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Key Points:
- Wood is found to be highly mobile in lowland forest streams
- Wood is shown to cycle through logjams as it moves down the channel network
- Length of wood relative to channel width is a partial control on mobility

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The influence of geomorphology on large wood dynamics in a low gradient headwater stream

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Abstract Understanding large wood dynamics is critical for a range of disciplines including flood risk management, ecology and geomorphology. Despite the importance of wood in rivers, our understanding of the mobility of large wood remains limited. In this study individual pieces of large wood were tagged and surveyed over a 32 month period within a third and fourth order lowland forest river. Individual pieces of wood were found to be highly mobile, with 75% of pieces moving during the survey period, and a maximum transport distance of 5.6 km. Multivariate analyses of data from this study and two other published studies identified dimensionless wood length as the important factor in explaining likelihood of movement. A length threshold of 2.5 channel widths is identified for near functional immobility, with few pieces above this size moving. In addition, for this study, wood type, branching complexity, location and dimensionless wood diameter were found to be important in determining mobility only for sinuous reaches with readily inundated floodplains. Where logjams persist over multiple years they were shown to be reworked, with component pieces being transported away and replaced by newly trapped pieces. The findings of this study have implications for river management and restoration. The high mobility observed in this study demonstrates that only very large pieces of wood of length greater than 2.5 channel widths should be considered functionally immobile. For pieces of wood of length less than the channel width the possibility of high rates of mobility and long transport distances should be anticipated.

1. Introduction

The geomorphological and ecological effects of large wood within forested streams have been widely documented within the literature; conversely, the mobility of large wood within small river channels has hitherto received less attention [*Wohl et al*., 2010; *MacVicar and Piégay*, 2012; *Schenk et al*., 2014]. Large wood within forested streams is recognized as a crucial component of vibrant and healthy aquatic ecosystems [*Reich et al*., 2003; *Shields et al*., 2006; *Sear et al*., 2010].

Both individual pieces of wood and logjams act to: trap and store sediment [*Lisle*, 1995; *Brummer et al*., 2006] and organic matter [*Collins et al*., 2002; *Bilby*, 2003; *Daniels*, 2006], dissipate flood wave energy [*Gregory et al*., 1985; *Kitts*, 2011; *Sholtes and Doyle*, 2011; *Thomas and Nisbet*, 2012], and create and maintain greater geomorphic diversity [*Lisle*, 1986; *Abbe and Montgomery*, 1996; *Gurnell et al*., 2000; *Sear et al*., 2010] which in turn provides habitat and refuges for a variety of aquatic and terrestrial organisms [*Collins et al*., 2012]. Wood acts as a autogenic ecosystem engineer [*Jones et al*., 1994]; increasing the frequency and depth of pools in the presence of logjams which are important refuges for salmonids [*Lisle*, 1995; *Montgomery et al*., 1995; *Abbe and Montgomery*, 1996; *Collins et al*., 2002], creating variations in hydrodynamics that leads to deposition of gravels suitable for salmonid spawning [*Wheaton et al*., 2004], and provide habitat and a food source for a variety of macroinvertebrates [*Harmon et al*., 1986; *Benke and Wallace*, 2003].

The creation of geomorphological diversity and new habitats in association with large wood are a result of wood mediated variations in local hydraulics which result in altered patterns of sediment erosion and deposition. For large wood to influence local erosion and deposition patterns it needs to be retained in a stable position long enough for the hydraulic changes it imposes to alter local geomorphology [*Millington and Sear*, 2007]. Therefore, the stability of large wood in a system, and thus a lack of mobility is a prerequisite for many ecological benefits [*Millington and Sear*, 2007; *Sear et al*., 2010]. Conversely mobile large wood can cause problems to infrastructure if trapped by bridge piers, causing navigation difficulties [*Gurnell et al*., 2002; *Piegay*, 2003], scour [*Diehl*, 1997] and flooding [*Jeffries et al*., 2003].

Historically, large wood has been removed from many rivers [*Brooks et al*., 2004] but more recently river restoration programmes have used artificial emplacement of large wood in an attempt to improve the ecological conditions in impaired aquatic ecosystems [e.g., *Collins et al*., 2002; *Reich et al*., 2003; *Brooks et al*., 2004; *Shields et al*., 2006; *Vaughan et al*., 2009]. The potential for using the flood attenuation effects of large wood logjams [*Gregory et al*., 1985; *Sholtes and Doyle*, 2011; *Thomas and Nisbet*, 2012] as part of catchment scale flood risk management is also receiving increasing attention [*Defra*, 2005, 2007; *Johnson and Priest*, 2008]. Crucial to the success of engineered logjams in both providing new habitats and attenuating flood waves is the ability to forecast the stability of wood structures, and to understand the factors influencing and controlling large wood mobility.

The mobility of large wood has been linked to the concept of "reach retention"; the ability of a river to trap and retain organic and inorganic matter, including mobile wood, in the channel [*Millington and Sear*, 2007]. Reach retention and trapping of large wood is dependent on the geomorphological complexity of the channel [*Braudrick et al*., 1997; *Sheldon and Thoms*, 2006; *Millington and Sear*, 2007] as well as the frequency of in-channel obstructions such as boulders [*Bocchiola et al*., 2006a] and logjams [*Bilby and Likens*, 1980; *Ehrman and Lamberti*, 1992; *Bocchiola et al*., 2006a; *Daniels*, 2006; *Millington and Sear*, 2007]. Thus in any channel, the mobility of large wood should be inversely proportional to both the complexity of the channel pattern and the wood loading to the channel [*Wohl and Cadol*, 2011].

Previous studies of wood piece mobility have found wood length to be important, with ratios of large wood length to channel width of 1:1 found to define a threshold of mobility below which wood is highly mobile [*Lienkaemper and Swanson*, 1987; *Braudrick et al*., 1997; *Gurnell et al*., 2002]. A threshold of wood length to channel width of 1:1 has a physical basis in defining the upper size limit for freely mobile wood within a confined channel, as below this length wood can easily rotate within the channel in response to drag and lift forces to a preferential position for transport [*Braudrick et al*., 1997]. However, the large wood length to channel width threshold of 1:1 does not have a physical basis as a minimum threshold for functional immobility in unconfined channels connected to their floodplain. In large flood events in unconfined channels, mobile wood can float over the floodplain by-passing channel geomorphological constrictions. Under these conditions the entrainment of an individual piece of large wood is governed by the balance between buoyant and drag forces acting to mobilize it, and its resistance to these forces [*Shields and Alonso*, 2012]. The resistance of a piece of wood to being mobilized is dependant not only on piece length, but also diameter [*Haga et al*., 2002] and density [*Gurnell et al*., 2002]. Large wood of length approximately equal to, or greater than, channel width would be likely to become trapped or wedged in channel constrictions and against upright trees [*Bocchiola et al*., 2006a], but in the absence of trapping only wood with a sufficient submerged weight to resist the largest drag and lift forces produced by the river will be immobile under all river discharges.

Conceptually the wood delivered to a given stream can be divided into three broad size classes: wood sufficiently large to be functionally immobile due to its weight, intermediate sized wood for which mobility is dependent on local geomorphology and hydrology and small wood which is highly mobile [*Millington and Sear*, 2007].

Despite the importance of understanding large wood mobility in natural environments, direct field measurements of wood transport remain relatively rare [*Bertoldi et al*., 2013; *Schenk et al*., 2014], specifically there are relatively few short-term published data sets [*Wohl et al*., 2010], and limited research into wood dynamics [*Daniels*, 2006]. Therefore wood remains an incompletely quantified component of river systems [*MacVicar and Piégay*, 2012]. Although flume studies using wooden dowels to simulate large wood pieces are valuable in understanding some of the mechanisms of transport [e.g., *Braudrick et al*., 1997; *Bocchiola et al*., 2006b] field studies in varied settings are needed to better understand reach scale wood transport and retention in natural rivers [*Latterell and Naiman*, 2007; *Collins et al*., 2012]. *Wohl et al*. [2010] conclude "datasets .. of wood dynamics through time are extremely valuable in understanding temporal variations in wood recruitment, retention and function, and there is a great need for more of them."

This study aims to address the research gap in knowledge of large wood mobility in small, low gradient river channels over multiple years. We define large wood as a piece both at least 1 m in length, and at least 10 cm in diameter, we define a small river channel as that for which the channel width is less than the

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median wood piece length delivered to it [*Gurnell et al*., 2002]. The overall aim is to understand which pieces of wood in a river channel are more mobile and, once mobilized, what their transport distance is before being redeposited.

In order to address this key objective, data were collected on the position of individual tagged pieces of wood, as well as the physical characteristics and geomorphological setting of each piece. Specific objectives are; i) to examine the effects of geomorphology in governing large wood mobility and in trapping mobile wood in the channel, ii) to identify through a multivariate analysis those factors, including size, which contribute to the mobility of pieces of large wood, iii) to estimate transport lengths for mobilized large wood.

2. Methods

2.1. Study Site

This research was conducted on the Highland Water, a tributary of the Lymington River in the New Forest National Park, Hampshire, UK (Figure 1). The underlying geology of the catchment is Eocene Barton clay resulting in a "flashy" hydrological regime; despite its flashy nature the streams are low energy and meandering [*Piégay and Gurnell*, 1997; *Gurnell and Sweet*, 1998]. High flows are predominantly observed during winter months (October–February). Overlaying the Barton clays are a mix of alluvial deposits mainly Tertiary gravels, silt and gravel [*Gurnell and Sweet*, 1998], overlain by humus rich forest soils [*Sear et al*., 2010]. The relatively thin soil leads to shallow horizontal rooting of floodplain trees, that makes them susceptible to windthrow [*Brown*, 1997], which is the dominant method beech mortality and of wood delivery to river channels in the New Forest [*Tubbs*, 2001; *Spencer*, 2002].

Across the catchment the woodland is a mix of *Fagus sylvatica* (beech) with *Quercus petraea* (sessile oak), *Fraxinus Excelsior* (ash), *Alnus glutinosa* (alder), *Betula pendula* (birch) and some *Ilex aquifolium* (holly) [*Jeffries et al*., 2003], although in floodplain plantations the vast majority of trees are beech.

The New Forest is a patchwork of stream types due to a legacy of spatially distributed channel engineering to improve drainage [*Tubbs*, 2001; *Sear et al*., 2006] and subsequent river rehabilitation programmes [*Millington and Sear*, 2007; *Dixon*, 2014]. In addition the New Forest remains one of the few areas in Europe with sections of relatively unmanaged lowland forested river channels [*Gurnell and Sweet*, 1998] with connected riparian wet woodland [*Sear et al*., 2010]. The New Forest thus has a diversity of stream types that makes the catchment suitable for a study into wood mobility relative to channel geomorphology. Channels in the Highland Water catchment are gravel-bed and have bed slopes ranging from 0.011 in the headwaters to 0.002 in lowland reaches approaching the confluence with the Blackwater. The wide range of managed and unmanaged lowland river types represented in the study area means the results are globally relevant to gravel-bed rivers of similar size, gradient and forest composition.

2.2. Study Reaches

Five study reaches of the Highland Water, each of 150 meters stream length, were chosen as study sites for large wood mobility (Table 1 and Figure 1). These five reaches are representative of the broad range of geomorphological planform types found within the Highland Water, this allows comparisons to be made between two natural sinuous reaches, a reach in which the sinuous planform has been restored, and two artificially straightened and channelized reaches.

In order to analyze how geomorphological complexity affects the likelihood of large wood movement the five reaches were separated into two classes: channelized reaches, comprising reaches 3 and 5, and seminatural and restored reaches comprising reaches 1, 2 and 4 (Table 1).

Discharge in the river is recorded at two gauging stations (Figure 1), a pressure transducer recording every 5 min at Millyford Bridge, and a UK Environment Agency gauging station at Brockenhurst.

Density of riparian trees for each reach was estimated from aerial imagery. The area of the floodplain for each reach was defined as the break of slope in a digital elevation model, approximating the valley floor. Within this area tree stems were identified as the centre point of each tree crown in the aerial imagery. Such an approximation is justified in the study environment as the beech dominated forests have very sparse under croft vegetation and are predominantly single layer canopies.

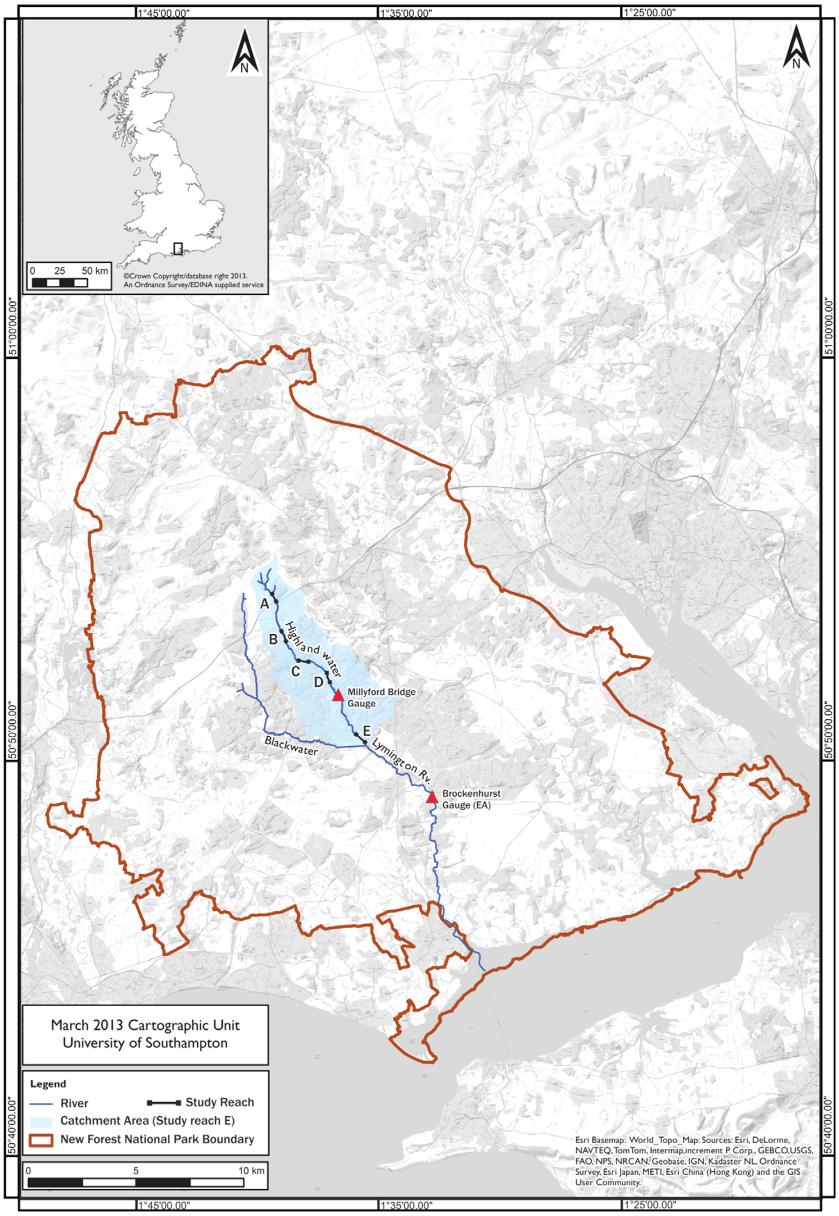

Figure 1. location map showing study reaches, catchment area draining to furthest downstream study reach and location of hydrometric gauges

2.3. Large Wood Tagging

Within each of the study reaches in August 2010, each piece of large wood was tagged using numbered, aluminium tree tags and secured with galvanized tree tag nails (n=162). A piece of large wood was defined as having both diameter $\geq$10 cm and length $\geq$1 m, to be included in the survey the wood had to be either in the channel, in the riparian zone, or on the floodplain. One tag was secured as close as practicable to each end of the piece of wood to aid visual identification and recovery in the event of movement and partial burial. Disturbance of large wood pieces was kept to a minimum whilst tagging. Size of tagged wood ranged from 10 to 58 cm diameter and 1 to 15 m length.

Tags were surveyed into a coordinate grid, established using an electronic total station and a network of 1 m wooden stakes driven into the floodplain surface to act as reference control points for future surveys. The absolute position of the stakes was established using handheld Global Positioning System (GPS). Under a forest canopy a total station gives a horizontal point accuracy with an error of <0.01 m and an

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Table 1. Summary Reach Characteristics

Reach	Average Bankfull Width (m)	Average Bankfull Depth (m)	Sinuosity	Strahler Reach Order	Slope (m/m)	Grain Size (D_{50}) (mm)	Bankside Tree Frequency (trees/100 m)[a]	Riparian Tree Density (trees/ha)	Site Description
A	3.00 ± 0.36	0.80 ± 0.26	1.75	Second	0.011	38	4.4	45.0	Seminatural meandering planform with evidence of bed downcutting
B	3.50 ± 0.46	1.15 ± 0.23	1.62	Third	0.005	23	5.4	18.9	Restored reach, connected to its floodplain and experiencing frequent over bank inundation
C	4.75 ± 0.00	1.03 ± 0.12	1.02	Third	0.006	37	7.8	39.3	Artificially straightened, deepened and widen reach, disconnected from its floodplain
D	3.37 ± 0.55	1.28 ± 0.33	1.54	Third	0.005	21	6.1	41.2	Seminatural reach with an extensive network of ephemeral floodplain channels
E	4.37 ± 0.12	1.77 ± 0.12	1.01	Fourth	0.002	45	4.1	26.2	Artificially straightened, deepened and widen reach, disconnected from its floodplain

[a]Bankside trees are defined as stems within one channel width of the river channel centerline.

inter-survey error of <0.1 m, compared to a mean error of ≤2 m using GPS [*Hasegawa and Yoshimura*, 2003]. In addition, a palm top Personal Data Assistant (PDA) was used to record descriptive variables of each piece of wood (Table 2).

The duration of the study was 32 months; following the initial survey the position of each tag was surveyed into the coordinate grid again in October 2010, May 2011, November 2011, and May 2013, with the exception of reach A which was not surveyed in November 2011 and reach E which was surveyed in January 2012, and not in May 2013. Prior to each survey any newly delivered, untagged pieces of large wood within each reach were tagged, and information about each new piece recorded (Table 2). If all pieces of large wood were not located inside the survey grid (the reach and <300 m downstream) for a given reach a walking survey was conducted, and their location recorded using a handheld GPS (accurate to ~2 m) [*Hasegawa and Yoshimura*, 2003].

Movement of large wood was calculated as the straight line distance between surveyed start and end points, as wood was observed during overbank flow to move in a predominantly down-valley direction,

Table 2. Information Collected by PDA, for Each Piece of Wood on the Position, Orientation, Environment, and Physical Characteristics

Wood Characteristic	Units/Categories
Length[a]	meters
Diameter 1[b]	meters
Diameter 2[b]	meters
Branched	Single stem/branched stem
Fractured end	Root wad, broken, sawn/axe cut, eroded, N/A
Wood type	Conifer, Broadleaf, Unknown
Living	Yes/No
Sprouting	Yes/No
Total Length with branches	meters
Rootwad Length	meters
Rootwad Diameter	meters
Decay Class	1–5 using decay class system of [*Robison and Beschta*, 1990]
Rooted in bed/bank/floodplain	Yes/No
Location/function of large wood	In channel, key logjam piece, racked logjam piece, on floodplain
Fine wood racked	Yes/No
Volume of fine wood racked	m^3
Partially buried/anchored with sediment	Yes/No
Magnetic Orientation	0–360°
In channel length	meters
Geomorphological effect	Yes/No for 15 geomorphological effects in association with large wood.

[a]Length was measured as the length of the main stem/trunk of the wood piece, excluding rootwad and branches (where present).
[b]Diameter was collected at both ends of each piece in order to allow volume to be estimated more accurately.

Table 3. Percentage of Large Wood Moving in Each Survey Across All Sites (Row 1), Grouped by Reach Type (Rows 2 and 3) and for Each Reach Individually[a]

	Whole Study			August 2010 to May 2011			May 2011 to October 2011			October 2011 to March 2013		
	Moved	Not Moved	ω_{max}	Moved	Not Moved	ω_{max}	Moved	Not Moved	ω_{max}	Moved	Not Moved	ω_{max}
All sites	75.5%	24.5%		50%	50%		62.1%	37.9%		61.5%	38.5%	
Channelized Reaches	67.2%	32.8%		29.4%	70.6%		61.8%	38.2%		70.4%	29.6%	
Seminatural and restored	80.0%	20.0%		61.3%	38.7%		62.3%	37.7%		63.3%	36.7%	
Reach A (headwater)	69.2%	30.8%	2.903	66.7%	33.3%	1.411	N/A	N/A	1.260	45.5%	54.5%	2.903
Reach B (restored)	83.8%	16.2%	1.423	61.1%	38.9%	0.691	75.0%	25.0%	0.617	63.0%	37.0%	1.423
Reach C (channelized)	75.8%	24.2%	40.330	32.1%	67.9%	19.591	72.7%	27.3%	17.497	70.4%	29.6%	40.330
Reach D (seminatural)	83.3%	16.7%	3.483	57.6%	42.4%	1.690	51.2%	48.8%	1.509	75.0%	25.0%	3.483
Reach E (channelized)	56.0%	44.0%	28.451	26.1%	73.9%	13.819	45.5%	54.5%	12.342	N/A	N/A	28.451
Q_{max} (m^3/s)	36.79			17.85			15.94			36.79		
POT[b]		37			5			1			31	

[a]Maximum discharge recorded at Brockenhurst gauging station and peaks over threshold are shown for each study period.
[b]POT (Peaks Over Threshold) defined as number of flood events exceeding bankfull discharge of 11 m^3/s at Brockenhurst.

floating at or near to the free surface and largely bypassing sinuous meander bends. Instantaneous data collection was not possible, and so the travel paths taken by mobile wood pieces were unknown. Given the cumulative margin for error in point accuracy (0.11–0.15 m) any movement calculated as 0.3 m or less was not considered as detectable movement.

Within each reach the bank full channel width and thalweg depth were measured at 25 m intervals using an electronic total station and a mean channel width and depth calculated. Large wood length and diameter were converted into dimensionless units (length, L* and diameter, D*) by dividing length by reach mean channel width and diameter by reach mean channel depth. Dimensionless transport distance is calculated as the measured transport distance for a given piece of wood divided by the mean transport distance.

2.4. Multivariate Analysis

A stepwise regression with backward elimination was used for all logistic and general linear regression analyses. All explanatory variables from Table 2 are initially included, covariates are excluded in a stepwise manner based on p value, in order to generate the most parsimonious model possible, where all covariates included have $p<\alpha$ and which still explains a high level of variance. A level of $\alpha=0.1$ was used for the analyses.

3. Results

Of the 162 pieces of large wood tagged, 39 were surveyed in the same location during the entire survey and 123 were found to have moved. Of the pieces moving 86 were surveyed in a new location giving a minimum transport distance. There was a great deal of variability in proportion of wood mobilized between each survey and between the individual reaches (Table 3).

The range of measured transport distance was 0.36–5600 m with six pieces moving in excess of 500 m; mean transport length of recorded movement was 148 m (standard deviation $\pm$653 m) with a median transport length of 5.3 m (sd $\pm$7.0 m). Some of the mobile pieces were recorded as having moved between initial and intermediate surveys, but were then not subsequently found at these new locations in later surveys, suggesting the possibility of further movement in excess of the calculated transport distance.

During the study there was substantial seasonal and inter-annual variability in discharges (Figure 2). The winters of 2010–2011 and 2011–2012 were relatively dry, and contributed to a widespread drought during the summer of 2012 in the Southern UK. Conversely, the winter of 2012–2013 was exceptionally wet and included two floods of peak magnitude 32 m^3/s or greater at Brockenhurst. The repeated high discharges during the winter of 2012–2013 frequently exceeded the gauging capacity of the Millyford Bridge hydrometric gauge (Figure 1), making readings unreliable, therefore data are shown in Figure 2 for the downstream gauge at Brockenhurst only.

Overall there is an increase in mobility during the 2012–2013 survey period coinciding with higher peak flow and a greater intensity of high flows, however the variability in mobility is much more pronounced in channelized reaches than in seminatural and restored reaches (Table 3).

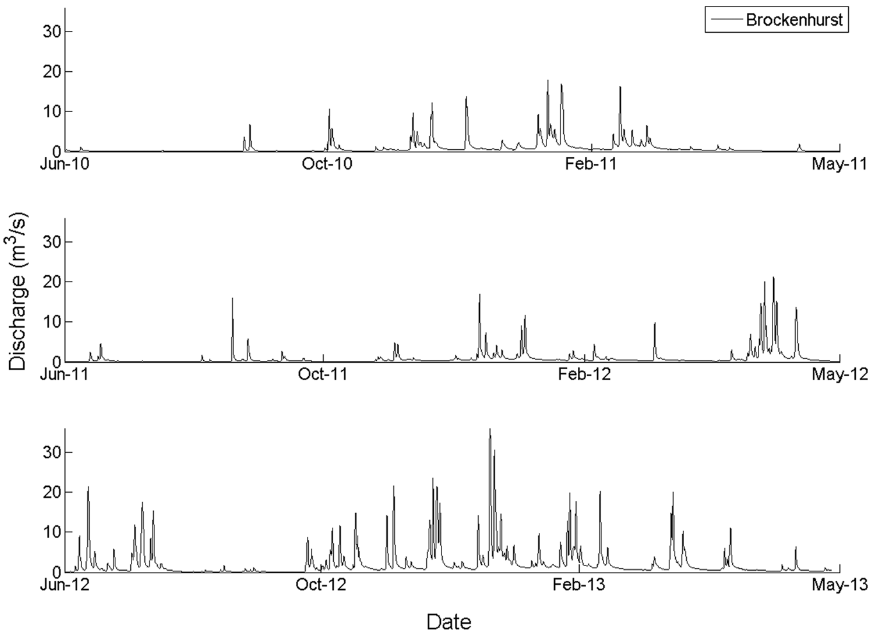

Figure 2. Hydrograph of flows at Lymington River at Brockenhurst gauging station for the duration of the study.

3.1. Wood Piece Controls on Movement

To determine which characteristics of large wood pieces from Table 2 were correlated to large wood movement, and to large wood moving $\geq$10 meters (equivalent to two mean channel widths) a binary logistic regression analysis was used.

The best model for large wood movement (G=18.767, DF=4, p=0.001) includes L* (p=0.068), wood type (p=0.001/0.051) and branching complexity (p=0.168). Branching complexity has a p value greater than α, however it was included as its removal does not improve the model's overall p value and the covariate has a relatively high odds ratio and individual p value near to α. The measure of association for concordant pairs for the model, which can be thought of as analogous to r-squared is 64.5%.

The best model from a binary logistic regression of large wood moving 10 meters or further (G = 19.875, DF = 4, p = 0.001, n=162) includes L* (p=0.002), wood type (p=0.023/0.053) and branching complexity (p=0.025). The measure of association for concordant pairs for the model, analogous to r-squared, is 74.2%.

3.1.1. Other Mobility Studies

Data were obtained from two other mobility studies; *Keim et al*. [2000] who tracked the movement of wood in third order streams in Oregon over 3 years and *Wohl and Goode* [2008] who mapped the position of wood in five Colorado Rocky Mountain streams over 11 years (Figure 3). The data show the distribution of D* and L* between sites, though that of *Wohl and Goode* [2008] has a smaller range of L*.

Binary logistic regression was performed on data from Figure 3 using movement as the response with L* ($p<0.001$) and D* (p = 0.021) as predictors (G=21.624, DF=2, $p<0.000$, n=434). For each predictive variable the odds ratio describes the change in likelihood of movement with an increase of one in the value of the predictive variable. The odds ratio for L* (OR=1.85) is much higher than that for D* (OR=0.16), indicating that although D* is a significant predictor, likelihood of movement is more sensitive to L*. Binary logistic regression performed on data from this study alone does not show statistically significant relationships between L*, D* and movement. The measure of association for concordant pairs, which can be thought of as analogous to r-squared, is 62.8%.

3.2. Geomorphological Complexity

Overall mobility is higher in the seminatural and restored reaches (80%) than in the channelized reaches (67.2%, p=0.003, Table 3). The seminatural and restored reaches display low variability between surveys with 61.3–63.3% mobility. Conversely in channelized reaches, there is greater variability in mobility between

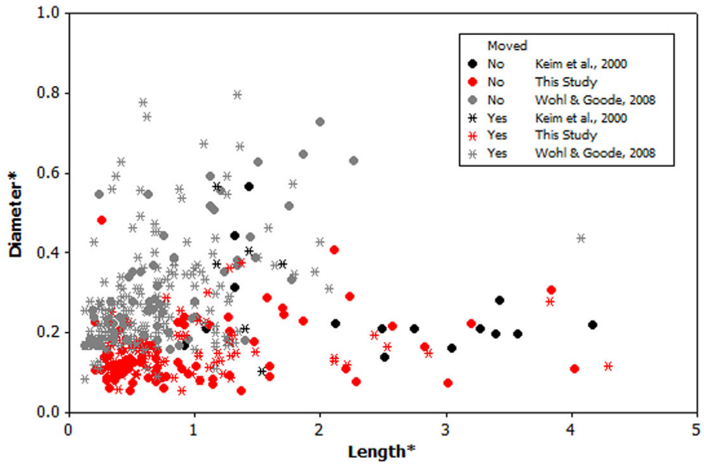

Figure 3. Plot showing movement as a function of dimensionless wood length and diameter for this study and data from *Keim et al*. [2000] and *Wohl and Goode* [2008].

the flood poor periods of October 2010 to May 2011 (26–32%) than during the subsequent flood rich periods (60–70%). Figure 4 shows plots of log movement against dimensionless length and diameter for the two classes of reach, this indicates there is a lower likelihood of movement with increasing piece size within both types of reach, however in channelized reaches there is no movement for large wood either of $L^* \geq 2.5$ or $D^* \geq 0.2$.

Binary logistic regression was used to analyze which characteristics of large wood are correlated with movement within the two separate reach classes. Although the best performing model for large wood showing any degree of movement in channelized reaches is statistically significant (G=8.106, DF=3, p=0.044) including L* and location as predictors, none of the individual covariates have a p value less than α. The best performing model for large wood moving in seminatural and restored reaches (G = 28.935, DF = 8, P< 0.001) includes L* (p=0.036), D* (p=0.064), branching complexity (p=0.021), starting location (p=0.024/0.732/0.615) and wood type (p=0.187/0.009). These two models, at a sample size of n=162, show there are substantial differences in the degree to which large wood characteristics govern mobility between geomorphologically homogenous and complex reaches.

Binary logistic regression was performed for large wood moving ten meters or more during the 32 month study in channelized reaches. The best performing model includes only D* (G = 4.291, DF = 1, p= 0.038). The best model for large wood moving ten meters or further in seminatural and restored reaches (G = 19.407, DF = 4, p= 0.001) includes L* (p=0.018), branching complexity (p=0.015) and wood type (p=0.006/0.030). Location and D* were not found to be statistically significant predictors (p>0.800) despite being good predictors of initial movement.

3.3. Transport Distance

There is an apparent decrease in transport distance with increasing L* shown in Figure 5, although analysis shows no statistically significant relationship, furthermore there are no statistically significant differences in transport distances between the channelized and seminatural reaches.

The best model from a multivariate general linear regression analysis of transport distance against large wood piece characteristics (from Table 1), has a very low r-squared (adjusted) = 7.17%, including L*, D* and wood type as coefficients.

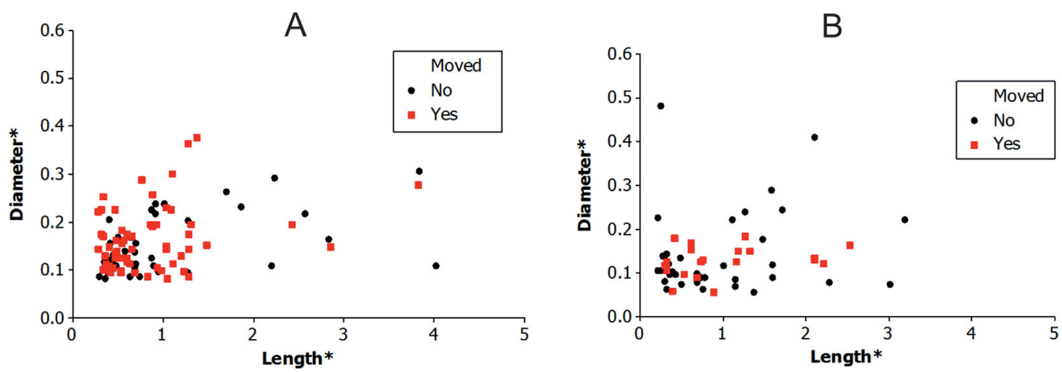

Figure 4. Movement of large wood relative to large wood size for (a) seminatural and restored reaches only, (b) channelized reaches only.

4. Discussion

The proportion of large wood confirmed as moving from its initial location over the three winter flood seasons of the study was 75.5%, however only 70.1% of these mobile pieces of wood were located and surveyed in a new position. Despite limitations of physical tags and markers [*MacVicar et al*., 2009], the proportion of tagged logs recovered is comparable with other large wood tagging studies [*Latterell and Naiman*, 2007].

The transport distances calculated in this study for mean (148.39 m), median (5.32 m) and furthest movement (5600 m) are high compared to those reported in other wood mobility studies (see Table 4). Longer recorded transport distances may partly be due to the experimental design used where a likely maximum transport distance was not assumed *a priori*, and a walking survey undertaken encompassing in excess of 10 km of river length. Although the majority of the furthest moving pieces of wood had lengths of less than 2 meters, transport distances of over 350 m for some longer pieces of wood indicates that whilst an increasing L* decreases the likelihood of a piece moving a substantial distance, it does not preclude such transport.

Mobile pieces of wood were preferentially trapped by logjams, with 69.8% of mobile pieces resurveyed within logjams, compared to 13.9% in the channel margins and 16.3% on the floodplain. The fraction of mobile wood trapped within logjams is similar to the overall proportion of wood found within logjams in the study river of 70.1% [*Dixon*, 2014] and the 51.9% of tagged pieces of wood original located in logjams. The effectiveness of logjams as trapping points has also been observed in other studies [e.g., *Abbe and Montgomery*, 2003; *Montgomery et al*., 2003; *Millington and Sear*, 2007; *Gurnell*, 2014], and suggests wood mobility could be very high in the absence of logjams.

4.1. Wood Piece Characteristics Controls on Movement

Binary logistic regression of data in this study shows L*, wood type and branching complexity are good predictors of large wood movement of 10 meters or further across all reaches and survey periods. Movement is less likely with increasing L*, this is due to both the increasing weight of the piece of large wood providing resistance to buoyant and drag forces acting to entrain the wood. Furthermore, pieces of wood longer than the channel width are more likely to become lodged in channel constrictions [*Bocchiola et al*., 2006a], and with increasing length only able to be transported near to parallel to the flow direction. This finding, along with Figures 3 and 5 confirms previous studies suggesting piece length is inversely related to mobility [e.g., *Lienkaemper and Swanson*, 1987; *Braudrick et al*., 1997; *Berg et al*., 1998; *Bocchiola et al*., 2008; *Curran*, 2010; *Máčka and Krejčí*, 2010]. We do not however find a threshold for higher mobility for piece lengths equal to one channel width as suggested by other studies [e.g., *Lienkaemper and Swanson*, 1987; *Braudrick et al*., 1997;

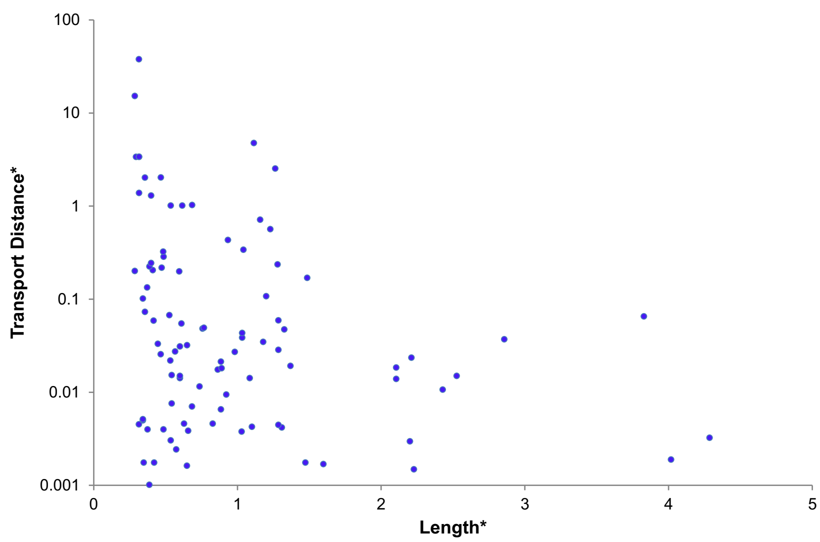

Figure 5. The relationship between large wood dimensionless length and transport distance for mobile large wood.

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Table 4. Comparison Between Mobility Rates and Transport Lengths Reported in This Study and Other Studies From the Literature

Location	Stream Order	Gradient	Catchment Area (km^2)	Channel Width (m)	Annual Transport Rate	Mean Transport Length	Median Transport Length	Maximum Transport length	Reference
This study (High Water, UK)	Third to fourth	0.002–0.011	2.5–16	4–5	50–62%	148 m	5.3 m	5.6 km	
Highland Water, UK—small dowels <1 m length	Fourth	0.005–0.008	6–13	4–5	N/A		48–400 m	1.2 km	*Millington and Sear* [2007]
Oyabu Basin, SW Japan	First to fourth	0.040	5.3	9	92% (9 months)	200–1400 m		~4 km	*Haga et al.* [2002]
Popular Creek, North Illinois, USA		0.001	56	15	83% (15 months)			77% of wood moved >0.6 km	*Daniels* [2006]
Little Topshaw Creek, North Central Mississippi, USA	Fourth	0.002	37	35	61%				*Shields et al.* [2004, 2008]
Sierra Nevada, California, USA	Second to fourth	0.021–0.078	8.3–25	2.1–12.8	0.8–31%	70–361 m			*Berg et al.* [1998]
NW Washington, USA		0.005–0.020	3.4–12.4		18%				*Grette* [1985] in *Berg et al.* [1998]
Queets River, Pacific NW, USA	Fifth	0.006	207–565	125				12 km	*Latterell and Naiman* [2007]
Rocky Branch, New York, USA	Second	0.065	7.4	8	25% (4 years)		35 m	>300 m	*Warren and Kraft* [2008]
Crow's Creek, Wyoming, USA	Second	0.055	49.5	7	18%				*Young* [1994]
Central Rocky Mountains, Colorado, USA	Headwater streams	0.013–0.098	9–32	4.3–6.5	16–23%				*Wohl and Goode* [2008]
Central Western Cascades, Oregon, USA	First to Fifth	0.030–0.370	0.1–60.5	3.5–24	<10–50%				*Lienkaemper and Swanson* [1987]
Tagliamento, Italy	Seventh	0.001–0.010	2580	1500	89%				*van der Nat et al.* [2003]
Oregon Coast Range, USA	Third	0.0004–0.011	7–15.5	6–7	32–56%	131–275 m		>700 m	*Keim et al.* [2000]

Gurnell et al., 2002], which may be partly attributable to the relatively low density of riparian and floodplain trees, reducing potential trapping locations.

Branching complexity is also a geometric constraint on movement with single stems less likely to become stabilized at trapping points such as channel constrictions, bed elements [*Buxton*, 2010] and against other pieces of wood [*Montgomery et al*., 2003] and with more complex branching pieces subject to lower combined forces due to complex interactions of wakes from individual branches causing variations in lift [*Shields and Alonso*, 2012]. Conifer pieces of large wood were found to be more likely to move and to move 10 m or further, despite there being no statistically significant difference in wood piece size between conifer, broadleaf and unknown wood types. The greater mobility of conifer pieces is due to the lower density of wood (0.370–0.453 g/cm^3 oven dry mass (*Brzeziecki and Kienast* [1994] in *Zanne et al*. [2009]; *Alden* [1997] in *Zanne et al*, [2009])) and lower specific gravity than wood from European broadleaf species (0.525–0.585 g/cm^3 oven dry mass) (*Brzeziecki and Kienast* [1994] in *Zanne et al*. [2009]; *Schutt et al*. [1994] in *Zanne et al*. [2009]). Large wood with a lower density, and thus a lower specific gravity will be more buoyant in water, and thus will float and become entrained more readily [*Shields and Alonso*, 2012]. Longer transport distances may also be more pronounced where riparian stem density is low as in the study river where buoyant wood can float over the floodplain in high flows with fewer potential trapping points.

4.1.1. Wood Piece Controls on Transport Distance

A general linear regression model of transport distance identifies L*, D* and wood type as statistically significant predictors, although the model only predicts a very small fraction (7.17%) of the variance in transport length. The low predictive power of the model is a combination of a lack of a direct measurement of density in the variables collected, and the large stochastic element in the transport of wood down a complex river channel [*Bocchiola et al*., 2006a] including the stochastic distribution of potential trapping sites. Logjams are important trapping sites; the distribution of logjams within the study river has been previously shown to be largely stochastic with only 16.8% of variance in logjam frequency per 100 m of channel length explained by a model including channel geomorphology and catchment characteristics [*Dixon*, 2014].

The relationship between large wood size and mobility has also been illustrated in other settings [e.g., *Bilby*, 1984; *Lienkaemper and Swanson*, 1987; *Daniels*, 2006; *Millington and Sear*, 2007]; however the model used here indicates that although statistically significant, L* and D* only have a low predictive power. Wood type is indicated by the model to be the most important individual predictor of variance in transport distance. This is due to the large difference in density between wood from conifers and broadleaves [*Chave et al*., 2009], resulting in greater buoyancy in conifers. In addition conifer large wood tends to consist of single straight pieces, whereas broadleaf species generate more complex branching pieces of wood which are more readily trapped. The importance of buoyancy in transport distance in small channels can be explained by a greater likelihood of highly buoyant pieces of wood moving over the top of channel obstructions such logjams and a greater likelihood of moving out of bank over shallow floodplain flows. The study environment contains reaches with relatively low riparian stem density, meaning wood which is floating over the floodplain will encounter fewer potential trapping points than in a complex forested floodplain, this may mean the influence of buoyancy is increasingly important in this setting. *Schenk et al*. [2014] also noted transport length in a large river was correlated with species, and conclude that further studies are needed to understand species specific buoyancy and transport in flood events. Further studies which either directly measure density in the field should find a statistically significant relationship between density factors and transport length.

Variables related closely to the geometric complexity of large wood relative to the channel are either found to have low predictive power (L*), or are not statistically significant (branching complexity). When the study site's floodplain is inundated, alternative flow paths develop which bypass the geomorphological complexity of the channel and any planform sinuosity, resulting in a change to a wide, shallow flow moving in a predominantly down-valley direction (Figure 6), in effect the river width becomes greater than all large wood pieces, and thus L* effectively decreases. The sparse under-story vegetation and relatively low riparian stem density in some reaches of the study environment results in fewer trapping locations for large wood moving via alternative overbank flow paths during large flood events. This lack of abundant trapping locations, as would be found in complex floodplain forests, is an additional reason for the lack of predictive power of L* in this environment.

4.2. Geomorphological Controls on Mobility

The monitoring period for this study encompassed three winter flood seasons, the first two of which experienced lower than average rainfall with only infrequent low magnitude flood events (Figure 2). During the final winter flood season there were periods of sustained, heavy rainfall leading to widespread regional flooding and multiple high magnitude discharge events in the study catchment. Despite high inter-annual variability in flood frequency and magnitude there was low variability in the percentage of logs mobilized between survey periods (Table 3) with annual mobility rates of 50–62%. Seminatural and restored reaches, characterized by higher sinuosity and lower bank heights show little inter-annual variability in the proportion of large wood mobilized (mean 61.9%, standard deviation 10.5%). Conversely, in channelized reaches, characterized as straight with high banks, 29.4% of large wood mobilized during the driest winter flood season and 70.4% mobilized during the winter with highest flows (32 month mean 49.4%, sd 21.5%).

4.2.1. Relationship Between Geomorphology, Discharge, and Mobility

The trend for channels with a meandering planform and low bank heights to display much lower variability in annual mobility despite inter-annual variations in flood magnitude and sequencing indicates the importance of discharge magnitude and timing as a control on wood dynamics [e.g., *Bilby*, 1984; *Haga et al*., 2002] is dampened in reaches with channelized morphologies. It is possible wood in channelized reaches experiences a greater range of hydraulic forces where even the largest flow events confined in bank, compared to seminatural and restored reaches where high flow events readily spread onto the floodplain.

In this study, within the seminatural reaches, fairly moderate discharges equivalent to around 2 m^3/s at the Brockenhurst gauging station result in at least some degree of overbank flow, whereas in the channelized reaches even the largest discharges recorded during the monitoring period were confined in-bank. The equation for unit stream power (ω), shows how stream power per unit width varies with slope, discharge and channel width:

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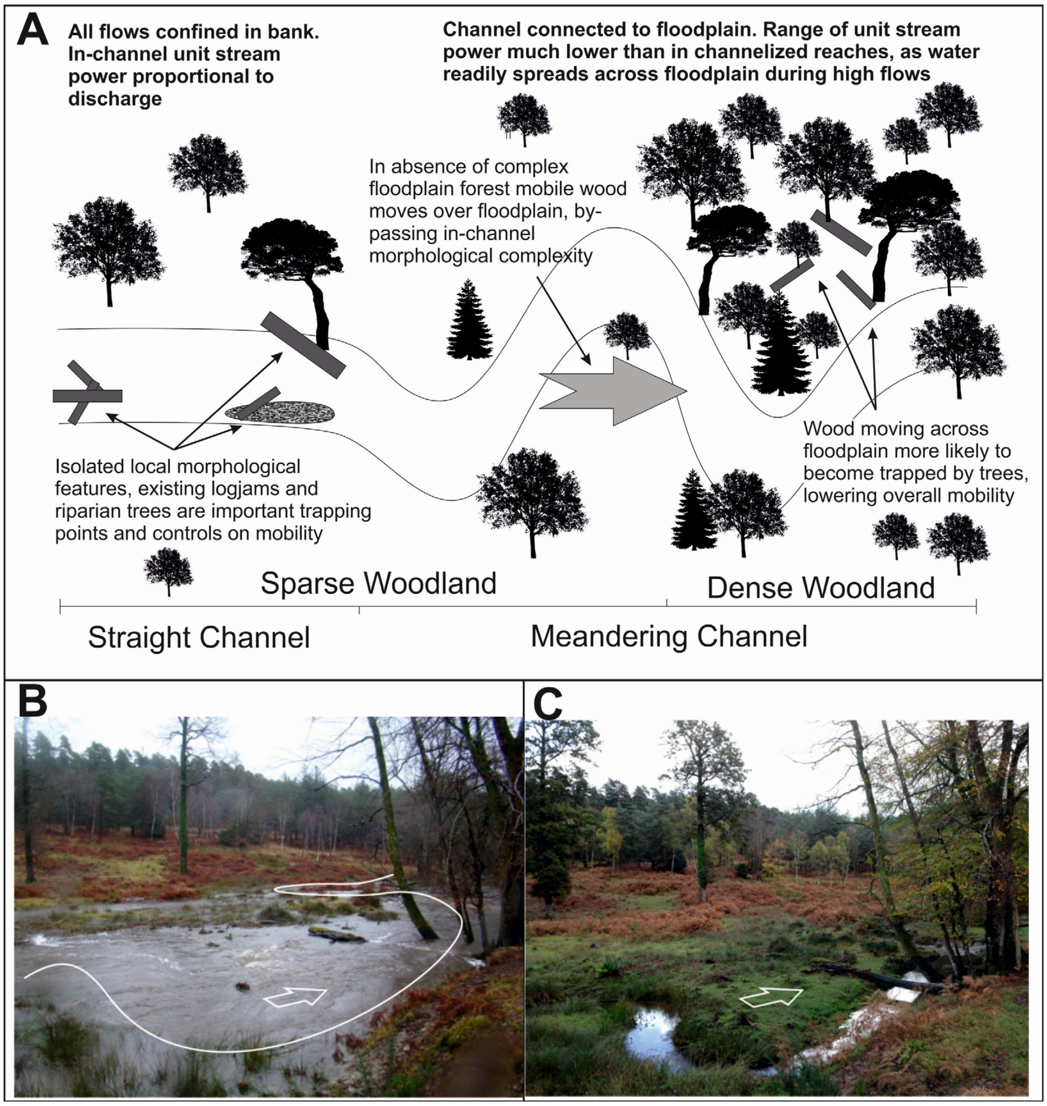

Figure 6. Conceptual model of variations in wood transport controls between three river environments: channelized, meandering with sparse tree density and meandering with high tree density. (a) Conceptual model showing relative importance of different controls on wood mobility and transport. (b and c) field photos demonstrating change in flow-pathways during high discharge event (Figure 6b) compared to base flow (Figure 6c) in a reach connected to its floodplain. In a high-discharge event flow over the floodplain is deep and moving via alternative flow-pathways in a predominantly down-valley direction, channel planform is sketched onto image as white line

$$\omega = \frac{\rho g Q S}{b} \tag{1}$$

Where ρ is density of water, g is acceleration due to gravity, Q is discharge, S is channel slope and b is channel width [*Bagnold*, 1966].

Within a wide, deep, confined channel, during a flood event unit stream power is proportional to discharge. In a channel connected to its floodplain, such as the seminatural and restored reaches, unit stream power shows a nonlinear relationship to discharge. Unit stream power increases linearly up to bank full discharge, however at the point flow inundates the floodplain, unit stream power drops as effective channel width increases and the channel and floodplain effectively behaves as a compound channel. Once the floodplain is inundated, total channel width greatly exceeds depth, and thus flow depth and unit stream power only increase gradually with further increasing discharge. This is reflected in calculations of maximum unit stream power for each reach during each inter-survey period in Table 3 which shows channelized reaches experienced maximum unit stream an order of magnitude greater than for seminatural and restored reaches. For a given range of flood discharges, wood within the channel is subjected to a narrower range of buoyant and drag forces in a meandering channel connected to its floodplain, compared to a box-shaped confined channel. Where flow over the floodplain become sufficiently deep, portions of flow may shift to a predominantly down-valley direction, bypassing the channel sinuosity (Figure 6).

Thus, wood within the channel in a meandering reach connected to its floodplain will not be substantially more likely to move in larger, compared to moderate flood events, whereas in channelized reaches wood will be more likely to move in larger events corresponding to higher flow velocities and larger hydraulic forces. The limited range of variability in mobility rates for meandering reaches is partly due to increased mobilization of wood located on the floodplain during larger overbank flood events.

4.2.2. Variations in Wood Piece Controls on Mobility With Geomorphological Setting

In addition to differences in overall mobility rates between channelized and seminatural or restored reaches, a binary logistic regression analysis of the characteristics of large wood as predictors of movement shows different patterns between reach types. For channelized reaches no individual characteristics of large wood are found to be significant covariate predictors of movement. Although previous studies have suggested channelized reaches can act as conduits with low retention of material [e.g., *Bilby and Likens*, 1980; *Gregory et al*., 1991; *Millington and Sear*, 2007], we would expect piece length to exert some control on movement in all reaches; it is likely the sample size is insufficient to pick out such relationships.

Within seminatural and restored reaches binary logistic regression shows wood piece characteristics are an important control on mobility. In addition to L*, D* and wood type (shown to be important for the whole data set; see section 4.1.1), location and branching complexity are also found to be statistically significant predictors of movement. Location is found to be more important in seminatural/restored reaches as floodplain wood can only be mobilized during overbank flows corresponding to large discharge events with a sufficient depth of flow over the floodplain in order to cause the wood to float [*Haga et al*., 2002], and due to the wider riparian and floodplain zones there is a greater proportion of wood pieces in floodplain locations within seminatural/restored reaches. Due to low flow velocities over the floodplain, drag forces will be minimized [*Shields and Alonso*, 2012] contributing to the importance of buoyancy as a control on mobility in this environment compared to the confined channelized sections. Branching complexity and L* control how likely a piece of wood is to be resistant to drag forces [*Shields and Alonso*, 2012], and longer pieces of wood with branches will be more likely to be trapped by upright trees, or wedged at geomorphological constrictions in the channel [*Buxton*, 2010], or floodplain [*Bocchiola et al*., 2006a].

Floodplain tree density in the study reaches is relatively sparse; 18.9–45.0 stems/ha, compared to 42–793 stems/ha for NW USA [*Naiman et al*., 1998], as a result wood piece characteristics which affect the trapping potential of the piece, such as length and branching complexity, are likely to be less important in controlling mobility and transport distance than in rivers flowing through complex forested floodplains.

A conceptual model summarizing the mobility of wood through three contrasting river environments: channelized, meandering connected to floodplain with sparse tree density and meandering connected to floodplain with high tree density is proposed in Figure 6.

4.3. Comparison With Other Studies

Mobility rates are highly dependent on setting with previous studies reporting annual mobility rates for large wood ranging from 0.8% in small step-pool channels [*Berg et al*., 1998] to 95% in a large braided river [*van der Nat et al*., 2003]. Table 4 shows results from other mobility studies in the literature. Comparisons between mobility studies are difficult due to variations in the reporting of reach characteristics and criteria for including large wood, however studies with catchment area, channel width and slope of the same order of magnitude as this study have found mobility rates ranging from 18% mean annual mobility (*Grette* [1985] in *Berg et al*. [1998]) to 89% over 4 months [*Daniels*, 2006]. The annual transport rates of 50–62% reported here do not support the estimate of *Gregory* [1992] that only 35% of the annual input of wood to New Forest streams is exported out of the system. Instead, our findings suggest large wood mobility rates in such temperate lowland rivers are higher than has previously been assumed and may reflect other systems with stable large wood loadings, but a high turnover of individual pieces [e.g., *Marcus et al*., 2002; *van der Nat et al*., 2003].

Binary logistic regression shows L* to be a statistically significant predictor of wood mobility for combined data from small channels in Southern UK, Colorado Rocky Mountain streams and third order streams of the

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Oregon Coastal Range. The channels monitored in this study, *Keim et al*. [2000] and *Wohl and Goode* [2008] are of similar absolute width (4–8 m), but are in different geomorphological settings. *Keim et al*. [2000] studied three channels in heavily logged commercial forest plantations ranging from low to high gradients, with sand and gravel substrate overlain onto sandstone bedrock and with a high seasonality in discharge patterns. *Wohl and Goode* [2008] studied five channels in subalpine forests with stable banks and step-pool sequences with seasonal discharge patterns dominated by annual snowmelt. Despite differences in geomorphological context between the studies, binary logistic regression shows wood piece length relative to channel width to be an important predictor of mobility for the aggregated data set.

Individually none of the three studies show a statistically significant relationship between L* and movement. This suggests there is a degree of randomness in the movement of individual pieces of wood, and that only with large data sets of large wood movement is the potential influence of a small number of outliers upon analysis minimized. These findings support the conclusions of a flume experiment by *Bocchiola et al*. [2006b] that the distance large wood moves is a random variable whose expectation and variance is dependent on stream power, inter-obstacle spacing and piece length.

Studies have suggested other large wood variables are important for log stability, however in this study no correlation was found between movement and either root wad presence/absence [*Montgomery et al*., 2003; *Curran*, 2010; *Merten et al*., 2010; *Collins et al*., 2012; *Schenk et al*., 2014], decay class [*Gurnell et al*., 2002], or large wood location [*Gurnell et al*., 2002; *Wohl and Goode*, 2008; *Curran*, 2010]. The majority of studies finding root wad presence/absence, decay and location to be important are from larger rivers than the Highland Water, thus these factors may be less important in smaller lowland channels.

4.4. Logjam Evolution

The break up and reformation of logjams in the same location [*Sear et al*., 2010; *Collins et al*., 2012; *Schenk et al*., 2014] as well as the cycling of large wood material downstream from one logjam to another was observed during the study (Figure 7), and suggests that although local large wood loadings within logjams can be constant, there is mobility of individual pieces. Tagging individual pieces of wood showed logjams which persist at the same location over several flood seasons are reworked, and despite containing the same key pieces anchoring the logjam, and appearing to have the same or similar architecture, there is high turnover of individual pieces[*Marcus et al*., 2002; *van der Nat et al*., 2003; *Latterell and Naiman*, 2007]. This broadly supports the theoretical logjam evolution of *Manners and Doyle* [2008], but suggests that not only is logjam evolution nonlinear with respect to time, but is also cyclical, with individual pieces of wood cycling through the system whilst local wood loadings remain relatively constant [*Marcus et al*., 2002].

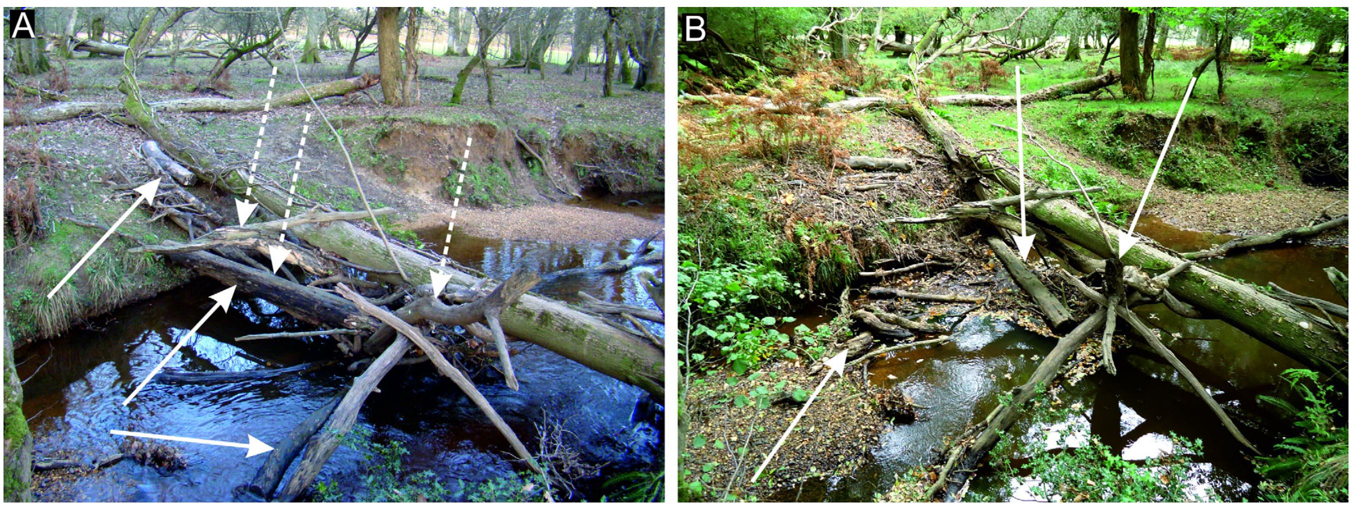

Figure 7. Field photographs showing reworking of component racked pieces of large wood in a logjam during the study, (a) 19 March 2011, (b) 4 October 2011. Solid arrows show pieces of tagged large wood which are not present in the logjam in photograph b, arrows with broken lines are tagged pieces which were previously recorded in another logjam ~120 m upstream in the September 2010 survey. Solid arrows show newly trapped pieces of wood not present in the logjam in photograph a.

5. Conclusion

This study has demonstrated large wood in small forest rivers can be highly mobile with over 75% of pieces moving during a two and a half year study. Transport distances for mobile large wood were found to be longer than expected with several pieces moving in excess of 500 m and a furthest recorded transport length of 5.6 km.

Multivariate analyses show dimensionless length to be an important factor explaining mobility and transport distance in all contexts with few pieces of dimensionless length over 2.5 moving. Multivariate analyses also show dimensionless diameter, branching complexity, wood type and location can all be important factors in explaining mobility and transport distance, but this depends on context. Statistically significant models were found for all multivariate analyses, but the majority of variance in transport distance remains unaccounted for by the variables collected. Density of wood was identified as an important variable which would need to be specifically measured in addition to proxy measurements in future studies.

In common with many large wood mobility studies using physical tags there were difficulties in locating and resurveying large wood that had moved from its original location with only around 70% of mobile pieces recovered. The transport distances reported here suggest that in other studies where a low proportion of tagged logs have been recovered, such pieces may have been transported far out of the study area; in effect the distance downstream in which a search for large wood is conducted may have been too short. If previous studies have failed to relocate some of the furthest moving pieces of wood due to strategic assumptions in the experimental design, average and maximum transport distances may have been underestimated.

Logjams formed around a stable key piece of large wood can persist for several years and through multiple high discharge events; we have shown that although such logjams may have the same function and structure, and may ostensibly appear the same, the component pieces of wood are often reworked and moved through the system. Logjams may be persistent features, but our research confirms that in low order rivers in mixed woodland, large wood cycles through logjams attaining substantial transport distances despite apparent channel complexity and locally stable large wood loadings.

This study has implications for the use of large wood as part of river restoration projects. Results suggest that in rivers with low riparian stem density wood less than 2.5 channel widths in length should be considered potentially mobile, and that wood less than the channel width in length should be considered potentially highly mobile. Logjams have been shown to be effective trapping sites for mobile large wood; river restoration and flood risk management schemes using large wood in small rivers without abundant riparian trees should therefore consider including pieces of wood in excess of 2.5 channel widths in length to act as focal points for logjam formation, these logjams will then trap and temporarily store mobile wood in the channel, reducing transport distances for mobile wood. The relationship between wood mobility, piece length and riparian stem density needs to be explored more fully in order to develop appropriate worldwide guidelines of wood dimensions for restoration. To this end there is a great need for standardization of reporting metrics to include riparian stem density measurements in studies of large wood mobility.

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