resulted in median and mean average values of 50 and 134 m (std = 266), a maximum transport distance of 5,661 m,

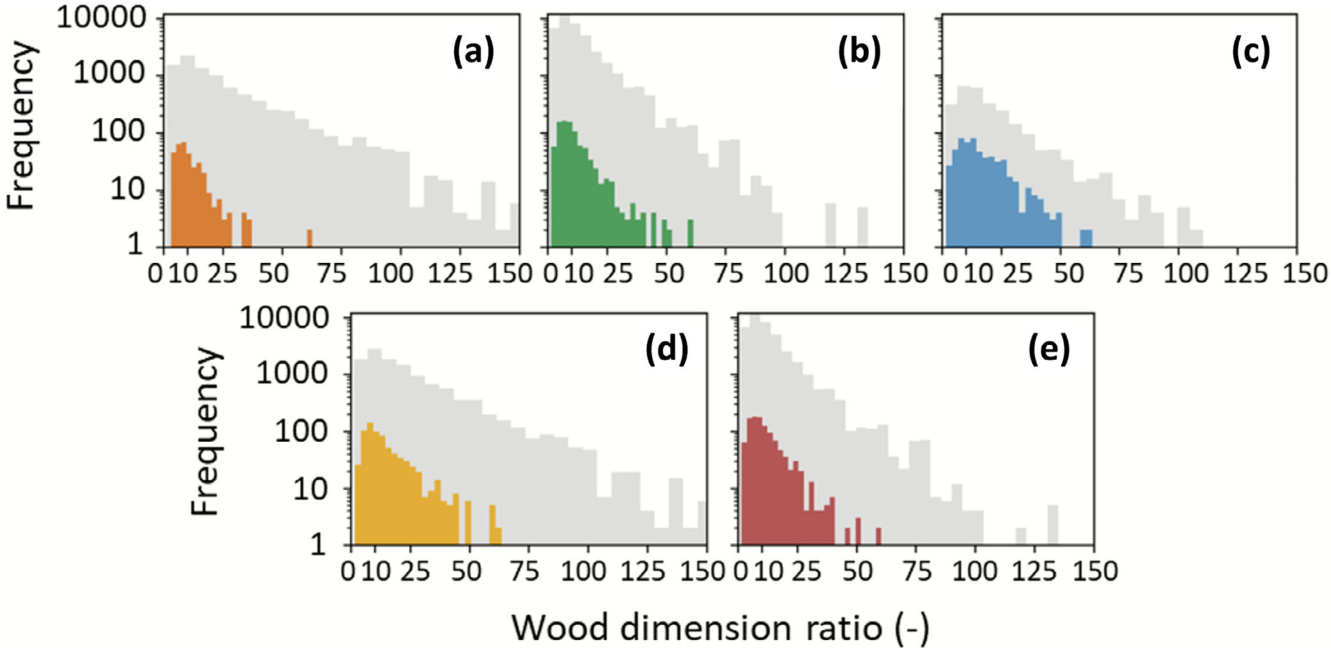

FIGURE 8 Histograms of wood dimension ratio values for wood in rivers classified by channel width: a) small, b) medium and c) relatively large, and channel gradient: d) moderate and e) high. Median, mean, standard deviation, skew values and Mann–Whitney U, and Kolmogorov–Smirnov results are shown in table S4. Additional statistics in Figure S9.

TABLE 3 Transport distance information for classified and individual river datasets. Percentiles (90,10) in table S5.

		Moved						Moved and not found					
Wood subset		Count	Median	Mean	Std	Max	Min	Count	Median	Mean	Std	Max	Min
All		1887	50.0	134.3	266.4	5661.0	2.3	4,092	329.7	706.2	876.9	5661.0	2.3
River Class	Small	399	34.0	71.6	290.7	5661.0	4.0	582	60.0	299.3	484.9	5661.0	4.0
	Medium	892	60.0	107.5	141.5	1516.0	5.0	1994	240.0	379.0	366.1	2172.5	5.0
	Relatively large	596	38.3	216.2	357.7	2763.0	2.3	1,516	1255.7	1292.9	1123.0	3475.1	2.3
Gradient Class	Low	63	44.0	190.3	713.4	5661.0	4.0	Does not include 'not Found' wood					
	Moderate	743	39.0	150.9	265.1	1521.6	3.0	1,473	581.7	966.9	999.3	2732.8	3.0
	High	1,081	54.0	119.6	214.1	2763.0	2.3	2,556	292.0	568.7	761.0	3475.1	2.3
Wood Length/ Channel Width	<0.5	1,575	50.0	141.7	248.8	2763.0	2.3	3,629	391.7	751.2	899.6	3475.1	2.3
	≥0.5	224	40.5	78.9	127.5	953.0	7.0	344	71.5	368.0	531.3	2705.3	7.0
	≥1.0	50	31.0	51.4	46.5	180.0	11.0	74	50.5	283.0	435.7	1786.0	11.0
Individual Rivers	Spöl	318	45.2	252.3	354.1	1521.6	3.0	843	1728.3	1455.7	1022.8	2732.8	3.0
	Avançon de Nant	253	26.2	184.4	373.6	2763.0	2.3	648	562.6	1128.0	1213.6	3475.1	2.3
	Pichún	15	41.0	69.3	74.1	251.0	7.0	21	32.3	60.2	65.1	251.0	7.0
	Vuelta de la Zorra	79	104.0	181.6	240.5	1448.0	5.0	107	171.0	319.3	362.5	1536.4	5.0
	Tres Arroyos	72	26.5	133.3	266.0	1516.0	5.0	239	494.2	541.4	478.0	2009.5	5.0
	El Toro	25	128.0	235.5	234.4	882.0	19.0	53	539.0	770.8	696.7	2172.5	10.2
	Mack Creek	716	60.0	92.3	91.2	520.0	10.0	1,595	230.0	345.6	313.8	1030.0	10.0
	North Fork, Caspar Creek	258	31.0	40.6	32.6	217.0	5.0	373	52.0	277.8	441.7	1822.3	5.0
	South Fork, Caspar Creek	88	47.5	80.3	88.3	637.0	7.0	150	144.5	395.2	450.1	1867.9	7.0
	Poplar Creek	25	89.0	80.3	58.5	225.0	9.0	This study does not include 'not Found' wood					

see Table 3 for sample statistics for all river datasets. Classes of average river width (small, medium, relatively large) and gradient (low, moderate, high) demonstrate similar median transport distances: 34, 60, 38, 44, 39 and 54 m, respectively, as seen in Figure S10 and Table 3. The corresponding average transport distances were 72, 108, 216, 190, 151 and 120 m, respectively. However, note that maximum

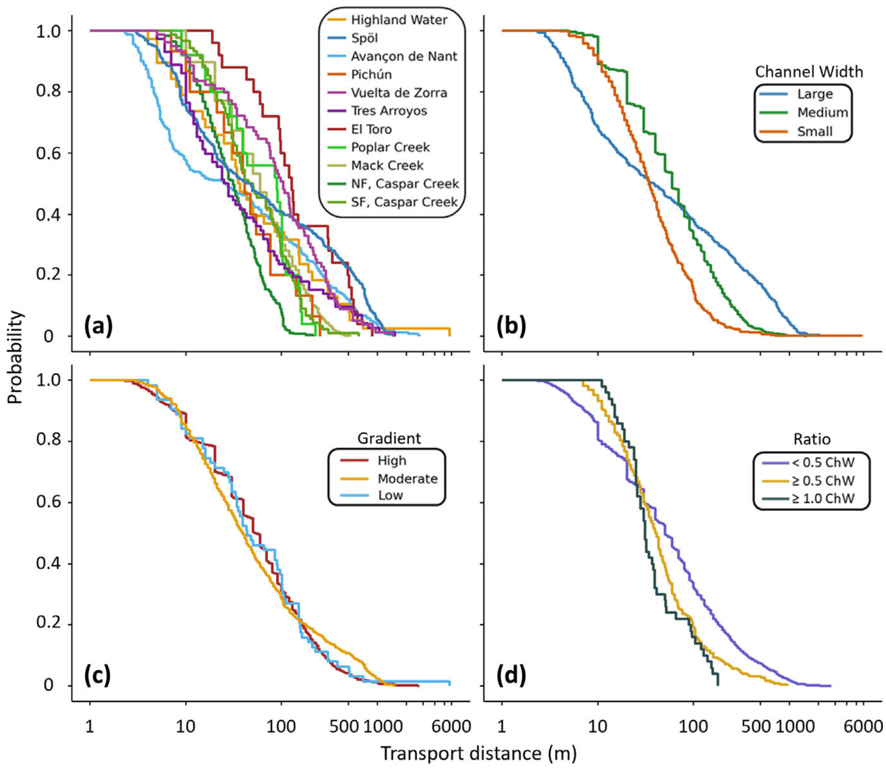

FIGURE 9 Probability functions of transport distances of moved wood. Panel a) is each of the 11 rivers' distributions shown individually, b) as classified sets according to mean average channel width, c) as classified sets according to mean average channel gradient and d) as Lw/Cw ratio classes. See Table 3 for statistical values, Figure S12 for statistical significance results, and Figure S11 for all data combined.

observed travel distances were constrained by survey lengths, which differed in the 11 rivers. Cumulative distribution functions (Figure 9) demonstrate that individual rivers and channel width classifications exhibit similar transport distances for approximately 60% of the data before unique differences occur among the datasets: 1) relatively large rivers observed a higher probability of movements from 100 to 1,100 m than medium and small rivers and 2) medium rivers had a greater probability to transport from 250 to 500 m than small rivers. For gradient classes, similar transport distances were observed for approximately 80% of observations before moderate gradient rivers observe a greater number of movements from 200 to 1,000 m. For ratio classes, wood pieces less than half the channel width have the shortest transport distances for 40% of observations but also the greatest transport distances for the remaining 60% while the inverse trends were observed for wood pieces greater than or equal to the channel width. The remaining ratio class, greater than or equal to half the channel width, exists between these two distributions.

Cumulative distribution functions and corresponding values based on all the datasets combined have also been included in Table 3 and the supporting information in Figure S11. Quantiles for transport distances have been added to the supporting information (Table S5).

3.3 | Frequency-magnitude relationships for wood volume and transport distance

Return periods of mobilized wood loads (m^3/ha) and maximum transport distances (m), empirically ranked using the Weibull method, are shown in Figure 10 for nine rivers and classified river datasets; see Table S6 for exact values. Relationships for wood load and distance seem relatively mixed without big differences between datasets, except for the maximum transport distances per channel width classification; large rivers observed longer transport distances than medium rivers and medium rivers longer distances than small rivers. Mack Creek and Caspar Creek North and South Forks had the highest return periods possible of computation due to their respective survey durations of 24 and 20 years.

GEV estimated the wood load (Figure 11) and maximum (90th percentile) transport distance (Figure 12) beyond a study's duration based on the shape of the data distribution. Exact values for GEV and Weibull methods are provided in Table 4 and S6, respectively. Generally, GEV predicts smaller wood loads than the Weibull method, and distance estimates are mixed. Predicted wood load movements never exceed the maximum instream wood storage load within the 100-year return period timeframe (Figure 11). El Toro has a mobilized load of 52.4 m^3/ha for a 100-year return period (Figure 11d). Studies with fewer than six observations were not plotted independently.

GEV indicated that small channels have greater amounts of wood load mobilization compared to relatively large channels and are surpassed by medium channels just after the 50-year return period; medium rivers have greater loads mobilized than small channels for longer return periods, see Figure 13 and Table 4. Moderate gradient channels predicted more wood load to mobilize than high gradient channels until return periods of 100 years. In terms of the ratio classes, similar wood loads are mobilized until after 2-year return periods from which the class being equal to or greater than half the channel width becomes the greatest. Wood travels shorter distances on smaller rivers than medium, which are shorter than for large rivers except for return periods less than 2 (Figure 13). Based on the 90th percentile of distance observations, moderate gradient rivers are estimated to have the greatest transport distances compared to low and high gradient rivers for return periods greater than 2 years (Table 4). For ratio classes, a clear trend emerged where the lower the ratio, the greater the transport distance.

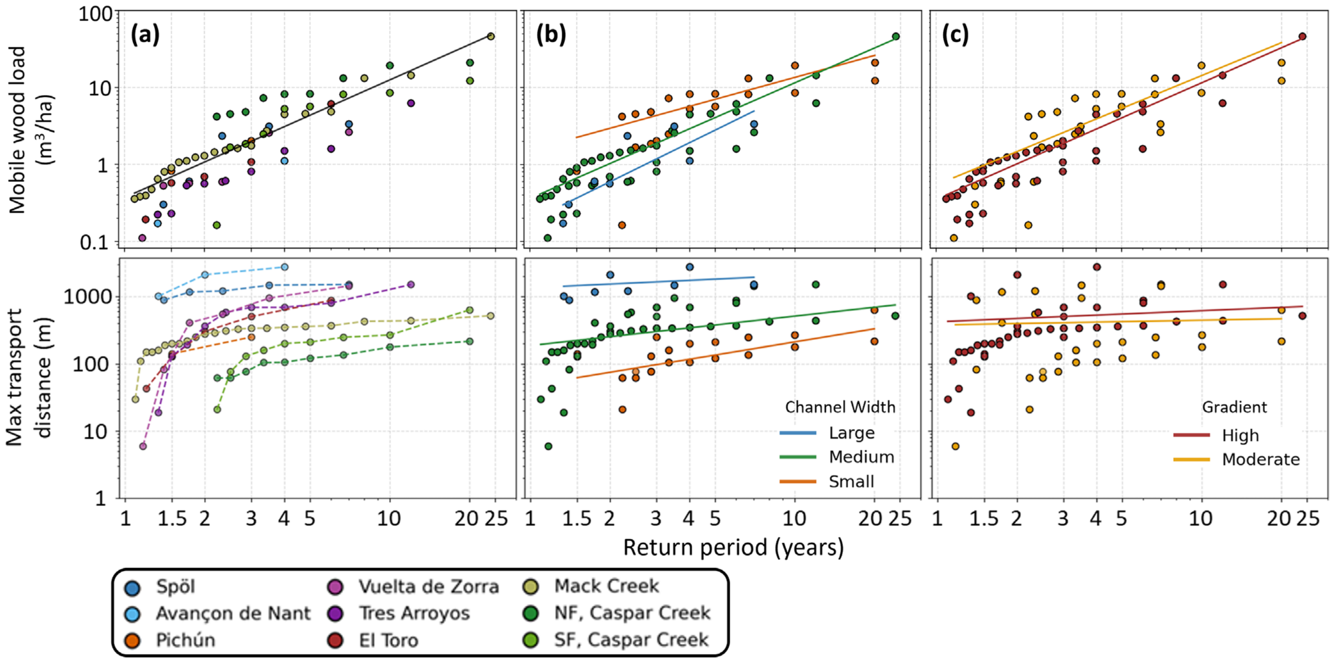

FIGURE 10 Empirically derived return periods, based on the Weibull method, for mobilized wood loads (top panels) and maximum transport distances (bottom panels) for a) individual rivers, b) channel width and c) channel gradient river classifications. The solid black line in the top panel of a is a log–log fit according to all the rivers ($log(load) = 1.53 * log(ReturnPeriod) - 0.43$; $r^2 = 0.84$). See table S6 for load and transport distances available per dataset per return periods.

4 | DISCUSSION

4.1 | Wood mobility and entrainment

As expected, our results showed that relatively large rivers (defined as channel width ≥ 15 m in this study) mobilize the highest proportion of wood compared to medium (5.5–15 m) and small (≤ 5.5 m) rivers, both in wood volume and number of wood pieces. Relatively large rivers not only move more of the available wood but also exhibit greater variability in terms of mobilized proportion of wood, likely because wood recruitment, supply and storage are relatively limited in these rivers, while transport capacity is greater (Bilby & Ward, 1989; Finch et al., 2025; Kramer & Wohl, 2017; Rickli et al., 2018; Ruiz-Villanueva et al., 2016b). In contrast, small and medium rivers tend to mobilize greater wood loads more frequently (as shown by the lower return periods for higher loads, compared to relatively larger rivers). This aligns with the empirical findings of the Weibull-ranked method, which recognized small rivers as moving greater wood loads than medium rivers at short return periods, but medium rivers ultimately surpassing small rivers at greater return periods; both small and medium having greater wood loads than large rivers. However, large rivers transport greater distances than both small and medium, and medium further than small. Gradient classes show moderate rivers to have greater loads and distances than other classes. Although our estimates do not explicitly consider the frequency of floods mobilizing the wood, the frequency at which wood is mobilized (its return interval) is controlled by how often floods occur: that is, by the hydrological return period (Gregory et al., 2024). Therefore, more frequent high flow events on smaller systems may result in greater magnitudes of movements at low recurrence intervals but trapping and obstructions reduce small systems' maximum potential at higher recurrence intervals despite greater wood abundance as discussed in Ruiz-Villanueva et al. (2016b). Medium channels seem to have sufficiently wide channels and wood abundance as they are predicted to mobilize the greatest loads at high recurrence intervals. It is still necessary to stress that what we defined as medium and large channels here relate to their relative size (similarly to what was proposed by Gurnell et al., 2002); and the estimated transported wood loads may be underestimated, as they refer only to the volume of wood that was observed to be moved. Still, the potential for greater wood volumes in transport is expected as the source of wood in storage increases. Our findings are consistent with studies that show a negative correlation between wood mobility and total wood load, where large channels show the greatest mobility and store less wood compared to smaller systems (Wohl & Scott, 2017). Including larger rivers with higher wood storage in future analyses would help clarify whether this pattern holds across a broader range of river types. Additionally, further research should address downstream wood mobility to capture regional variations across different channel types and gradients. This aspect is further discussed in the following section.

The ratio classes' mobile wood load is a unique set of circumstances as the classes are closely related to the length, thus the volume and ultimately the wood load. Smaller pieces move most frequently but constitute a smaller volume, generally, than other classes, which results in the load appearing to be less than other classes. The middle class, equal to or greater than half the channel width, has considerable volume and mobility as it has the greatest mobilized wood loads and is second in terms of transport distances. Less than 1% of wood pieces greater than the channel width were mobilized, and when they were mobilized, they were transported the shortest distances. Transport distances are clearly related to the size of the wood piece in relation to channel width, which exhibits a trend of having travelled shorter distances the greater the length of the wood piece relative to the channel width. A similar phenomenon occurs

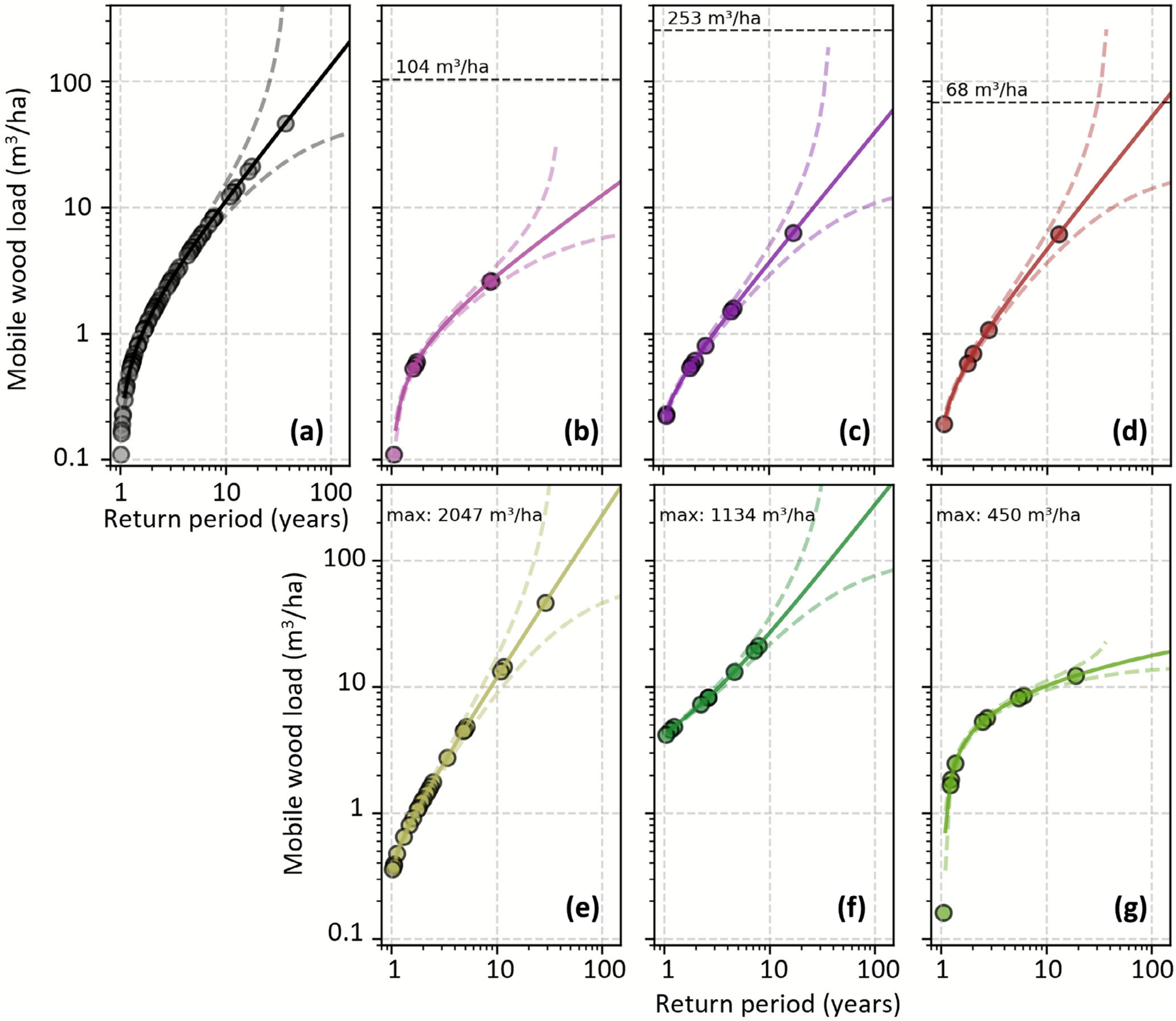

FIGURE 11 Return periods, in years, for mobile wood load (m^3/ha) for a) all the rivers combined and six of the eight rivers that comprise the combined dataset: b) Vuelta de Zorra, c) Tres Arroyos, d) El Toro, e) Mack Creek, f) north fork, Caspar Creek and g) south fork, Caspar Creek, based on general extreme value distribution. Avançon de Nant and Spöl are used in the combined dataset but had less than six observations for a strong statistical relationship to be constructed on their own. The dashed black line, when present, represents the maximum observed wood load during any survey at the study site. Wood loads are still included, in the top left-hand corner of the respective panel, if the observed load exceeded the y-axis limits. See Table 4 for exact values per return period.

when observing mobilized wood load relative to the river size classes that describe smaller channels as having greater loads mobilized than larger rivers; however, the greater spatial area of large rivers may result in greater volumes of mobilized wood than small rivers. Nonetheless, relatively large rivers have the greatest transport distances for the Weibull and GEV results, which agrees with the ratio class transport distances, as more pieces would likely have a smaller ratio of wood length to channel width in these wider rivers.

Wood supply and size also influence mobility patterns: smaller rivers generally move slightly larger wood pieces, in terms of their diameter but also length and volume according to our dataset, likely due to increased trapping potential from narrow channels, frequent obstructions and proximity to their recruitment sites resulting in stored wood also being generally larger, as suggested by previous studies (Gurnell et al., 2002; Wohl & Scott, 2017). In contrast, relatively large rivers tend to mobilize more elongated wood, as indicated by higher wood dimension ratio (DR) values. Interestingly, moderate-gradient rivers appear to mobilize and retain larger wood pieces (in terms of length) than high-gradient ones, which contradicts the expectation that steeper gradients facilitate wood fragmentation (Seo & Nakamura, 2009), resulting in smaller pieces being more prevalent on lower gradient systems. However, the local forest structure, specifically tree height (Wyżga et al., 2015), as well as the supply processes (i.e., recruitment mechanisms such as treefall versus landslides) are additional, relevant controls on instream wood size distributions than solely fragmentation (Steeb et al., 2017). Nonetheless, this discrepancy may reflect complex interactions among channel morphology, wood transport processes, supply and other controls in our dataset, which make gradient classes less representative of wood mobility through river systems than channel width classes, where wood size is demonstrated to decrease progressively as river size increases. In connection with wood piece length to channel width

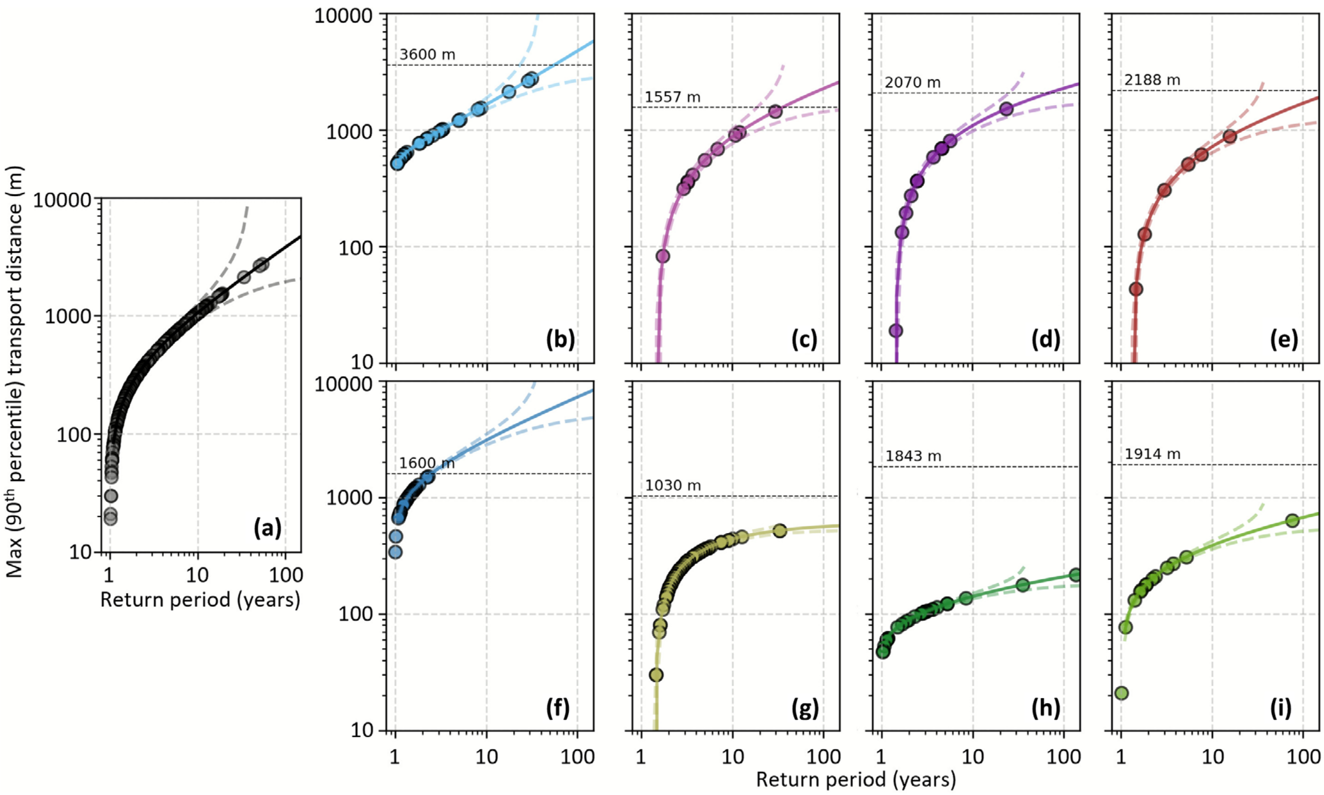

FIGURE 12 Return periods, in years, for maximum transport distances (based on the 90th percentile of observations per year), in meters, of mobilized wood for a) all of the rivers combined and eight rivers, b) Spöl, c) Vuelta de Zorra, d) Tres Arroyos, e) El Toro, f) Avançon de Nant h) Mack Creek, h) north fork, Caspar Creek, i) south fork, Caspar Creek, based on general extreme value distribution. Highland water, Poplar Creek and Pichún are included in the combined (n < 6). The dashed black line, in each panel, represents the length of the river survey. See Table 4 for exact values per return period.

relationships, in many of the studied rivers, transported wood tended to be shorter than the bankfull width (Lienkaemper & Swanson, 1987; Nakamura & Swanson, 1993). In fact, mobile wood pieces have similar lengths regardless of width class according to our dataset (except for small rivers, which moved longer pieces), so we cannot justify longer pieces being necessarily more mobile, in terms of entrainment probability, on larger rivers, which may be in part due to their incorporation as key pieces (Gurnell et al., 2002) or supply factors such as fragmentation during transport to larger systems (Seo & Nakamura, 2009) and local canopy height (Wyżga et al., 2015). While diameter seemed to play a more important role in the studied rivers, with small rivers moving thicker pieces than relatively large rivers, where water depth may be shallower, and multiple channels may be expected (as discussed by Ruiz-Villanueva et al., 2016d).

As observed in other studies, jam association influences wood mobility (Benda & Sias, 2003; Jochner et al., 2015), with varying effects across different river systems. For example, jams seemed to increase wood movement probability in El Toro and the forks of Caspar Creek, while reducing mobility in the Spöl and Avançon de Nant. These contrasting patterns suggest that jam formation and stability play a critical role in wood entrainment and deposition (e.g., Jochner et al., 2015), which can vary significantly depending on local geomorphic and hydrologic conditions. Our dataset supports Benda & Sias (2003) recognition of jam size increasing downstream as medium and relatively large rivers have proportionally more wood in jams than small rivers, but gradient classes, again, do not follow the expected trend, likely due to complex interactions mentioned in the previous paragraph.

Despite mobile wood most commonly showing signs of decay, fresh and intermediately decayed wood was proportionally more mobile in all rivers (Aarnink, 2025; Finch et al., 2025; Gregory et al., 2024; Iroumé et al., 2018), indicating that freshly recruited wood tends to move more easily than decayed wood, despite decayed wood being potentially more buoyant (Ruiz-Villanueva et al., 2016a). Wood density commonly decreases during prolonged residence time in rivers (Thévenet, Citterio, & Piégay, 1998), and decay can represent residence time, so decayed wood can be inferred to have been in the channel longer than fresh and intermediate wood pieces (Gurnell et al., 2002). Therefore, decayed wood may have been moved and accumulated in jams, or buried, preventing its movement. In addition, Finch et al. (2025) demonstrated the transport distances for decayed wood were often shorter than fresh and intermediate wood, despite often being shorter in length, which could extend their residence time and be the result of lighter densities influencing deposition probability. Other initial conditions, like burial and orientation, also determine wood mobility, although they appear to be river dependent. High sediment transport in Swiss, gravel rivers (Rickli et al., 2018; Ruiz-Villanueva et al., 2016b) may both enhance or undermine effects of anchoring associated with burial (Wohl et al., 2023) and affect mobility. Parallel pieces mobilize more often than oblique pieces like fresh and intermediately decayed pieces when compared to decayed wood. Perpendicular pieces exceeded movement probabilities than parallel

TABLE 4 Return periods (RP) of mobilized wood loads and max transport distances according to general extreme value distribution. Blank cells represent negative values which were not included. Grey cells represent insufficient data.

			River class			Gradient class			Wood length/ channel width			Individual Rivers										
	RP	All	Small	Med.	Relatively large	Low	Mod.	High	<0.5	≥0.5	≥1.0	Spöl	Nant	VdZ	Tres Arr.	El Toro	Mack Creek	NF Caspar	SF Caspar	High. Wat.	Pop. Creek	Pich.
Mobile wood load (m^3/ha)	1.1	0.3	1.2	0.3	0.1		0.5	0.3	0.2	0.1	0.2			0.2	0.2	0.2	0.4	4.4	0.7			
	1.5	0.8	3.7	0.6	0.4		1.9	0.6	0.5	0.5	0.6			0.5	0.4	0.4	0.8	5.5	3.0			
	2	1.5	5.4	1.0	0.7		3.2	1.0	0.8	0.9	0.9			0.7	0.6	0.7	1.3	6.7	4.4			
	5	5.0	10.3	3.0	2.0		7.9	2.9	2.4	3.7	2.7			1.7	1.7	2.1	4.6	13.9	7.8			
	10	11.1	14.4	5.9	3.6		13.1	6.0	4.7	9.3	5.3			2.8	3.6	4.6	11.7	26.6	10.1			
	25	29.8	20.5	13.8	7.1		23.5	14.5	10.3	28.6	12.3			5.2	9.2	12.1	37.8	65.1	13.1			
	50	63.1	26.1	26.1	11.9		35.9	28.3	18.6	67.3	22.9			8.1	18.9	25.2	93.0	133.7	15.3			
	100	132.6	32.6	49.2	19.6		54.1	54.9	33.4	157	42.9			12.5	38.7	52.4	227.8	277.0	17.6			
Max transport distance (m); 90th perc.	1.1	84	52	103		151		121	23	28	17	695	556					56	69			
	1.5	204	88	206	124	272	134	237	158	64	33	1,086	692	3	37	47	42	77	141			
	2	307	120	276	345	376	295	326	274	96	47	1,386	809	147	240	163	165	90	188			
	5	666	228	451	859	738	858	596	678	206	95	2,280	1,217	540	729	469	358	120	302			
	10	1,054	346	583	1,214	1,129	1,466	845	1,114	325	147	3,093	1,658	864	1,080	712	439	141	386			
	25	1785	567	759	1,653	1865	2,610	1,249	1937	550	246	4,397	2,488	1,338	1,533	1,056	505	168	494			
	50	2,624	821	906	1991	2,710	3,923	1,652	2,880	807	358	5,680	3,440	1766	1895	1,356	538	188	582			
	100	3,811	1,180	1,062	2,330	3,906	5,781	2,156	4,214	1,171	518	7,270	4,788	2,258	1,169	1,690	561	208	673			

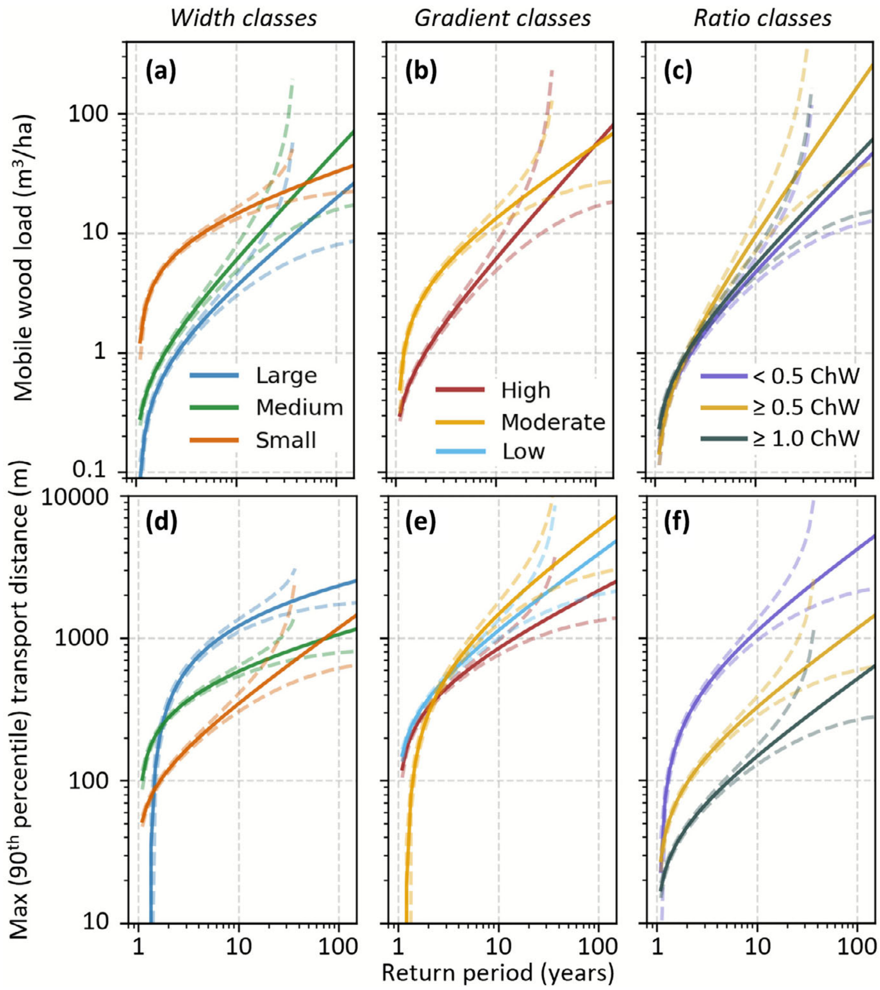

FIGURE 13 Return periods for mobile wood loads for a) channel width class, b) gradient class and c) ratio class in top panels. Return periods for maximum transport distance (90th percentile) for d) width class, e) gradient class and f) ratio class. The low channel gradient class did not have sufficient data for computing mobile wood load. See Table 4 for exact values per return period.

pieces for only two high gradient rivers (Avançon de Nant – relatively large-sized, El Toro – medium-sized), where higher stream power (Wohl, 2017), larger drag force (Gippel, 1995) and high turbulence result in rapid flow direction changes (Montgomery & Buffington, 1997) which may explain higher mobility for perpendicular pieces in high gradient rivers. While we would like to be able to associate these phenomena with supply, our other initial conditions and elements such as bracing (Kramer & Wohl, 2017), more factors such as channel features and characteristics are also influencing these mobility patterns which stresses the need for further investigation in this area of study.

4.2 | Data limitations and future research

The compiled datasets were gathered from a diverse range of rivers, from headwaters, mountainous streams to relatively lowland-valley plains, on several continents, where observations of naturally occurring wood mobility over time were available. While this database represents a unique source of information and allows us to explore similarities and differences in wood mobility among these rivers, several limitations must be discussed. First, caution is warranted when interpreting variability between spatially proximate rivers, such as the NF and SF Forks of Caspar Creek, as historical logging practices and other factors may have local influences on wood dynamics.

Additionally, floods observed on the rivers were of a limited magnitude, and in the case of the Spöl, experimental floods were designed to mimic floods of 2-year return periods (Finch et al., 2025). No major events such as a forest fire, mass wasting or extreme floods occurred at any study site during their respective study period. Mack Creek did experience a flood event with a 41-year recurrence interval in 1996 and recognized less wood movement and a narrower range in the lengths of wood pieces mobilized as the flood recurrence interval decreased (Gregory et al., 2024). Other studies also recognized an increase in wood mobilization following larger flood events (Aarnink, 2025; Dixon & Sear, 2014; Finch et al., 2025; Iroumé et al., 2018; Lininger & Hilton, 2022). Differences in wood storage affect wood mobility for floods of similar magnitude as well as the structure of the hydrograph, particularly the ratio of the rising to falling limb duration (Finch et al., 2025), which aligns with evidence outlined by Kramer & Wohl (2017) and Ruiz-Villanueva et al. (2016c) emphasizing the role of the rising limb of the flood. In Poplar Creek, all wood pieces had been lost or had not moved by the second survey event, so interpretations in relation to the hydrograph are challenging and extending the survey's length of 600 m would likely improve results (Daniels, 2006). In comparison to extreme scenarios, investigative findings on Swiss rivers reported by Rickli et al. (2018) and Steeb et al. (2017) following a severe flood demonstrated that more than half of the wood was fresh, in-channel wood transport was limited and lateral recruitment was a pervasive element driving wood abundance during such a scenario. Post-fire recruitment of wood in the North Fork Boise River was also recognized as having delivered extremely large volumes of wood to the channel (Benda et al., 2003). Therefore, our findings represent wood mobility and entrainment under 'non-extreme', relatively frequent flood scenarios. Therefore, larger wood volumes and longer transport distances can be expected during extreme events, even larger than our estimates, as was observed for example in some recent large floods, like the 2021 flood in central Europe, which greatly exceeded the 100-year return period discharge (Ludwig et al., 2023).

Furthermore, the duration of river monitoring influences the observed variability (Leopold, 1994), meaning that the behaviours described here reflect a temporal snapshot and may change over time. Moreover, estimating recurrence intervals and probabilities of exceedance is non-stationarity due to hydrological and land use changes, aspects that have not been considered here. Non-stationarity in flood frequency is widely recognized in hydrology, which has begun to apply atmospheric and precipitation variables to improve predictions (Chen, Papadikis, & Jun, 2021; Galloway, 2011; López & Francés, 2013). In-channel wood flux, as mentioned before, is intrinsically linked to hydrology (Gregory et al., 2024), but will require additional variables such as forest coverage, landscape stability, as well as more validation data to be properly forecasted.

Data preprocessing was required to homogenize the information reported by each study. For example, decay categories were simplified in some cases. Visual decay has been applied using a classification with 3 to 7 classes (Ruiz-Villanueva et al., 2016b); however, previous studies have shown that having a classification of more than three categories may be challenging (MacVicar et al., 2009), therefore we decided to keep only three classes. Still, the grouping of some classes from a more extended classification could result in slightly different results.

Previous studies have recognized wood piece position in respect to the channel and water level as a strong predictor of movement, particularly for those submerged at least 70% (Bosio et al., 2021) and for those in the active channel (Lininger & Hilton, 2022). Iroumé et al. (2018) noticed wood at the bankfull line was transported longer distances than wood in other geomorphic positions. Future work may homogenize available data (Gregory et al., 2024; Iroumé et al., 2018; Lininger & Hilton, 2022) but more studies which record position would broaden our understanding of position's role in wood mobility. Limited data availability dissuaded any position analysis to be performed within this work.

Including large and very large and great rivers such as the Tagliamento, Ain, Rhône and Sacramento (Table 1) would enhance the dataset, as these substantial systems may represent a unique class not yet captured in this study (Kramer & Wohl, 2017). Expanding the dataset to include downstream systems (e.g., Kramer et al., 2017) from those already observed would also improve our understanding, allowing analysis of wood mobility and entrainment across mountain, piedmont and coastal plain planforms within each region.

A major challenge in understanding wood mobility is the occurrence of 'notFound' wood (i.e., pieces that cannot be located after tagging). In relatively large rivers, this may result from burial or long-distance transport beyond the survey area, as suggested for the Spöl (Finch et al., 2025) and Avançon de Nant (Aarnink, 2025), which are characterized by high sediment transport (Rickli et al., 2018; Ruiz-Villanueva et al., 2016b). However, breakage, obscuration and loss of tags are also possible processes which would lead to the disappearance of tags. Nonetheless, this phenomenon underscores the importance of considering tag loss and long-range transport when interpreting wood mobility data. Assuming notFound wood has travelled at least the distance from its last known location to the end of the surveyed area is an explorative approach that warrants caution in general and particularly for studies whose known transport distances are commonly far less than the censored distance to the outlet which is given to them. The number of wood movements increases to 4,092 with median and average transport distances of 330 and 706 (std = 877; Figure S10 for boxplots, Table 3 for values and Figure 14 for cumulative distribution functions). The median and mean values are substantially greater than for the Moved distribution and are entirely conflated by a major assumption that all notFound pieces exited the system, so we stress this analysis is an explorative finding and a strong assumption.

Efforts to avoid loss of wood pieces included the use of multiple tags (Berg et al., 1998; Haga et al., 2002; Iroumé et al., 2010, 2018; Dixon & Sear, 2014; Gregory et al., 2024) or installations of RFIDs (Aarnink, 2025; Jochner et al., 2015; MacVicar et al., 2009; Ravazzolo et al., 2015; Schenk et al., 2014; Wyżga et al., 2017), but a variety of processes persist which makes notFound wood nearly impossible to eliminate. Therefore, additional studies are required to further explore the analysis of such subsets.

5 | CONCLUSIONS

Our findings indicate that the relatively larger rivers included in this study (here defined as channel width ≥ 15 m) mobilize the highest proportion of wood but retain comparatively low volumes in storage. Both large and low-gradient rivers exhibit the longest observed transport distances; however, transport distances exceeding 1 km were rare. Wood pieces less than half the channel width are mobilized more often and travel further than other classes but constitute lesser volumes.

Mobilized wood piece length does not appear to follow a systematic trend of becoming longer in channels wider than 5.5 m, while wood diameter seems to play a greater role in mobility particularly across different channel width classes. Channel gradient, for the studied streams, shows less influence on wood dynamics compared to channel width. However, wood supply, availability, species and additional channel morphology characteristics are contingent factors controlling our observations.

Predicted wood mobilization loads remain below observed storage levels for all rivers, even for very large return periods. This suggests that typical flood events are unlikely to mobilize large quantities of stored instream wood. Consequently, river and forest management efforts targeting wood-related hazards should prioritize mass wasting events, or other episodic recruitment processes, which may result in greater wood volumes supplied to the river systems than removing the stored wood in rivers.

To advance understanding of instream wood processes and inform strategies in river restoration, forest management and flood mitigation, future studies should expand upon the current dataset.

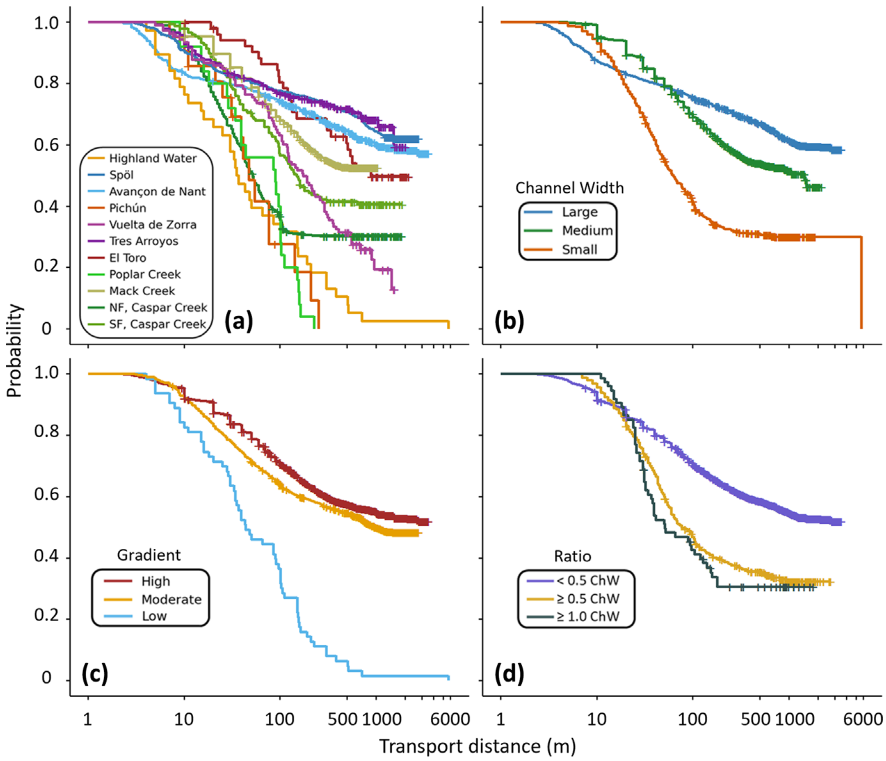

FIGURE 14 Probability functions of transport distances of moved and notFound wood combined. NotFound values were included as censored data. Panel a) is each of the 11 rivers' distributions shown individually, b) as classified sets according to mean average channel width, c) as classified sets according to mean average channel gradient and d) based on Lw/Cw ratio classes. See Table 3 for statistical values, Figure S13 for statistical significance results, and Figure S11 for all data combined.

AUTHOR CONTRIBUTIONS

Bryce D. Finch: Conceptualization; writing—original draft; methodology; investigation; visualization; formal analysis; software; writing—review and editing. **Johan L. Aarnink**: Investigation. **Andrés Iroumé**: Investigation. **Katherine B. Lininger**: Investigation; writing—review and editing. **Susan Hilton**: Investigation; writing—review and editing. **Stanley Gregory**: Investigation; writing—review and editing. **Virginia Ruiz-Villanueva**: Conceptualization; funding acquisition; writing—original draft; methodology; investigation; resources; supervision; writing—review and editing.

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DATA AVAILABILITY STATEMENT

Most of the data used in this analysis has been made publicly available and their respective links can be found within each of the original publications (also listed below). The Chilean dataset would need to be requested from the original author.

Spöl River, Switzerland dataset: at https://doi.org/10.5281/zenodo.13827962 (Wood Survey Database; Finch & Ruiz-Villanueva, 2024).

Mack Creek, Oregon, USA dataset: in H.J. Andrews Experimental Forest at https://andlter.forestry.oregonstate.edu/data/catalog/datacatalog.aspx.

North Fork and South Fork Caspar Creek, California, USA dataset: CU Boulder Data Repository (https://doi.org/10.25810/1c5d-4k36; Hilton et al., 2022). Additionally, at Caspar Creek Experimental Watersheds Phase 2 (1985–2017) data archive (3rd Edition), at https://doi.org/10.2737/RDS-2020-0018-3.

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SUPPORTING INFORMATION

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