EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **36**, 1137–1151 (2011)

(wileyonlinelibrary.com) DOI: 10.1002/esp.2135

Distribution and characterization of in-channel large wood in relation to geomorphic patterns on a low-gradient river

Bertrand Moulin,[1] Edward R. Schenk[2]* and Cliff R. Hupp[2]
[1] AEMGEO – University of Lyon, CNRS UMR 5600 - Environnement Ville et Société, Site of École Normale Supérieure de Lyon, 15 Parvis René Descartes, BP 7000, 69342, Lyon cedex 07, France
[2] US Geological Survey, 12205 Sunrise Valley Dr., Reston, VA 20192, USA

Received 30 August 2010; Revised 5 January 2011; Accepted 10 January 2011

* Correspondence to: E. R. Schenk, US Geological Survey, 12205 Sunrise Valley Dr., Reston, VA 20192, USA. E-mail: eschenk@usgs.gov

ESPL
Earth Surface Processes and Landforms

ABSTRACT: A 177 river km georeferenced aerial survey of in-channel large wood (LW) on the lower Roanoke River, NC was conducted to determine LW dynamics and distributions on an eastern USA low-gradient large river. Results indicate a system with approximately 75% of the LW available for transport either as detached individual LW or as LW in log jams. There were approximately 55 individual LW per river km and another 59 pieces in log jams per river km. Individual LW is a product of bank erosion (73% is produced through erosion) and is isolated on the mid and upper banks at low flow. This LW does not appear to be important for either aquatic habitat or as a human risk. Log jams rest near or at water level making them a factor in bank complexity in an otherwise homogenous fine-grained channel. A segmentation test was performed using LW frequency by river km to detect breaks in longitudinal distribution and to define homogeneous reaches of LW frequency. Homogeneous reaches were then analyzed to determine their relationship to bank height, channel width/depth, sinuosity, and gradient. Results show that log jams are a product of LW transport and occur more frequently in areas with high snag concentrations, low to intermediate bank heights, high sinuosity, high local LW recruitment rates, and narrow channel widths. The largest concentration of log jams (21.5 log jams/km) occurs in an actively eroding reach. Log jam concentrations downstream of this reach are lower due to a loss of river competency as the channel reaches sea level and the concurrent development of unvegetated mudflats separating the active channel from the floodplain forest. Substantial LW transport occurs on this low-gradient, dam-regulated large river; this study, paired with future research on transport mechanisms should provide resource managers and policymakers with options to better manage aquatic habitat while mitigating possible negative impacts to human interests. Copyright © 2011 John Wiley & Sons, Ltd.

Introduction

Numerous studies have documented the geomorphic importance of large wood (LW) in streams and rivers (Harmon *et al.*, 1986; Smock *et al.*, 1989; Gurnell and Sweet, 1998; Gregory *et al.*, 2003). The term 'large wood' as used in the present study, refers to tree trunks, roots, and branches with lengths greater than 3 m and diameters greater than 0.2 m. LW provides critical habitat in aquatic ecosystems in small and large streams (Maridet, 1994; Thevenet, 1998; Gregory *et al.*, 2003), and may be singularly important in low-gradient, fine-grained systems, where it provides most to all of the structure for invertebrate fauna and refugia for fishes (Benke and Wallace, 1989, 2003). LW affects hydraulic roughness (Gippel, 1995; Hygelund and Manga, 2003; Manners *et al.*, 2007), in-channel lateral water velocity distribution (Sedell *et al.*, 1988) and the longitudinal (Keller and Swanson, 1979; Bilby and Ward, 1991; Abbe and Montgomery, 1996) and lateral profile of channels (Wallerstein and Thorne 2004). Further, it is commonly associated with sediment transport and storage (floodplains and bars) and vertical stability of the channel bed (Daniels, 2006; Skalak and Pizzuto, 2010). LW increases the morphological complexity of a channel and its floodplain (Bilby and Ward, 1989; Abbe and Montgomery, 1996; Steel *et al.*, 2003) and strongly influences the development of riparian vegetation (Piégay, 2003; Pettit *et al.*, 2004).

Studies have investigated the importance of in-channel LW on macroinvertebrate production, fishery ecology, and biogeochemical cycling in south-eastern US rivers (Bisson *et al.*, 1987, 2003; Bilby, 2003; Dolloff and Warren, 2003; Zalewski *et al.*, 2003). LW appears to be particularly important in contributing to stream foodwebs as invertebrate diversity, habitat-specific abundance, biomass, and productivity are greater on submerged wood than on or within other aquatic habitats.

Despite the ecological benefits of LW, it poses a problem to some human activities on rivers. It may disrupt navigation, including commercial marine operations on large rivers (Gurnell *et al.* 2002; Piégay, 2003) and recreational navigation on smaller rivers. LW might also damage infrastructure when it accumulates on or near structures such as bridge piers by increasing hydraulic head and/or increasing bridge scour (Diehl, 1997; Wallerstein, 1998; Kothyari and Ranga Raju, 2001). LW may also increase local flooding if log jams impede flow.

In-channel wood characteristics have been studied in terms of origin, mechanism of recruitment, and biomass abundance. However, most studies have been conducted on gravel-bed rivers, common in the Pacific Northwest of the USA and Canada, upland UK, France, Italy and New Zealand (Mosley, 1981; Bryant, 1983; Robinson and Beschta, 1990; Nakamura and Swanson, 1993; Smith *et al.*, 1993; Fetherston *et al.*, 1995; Hogan *et al.*, 1986; Piégay *et al.*, 1999; Gurnell *et al.*, 2000; Baillie *et al.*, 2008). There have been some recent studies on the eastern coast of the USA, but these are largely restricted to headwater and small catchment areas less than 500 km^2 (Daniels, 2006; Cordova *et al.*, 2007; Magilligan *et al.*, 2008). Further, most LW studies have occurred along isolated reaches or sub-basins. Few investigations such as those by Gregory and Davis (1993), Piégay *et al.* (1999), and Moulin and Piégay (2004) have covered basin-wide processes or have been conducted along large sand-bed rivers of the low-gradient coastal plain of south-eastern USA (Triska, 1984). In general, LW dynamics are poorly described and understood along coastal plain rivers relative to high-gradient systems.

Initial studies of LW within channels suggest that LW distribution is a function of the length of pieces entering the channel and the ambient channel width (Likens and Bilby, 1982; Gurnell, 2003). As the size of the river increases, the importance of the relationship between piece length and channel width decreases. Where the average piece length is shorter than the width of the channel, the location of LW occurs on predisposed sites characterized by high roughness. Such sites include: the upstream end of point bars, along small secondary channels, sand and gravel banks (rollers), small vegetated islands, and human obstructions such as bridge piers (Swanson and Lienkaemper, 1982; Piégay and Gurnell, 1997; Gurnell *et al.*, 2000; Marcus *et al.*, 2002; Van der Nat *et al.*, 2003). These potential deposition sites differ according to river pattern but are significantly correlated with high roughness, which may form an obstacle to flow (Piégay, 2003). Deposition sites for LW can thus be identified and predicted using sensitivity analyses (Piégay and Marston, 1998; Lassettre *et al.*, 2007).

We studied the channel geometry and the distribution, origin, and conditions of LW deposition to predict zones of LW deposition on low-gradient large rivers. The research was conducted on 177 river km of the 210 km long lower Roanoke River, North Carolina. The purpose was to describe and interpret the temporal and spatial dynamics of LW recruitment, transport, and subsequent downstream storage along a large low-gradient coastal plain river. Results should provide fundamental information for management in terms of the influence of and impacts on flow regime/flood patterns and infrastructure (bridges, dams, levees, etc.) and risk management by providing information on the processes that determine LW recruitment reaches and areas of accumulation. These results should also provide insight for interpretation of aquatic biodiversity and other ecological processes. Finally, the research integrates a third aspect defined by Piégay (2003), which considers wood as a transported element like gravel or suspended sediment that can be synthesized and distinctly interpreted (Piégay, 2003; Moulin and Piégay, 2004; MacVicar *et al.*, 2009).

Study Area

The study reach on the coastal plain section of the Roanoke River extends downstream of the Roanoke Rapids dam to the Albemarle Sound (210 km), in north-eastern North Carolina (Figure 1). The river reach is entirely located on the northern coastal plain of North Carolina, an area of broad upland plains with low relief and broad, sometimes underfit, bottomlands (Hupp, 2000; Hupp *et al.*, 2009). This region is characterized by humid temperate climatic conditions with a mean annual temperature of 15.8 °C and average annual precipitation of 1267 mm as measured at Williamston, NC, elev. 6.1 m above sea level (station 319440 Williamston 1E, 1971–2000 Climate Normals, State Climate office of North Carolina). The average daily discharge (1964–2003) is 228 m^3/s as measured

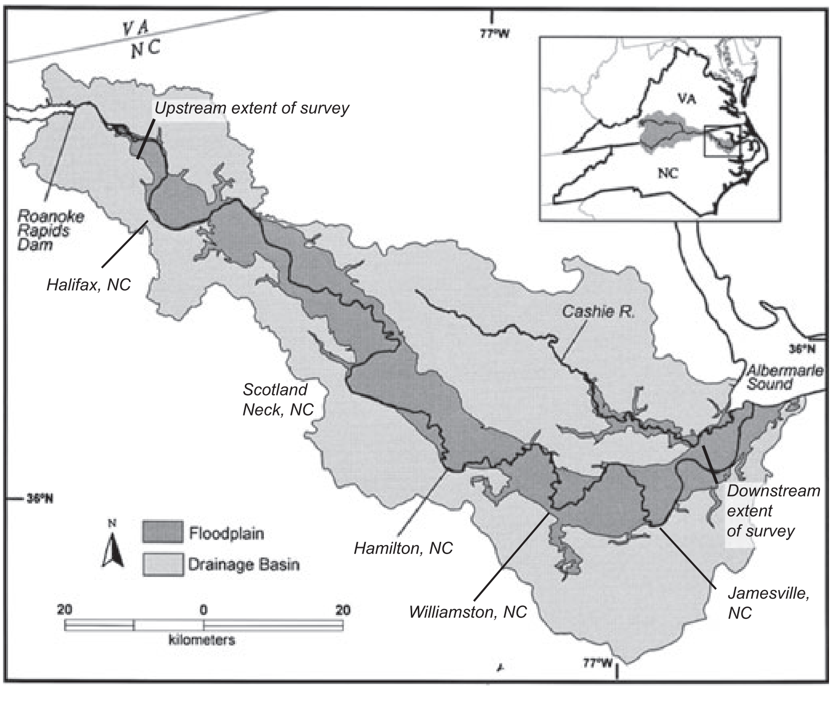

Figure 1. The Lower Roanoke River, a 210 km river reach bounded by the Roanoke Rapids Dam and the Albemarle Sound (adapted from Townsend, 2001). Our 177 river km study site is delineated.

immediately downstream of the Roanoke Rapids Dam, NC (USGS streamflow gage 02080500, Figure 1). Daily discharges, measured over a span of 43 years, range from 25.3 to 562.8 m^3/s. Prior to dam construction (early 1950s), annual peak flows regularly ranged from about 1400 to 2800 m^3/s with an extreme flow of 7000 m^3/s in 1940. Since construction of the dam, streamflow has only reached 1120 m^3/s once with a normal maximum of 980 m^3/s; annual flows are rarely less than 28 m^3/s and most peaks are held around 560 m^3/s (Hupp *et al.*, 2009). Normal non-hydropeaking flows are maintained at approximately 57 m^3/s (video footage was taken during this discharge) with nearly daily hydropeaking flows at 560 m^3/s. Discharge may occasionally fall below 57 m^3/s during droughts or may be held at or above 560 m^3/s during or shortly after large precipitation events in the upstream watershed. Water stage information is recorded at six streamflow gages along the lower river beginning at Roanoke Rapids, NC near the dam, and in downstream order, at Halifax, Scotland Neck, Hamilton, Williamston, and Jamesville, NC, nearest to the Albemarle Sound (Figure 1).

The lower Roanoke River flows eastward as a largely single threaded meandering stream from near the Fall Line to the Albemarle Sound (Figure 1) across Miocene sedimentary material overlain by Quaternary Alluvium (Hupp *et al.*, 2009). The sedimentary material consists largely of unconsolidated fine sands, silt, and clay, although the clay deposits may be indurated.

Additionally, the floodplain along the lower river trapped a large volume of sediment associated with post-colonial agriculture (Hupp *et al.*, 2009). The river is generally incised through the legacy sediment and other coastal plain sediments; although erosion on cut banks and many straight reaches appears active, there is limited point-bar development. This legacy sediment may be between 4 and 6 m in depth along upstream reaches of the lower river, which thins downstream to near zero at the Albemarle Sound (Hupp *et al.*, 2009). Extensive mudflats occur in-channel between river kms 152 (near Jamesville, NC, Figure 1) and the Sound replacing banks as a storage location for in-channel LW. Mudflats are generally unvegetated, partially submerged, and distinct from the bank. The floodplain along the study reach supports the largest contiguous bottomland hardwood forest on the Atlantic coastal plain (Hupp, 2000).

Methodology

This study utilized georeferenced footage produced in March 2007 by contractors for Virginia Dominion Power, Inc. (hereafter referred to as 'Dominion', the energy conglomerate that operates the Roanoke Rapids Dam). The video was taken by a helicopter travelling at approximately 55 km/h just above the tree canopy (approximately 60 m above ground surface) between Plymouth, NC and the Roanoke Rapids Dam. Information from the video footage was reduced and organized by spatial distribution, physical characteristics of accumulated wood, and recruitment mechanism along a 177 km coastal plain section of the Roanoke River. The video recorded one bank continuously (south bank on the upstream part of the flight and north bank on the downstream part of the flight) and included a continuously recorded time stamp and GPS position. The video's GPS position was groundtruthed using pre-defined points on the bank and pre-determined landmarks (e.g. highway bridge locations). Two technicians observed the video and recorded LW that was larger than approximately 3 m long and 0.2 m wide. The length and width lower limits were determined using the smallest scale that could be consistently determined using the video. Length and width was estimated relative to people, boats, and structures available throughout the 10 h video. Log jams, areas where three or more individual detached LW accumulate, were also noted. LW was recorded in the channel and on the banks; but not on the floodplain. We define LW available for transport as any detached individual LW and any LW in log jams; future LW is defined as snags and dead standing trees.

The video database was populated with eight variables per individual LW and four variables per log jam (Figure 2). The video's time stamp was used to record the longitudinal position of LW. This was later translated into river kilometers using a pre-existing database created by Dominion's contractor. Individual pieces of LW were categorized as either detached, or as one of two types of potential LW. Potential LW includes 'snags', leaning trees angled more than 45° towards the channel or trees on bank edges with more than half of the root structure exposed due to bank erosion, and 'dead standing trees', dead trees with a trunk angle less than 45° from vertical. Detached LW and log jams were noted for position relative to channel (parallel, oblique, or perpendicular) and location on

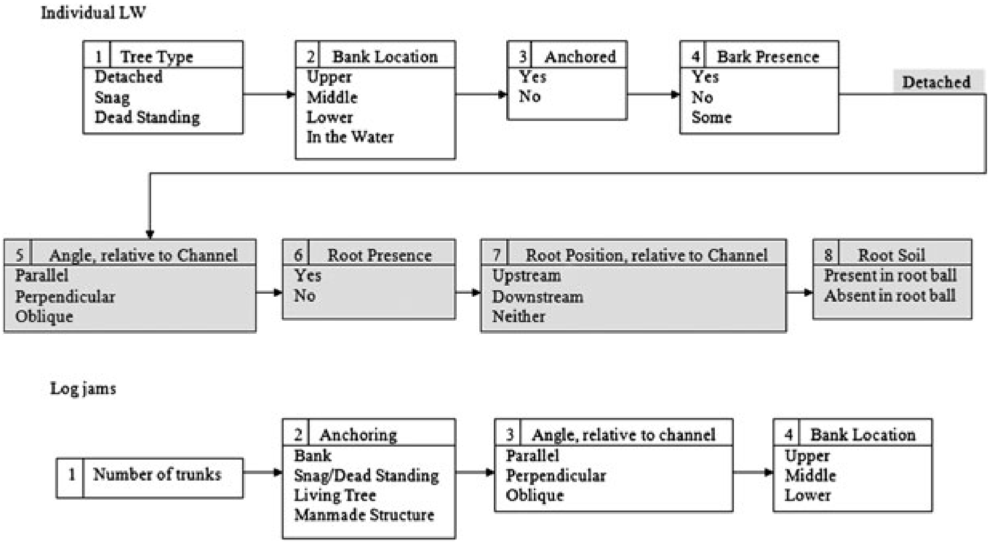

Figure 2. Key used to populate the LW database. Variables were picked to distinguish wood recruitment (available for transport), potential recruitment, and accumulation.

the bank (upper, middle, lower). Bank location was recorded as lower 1/3, middle 1/3, or upper 1/3 of the exposed bank at mean-low water (when the video was recorded). Bank location and LW position relative to channel allowed for interpretation of previous transport and the depositional environment. The presence of roots, branches, and bark was noted to determine the relative age of the LW (relative to its death and transport time). Root position relative to the channel was also noted, when applicable, to verify that the LW had been deposited from an upstream site. Roots were noted as to whether they retained soil, which when present indicates the LW has only recently entered the channel.

Both individual LW and log jams were evaluated for bank anchoring. Individual LW anchoring was described as LW that had a portion of its roots still embedded in the bank surface. Log jam anchoring was described as either occurring due to bank features, a standing snag, living tree(s), or structures (bridge pilings, docks, boat ramps, etc.). The additional data collected for log jams facilitates determination of the reason for a log jam's particular location.

One weakness of an aerial LW survey is the inability to inventory submerged LW that constitutes a significant proportion of LW in large rivers (Angradi *et al.*, 2010). Quantification of submerged LW in large deep rivers would allow for a better comparison with shallow or small rivers and streams.

Bank morphology information and a bank-erosion index were measured every 1.6 km between Halifax, NC and the mouth of the river and analyzed to detect correlation with the LW database. These measurements were taken on bathymetric cruises for a related study of bank stability (Hupp *et al.*, 2009). The bank-erosion index was determined by assessing a 100 m reach every 1.6 km for bank erosion in terms of either fluvial erosion, as evidenced by trees with exposed roots, or mass wasting, as evidenced by slump block or rotational failure bank scars. Stable surfaces were evident by herbaceous or grass cover. For the purpose of this study the index was simplified to 0 = no erosion, 1 = fluvial erosion, 2 = historical mass wasting, 3 = fresh mass wasting.

LW volume and mass determination

LW volumes were determined to allow for comparison of LW abundance and biomass with other rivers using diameter and length measurements from 134 radio tagged individual LW used for a concurrent LW transport study. Average volumes for individual pieces of wood were calculated by assuming a cylindrical shape for a given length and geometric mean diameter (Lienkaemper and Swanson, 1987). Biomass within the channel was estimated from the calculated mean volume and an average wood density of 0.50 Mg/m^3 used in most studies of woody debris in aquatic systems (Harmon *et al.*, 1986). The value corresponds to the average specific gravity of soft wood, because in many cases real densities cannot be easily obtained, especially when studying woody debris in aquatic environments.

Statistical segmentation of longitudinal LW frequency

A segmentation test was performed using LW frequency by river km for detached individual LW and log jams to detect breaks in the longitudinal distribution and to define homogeneous reaches in terms of wood deposits. A modified non-parametric Mann–Whitney test (Pettit, 1979) was used to create the segment breaks. The null hypothesis was the absence of change in the sequence *Xi* of size *N*. Statistically this requires partitioning homogeneous contiguous classes (linear segments). The independent variable is river km and the frequency of LW is the dependent variable as shown by Lassettre *et al.* (2007) along the Ain River, France. The values of the two samples are grouped and classified by increasing order. The sum of the ranks of the components of each subsample in the total sample is then calculated. A statistic is defined using the two sums thus obtained in order to assess whether the two samples belong to the same population.

The Pettit method (1979) is a fairly robust, nonparametric test that is not influenced by the distribution slope of the studied variable. After detecting breaks in the distribution, we analyzed the relations in each homogeneous reach among wood deposits with the four geomorphic parameters (width/depth, slope, sinuosity, and bank height) from Hupp *et al.* (2009). We also investigated the relations between bank-erosion index and LW distribution.

Results

LW spatial distribution

The LW population of the north bank consisted of both LW available for transport and future LW (Table I, Figures. 3 and 4). LW along the south bank was surveyed at 21 representative locations for a total of 33.8 river km. The results of a paired student's t-test indicate that there is no significant difference between north and south bank LW distribution (detached individual LW concentration data, $P = 0.83$, $n = 21$). We, therefore, assume that the LW distribution of the south bank is similar to the fully observed and quantified north bank.

The distribution of detached individual LW is highly variable based on channel morphology and distance from the dam with an overall mean of 55 pieces per river km (both banks). Approximately 11 log jams occurred per river km with a mean of 60 pieces in jams per river km; the concentration of log jams was highly variable (Figure 4).

Of the LW available for transport (75% of all LW) approximately half are stored in jams and half as detached individual LW (Table I). Most detached individual LW is found on the upper bank with only 18% located in the channel during low flow (Figure 5a).

Individual detached LW and log jam characterization

General description and Pettit Test analysis for individual detached LW

LW age and previous transport history can be estimated by the present condition of the log, including decomposition, amount of physical abrasion from previous transport, and orientation

Table I. Large wood (LW) abundance and concentrations by LW type

	Available for transport		Future LW	
	Detached individual LW	Log jams	Snags	Dead trees
Pieces of LW	5368	5356	1863	1806
Biomass (Mg)	4026	4392	3009	
Biomass (Mg/km)	22.7	24.8	8.6	8.3

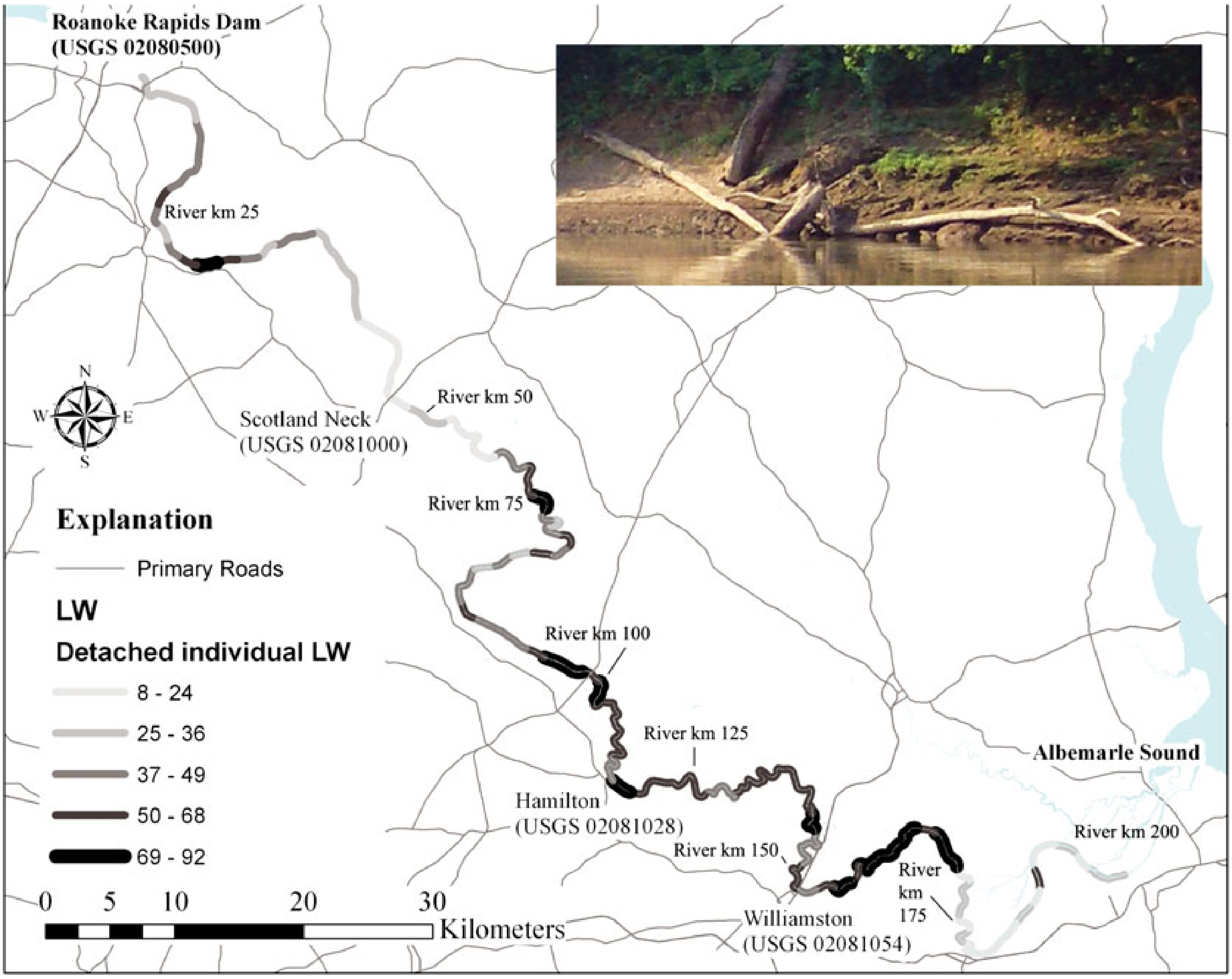

Figure 3. Detached individual LW by river km with USGS streamgages as points of reference. The x-axis of the histogram is measured in river kilometers from the Roanoke Rapids Dam. Photo is of four examples of detached individual LW, one partially submerged, two pieces low on the bank, and another on the mid-bank (57 m^3/s discharge, Photo credit: Edward Schenk). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

relative to the channel. The majority of detached wood had roots (Figure 5a). Among the individual detached LW possessing roots, 26.5% contained soil within the root ball, whereas the majority had 'cleaned' (devoid of soil in the root ball) roots. The roots were positioned upstream for more than 73.5% of the pieces. Most detached individual LW was orientated obliquely, in relation to the channel, and was positioned on the mid to upper bank (Figure 5a).

We used Pettit's Test (Pettit, 1979) to create separate classes of detached individual LW based on roots, angle, bank localization, and branch and bark presence parameters. First-level results (Figure 6) suggest there are basically two different types of wood along the river, that without roots (class 3, which represent 23%), and that with roots (class 1 and 2, together equalling 73%). The second-level results (Figure 5) indicates there are two types of detached wood with roots distinguished by bark, bank location, and orientation. The three classes and their relation are depicted in Figure 5.

Class 1 ('transport' LW, representing 55% of the population of the detached wood) is characterized by the presence of roots for 100% of the individuals, 50% lay at an oblique angle to the bank, and 25% are perpendicular or parallel to the bank. Areas on or near the mean-low waterline contain 52% of the LW. Branches are present on 55% of the individuals and 71% of the individuals have no bark.

Class 2, 'new' LW (representing 15% of the population of the detached wood) is largely well preserved LW with 100% of their roots, branches, and bark. More than 77% of the individuals reside on the upper or middle bank and the trees are mostly positioned at angles perpendicular or oblique to the bank (42, and 48% of the mid and upper bank detached LW population, respectively), indicating that they have probably not been previously transported by streamflow.

Class 3, 'decayed' LW, (representing 23% of the population of the detached wood) is characterized by a lack of roots (100% of the individuals). More than 50% of the wood is situated on the upper and middle part of bank. About 65% of the wood has no branches and only 18% of the pieces have their entire bark. Resting angle is oblique (42%) or perpendicular (40%) indicating the wood has probably not been previously transported by a high-water event.

General description of log jams

Log jam variables were recorded to help determine processes of log jam formation; the variables included anchorage type, angle relative to channel, and bank position. The majority of log jams are anchored on snags (Figure 5b), however, the largest jams are on bridge piers (Figure 7). There are four bridges in the 177 km study reach; the bridges effectively trap 1% of the LW stored in jams.

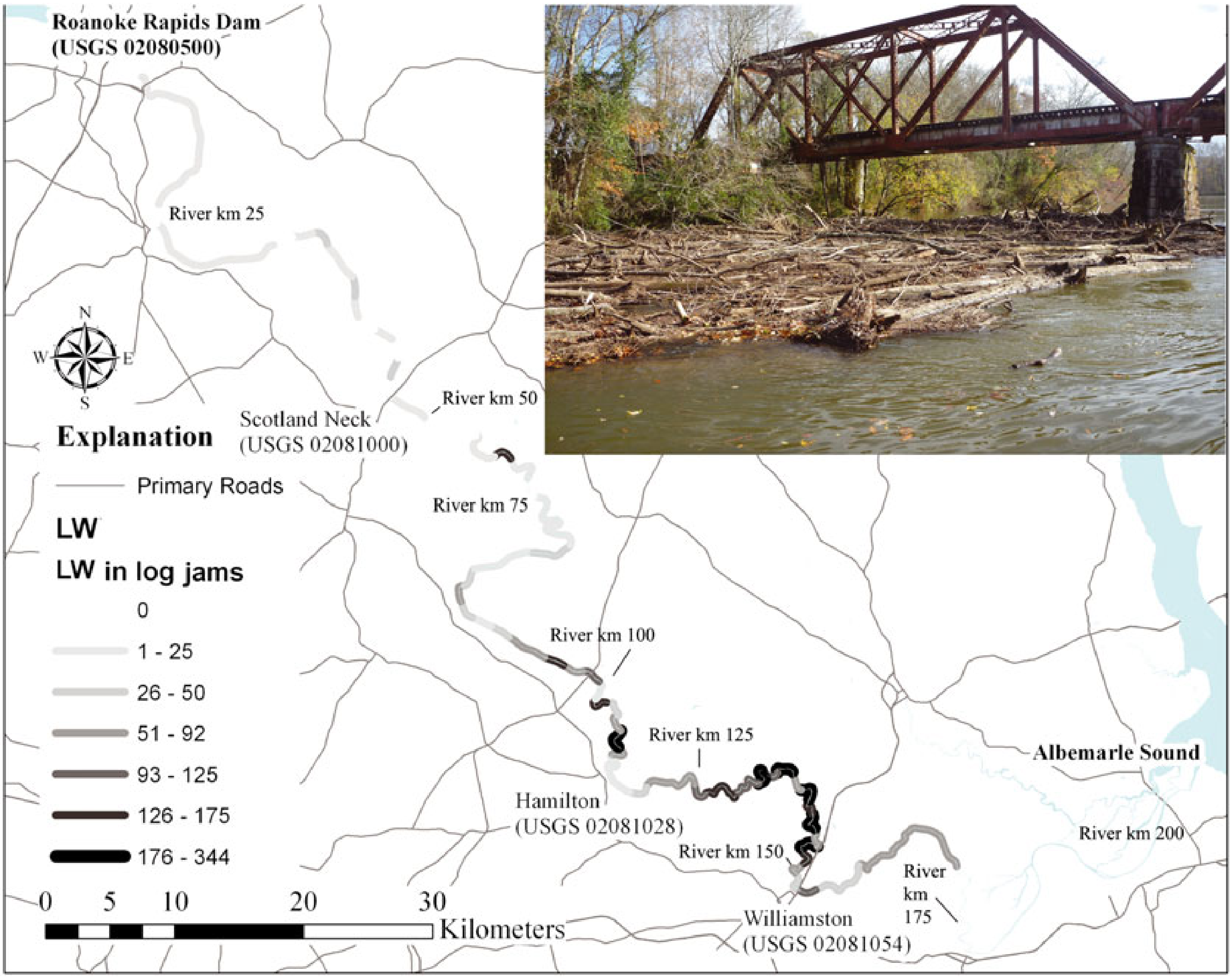

Figure 4. Sum of LW in log jams by river km with USGS streamgages as points of reference. Photo is from a floating portion of the largest log jam on the river during a flood (57 m^3/s discharge, photo credit: Edward Schenk). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The majority of log jams are located on the lower bank and in the water (Figure 5b). This indicates a high potential for further transport and also indicates a high potential for trapping additional individual LW through higher bank roughness created by the jam. Most jams (70%) are available nearly year round as aquatic habitat, positioned either on the lower bank or submerged at low-water flows. The majority of the jams have a local impact on channel flow with 75% of the log jams in an oblique orientation relative to the channel (Figure 5b). Qualitative observations over most of a decade suggest that, in general, jams occur in the same location throughout any given year. The residence time of individual pieces of LW in a particular jam is unknown, as are overall jam dynamics.

LW accumulation type, abundance, and estimates for biomass and volume

Detached individual LW, account for approximately half of the LW available for transport (Table I). Log jams represent 10% of the LW population but store 52% of the LW available for transport. Potential future LW, in the form of snags and dead standing trees, account for 19.5% and 19%, respectively, of the large woody debris present in the river, and are considered the non-mobile components of the LW population. LW concentrations are approximately 55 pieces/km for individual detached LW with an additional 11 log jams/km. The total concentration of wood available for transit is 115 pieces/km if pieces of LW in log jams are included.

LW biomass was estimated using width and length data from 134 randomly selected pieces between river km 70 and 150 using the 0.5 Mg/m^3 coefficient developed by Harmon *et al.* (1986). The mean diameter was 0.33 m and the mean length was 9.7 m. The average volume estimation indicates that total LW biomass was 11 427 Mg in 2008 for the 177 km of the lower Roanoke River. The mean biomass concentration was 64.5 Mg/km. Biomass concentrations and amounts for each LW class are available in Table I.

The greatest mass of LW, 8418 Mg (73.6% of the total mass of LW present in the channel), is available for transport while 3009 Mg (26.4% of the total mass of LW present in the channel) represent future recruitment. Future recruitment is an underestimate, as standing live trees on the floodplain in areas of active mass wasting have not been included in these analyses.

The mean biomass stock is approximately 0.0415 Mg/ha (4.1 Mg/km^2) at the watershed scale. Detached wood has a concentration of 0.01465 Mg/ha (1.465 Mg/km^2) while log jams are 0.0160 Mg/ha (1.60 Mg/km^2), angled snags are 0.0055 Mg/ha (0.55 Mg/km^2), and dead standing trees are 0.0054 Mg/ha (0.54 Mg/km^2).

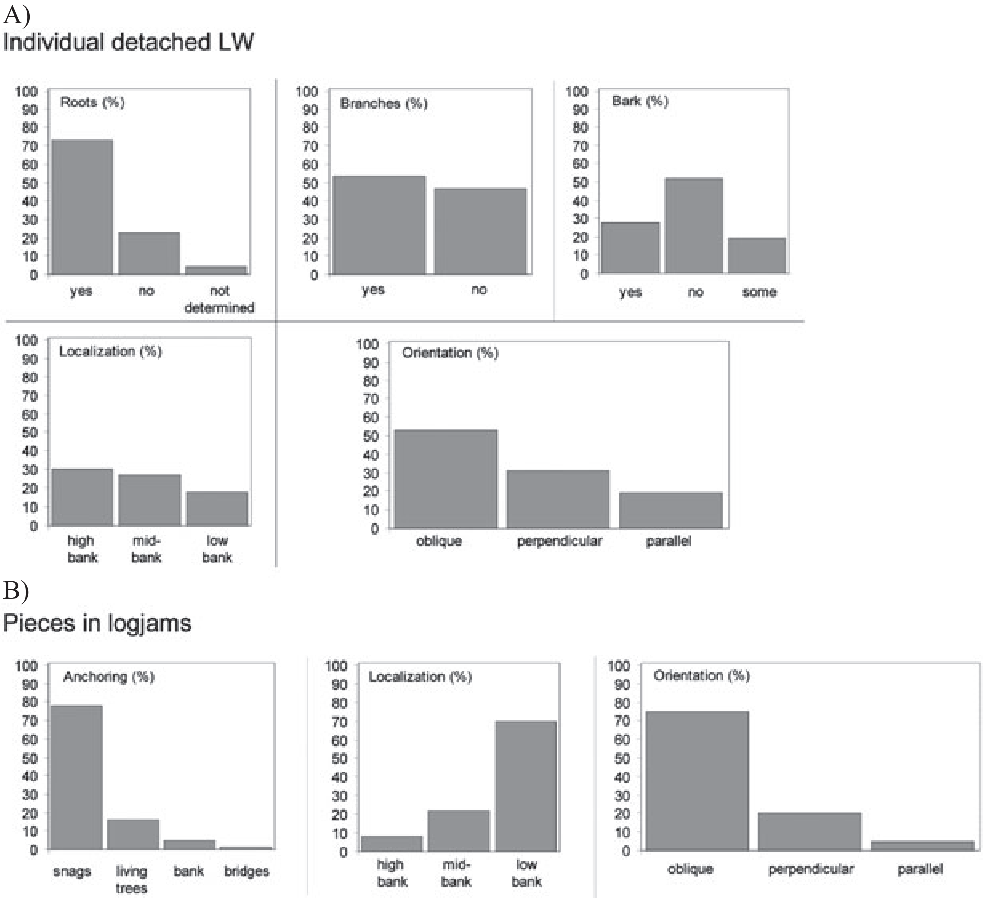

Figure 5. (A) Selected attributes for detached individual LW. The percentage of detached individual LW population that have ('yes') or do not have ('no') roots, branches, and bark are displayed. The percentage of detached individual LW population that reside on the lower, mid, and upper bank at low water (57 m^3/s discharge) and the orientation relative to the channel, are also provided. (B) Selected attributes for log jams, including anchoring type, localization on the bank at low water, and orientation relative to the channel.

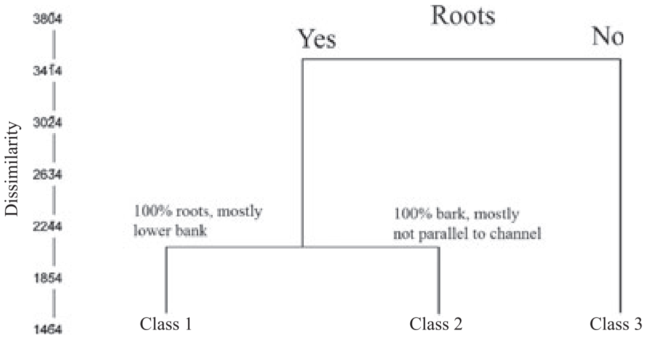

Figure 6. Dendrogram created by the Pettit Test for determining types of detached individual LW. Variables for the cluster analysis included percentage rootball intact (roots), percentage bark intact, branch condition, position on bank, and position relative to channel.

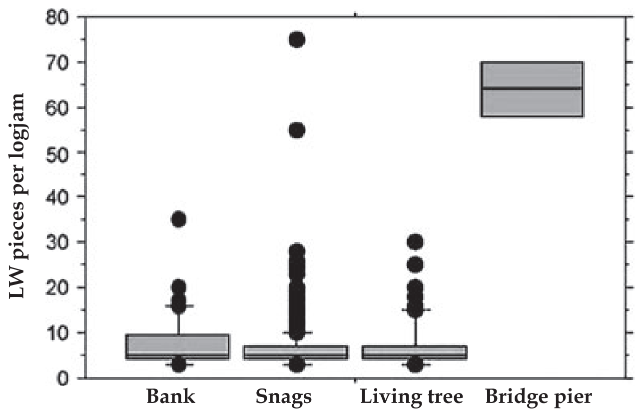

Figure 7. Log jam size (LW in individual log jams) by anchoring type.

Longitudinal distribution of detached LW 0and log jams in comparison with channel geometry

Detached individual LW

The Pettit Test results show five major breaks in longitudinal distribution creating six river reaches for individual LW (Figure 8). There is a significant (Kruskall–Wallis, $P < 0.001$, $n = 150$) difference among the four geomorphic parameters (W: D ratio, bank height, sinuosity, and gradient) and detached individual LW frequency. The six river reaches are also significantly different from each other (Kruskall–Wallis, $P < 0.001$, $n = 150$) in terms of the bank erosion index.

In general, reaches 1, 2, and 3 are characterized by a straight channel, with high banks and a high *W*:*D* ratio. Detached LW frequency of these three reaches represent 19% of the entire individual LW population, with a concentration ranging from 51.5 pieces/km for reach 1, 34.8 pieces/km for reach 2, and 22.35 pieces/km for reach 3. The three reaches are dominated by fluvial erosion (particle-by-particle erosion) with areas with little erosion. Mass wasting is uncommon in these upstream reaches (Figure 8).

Channel gradient and sinuosity on reach 4 are markedly higher and more consistent than upstream reaches; the *W*:*D* ratio and bank height decreases. The range of bank erosion

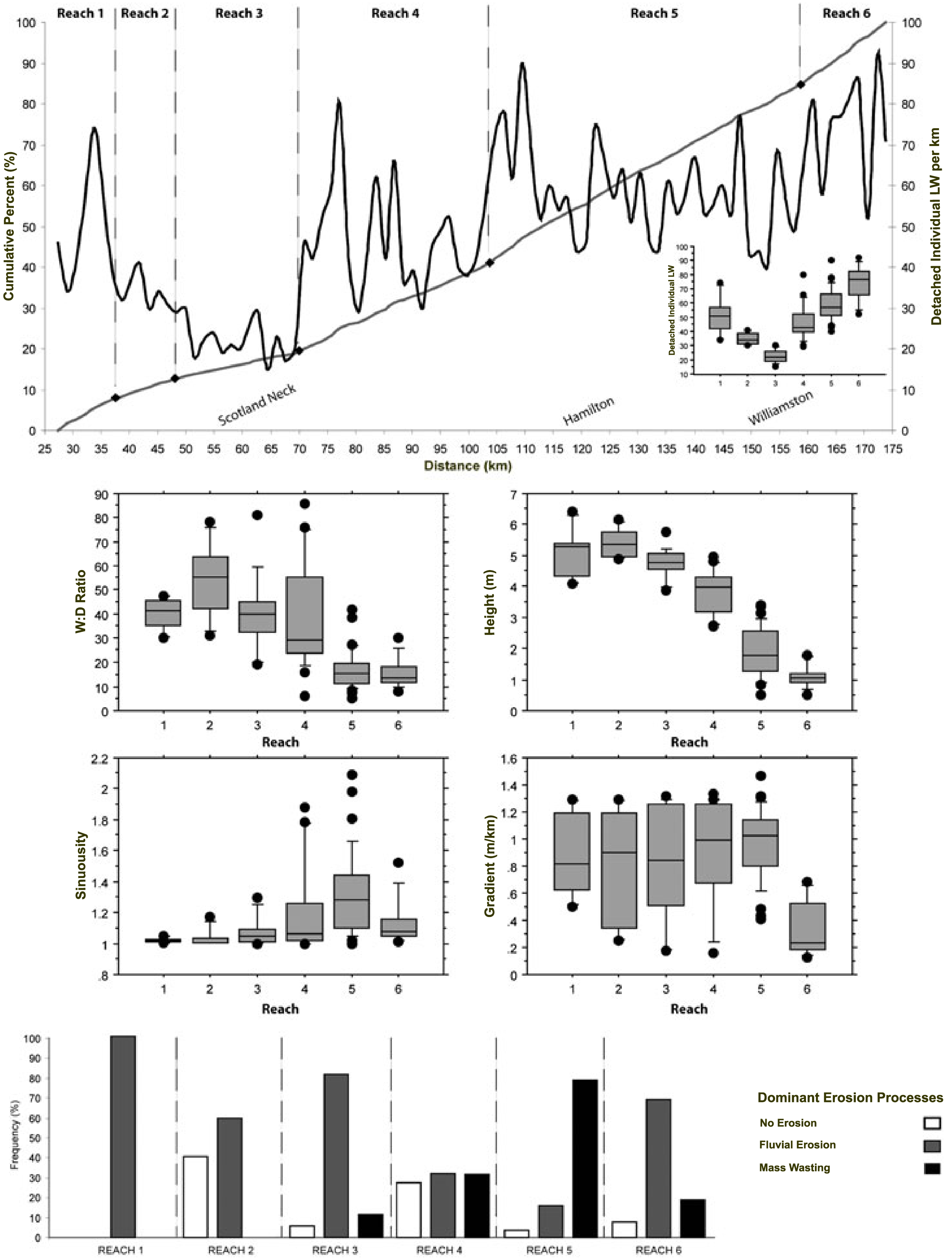

Figure 8. Distribution of individual detached LW by river km, and by statistically determined river reach using the Pettit Test. The solid gray line is the cumulative percentage of detached individual LW, the solid black line is the LW concentration. Geomorphic information, in terms of *W*:*D* ratio, bank height (m), sinuosity, and channel gradient, are provided as boxplots separated by statistical reach (resolution = 1 measurement/1.6 river km). Bank erosion index developed to measure mass wasting. A higher index value indicates a greater frequency of mass wasting. Detailed methods of both fluvial erosion monitoring and the bank erosion index are provided in Hupp *et al.* (2009).

index values is large; zero erosion (30% of the sample), 35% with fluvial erosion, and 35% with mass wasting. The detached LW frequency increases compared with upstream reaches with 20.5% of the reach having a concentration of 46.8 pieces/km.

Sinuosity and gradient are highest in reach 5. *W*:*D* ratios and bank heights are generally low and variable. Within this reach the frequency of detached LW is high, 44.5%, with a concentration of 58.34 pieces/km and nearly half of the total LW population. Mass wasting is dominant occurring in about 80% of the reach.

The furthest downstream reach, reach 6, is characterized by the lowest *W*:*D* ratio, bank height, sinuosity, and gradient. Detached LW frequency is 16%, but the concentration is the highest of any of the reaches: 74.1 pieces/km. Fluvial erosion is the dominant erosional process.

Results indicate that reductions in *W*:*D* ratio and bank height associated with increases in sinuosity and channel gradient create conditions that promote a high frequency of detached individual LW. Concentrations of LW may increase with diversity of erosion processes and especially mass wasting. Only along reach 6, near the Albemarle Sound and sea level, are LW concentrations high (long-term accumulation) and variation in sinuosity and channel gradient low.

Log jams

The statistical segmentation results identified three major breaks in log jam distribution creating four distinct river segments (Figure 9). These breaks are different from the ones for the detached individual LW owing to the difference in longitudinal distribution of LW for the two groups. There is a significant difference (Kruskall–Wallis, $P<0.001$, $n=150$) among the four geomorphic parameters (*W*:*D* ratio, bank height, sinuosity, and gradient) and log jam frequency for each reach. There is also a significant difference (Kruskall–Wallis, $P<0.001$, $n=150$) between each reach in terms of log jam frequency and the bank erosion index.

The characteristics of the furthest upstream reach are nearly identical to that of the first three detached individual LW reaches. The upstream log jam reach consists of a relatively straight channel with high banks, variable gradient, and a high *W*:*D* ratio. Log jam frequency is 11.5% of the entire LW population; with the lowest concentration of any of the reaches at 2.2 log jams/km. Fluvial erosion is the dominant bank erosion process. The second reach has a lower *W*:*D* ratio, bank heights, and greater variability in log jam distribution than the first reach. Gradient is higher than in reach 1 and bank erosion is characterized mostly by mass wasting processes. Log jam frequency is 26% of the entire population with a concentration of 9.95 log jams/km. The third reach is characterized by a narrowing channel with low bank heights. The gradient is the highest of all reaches, as is sinuosity, with meanders occurring frequently and consistently. Log jams make up 46.5% of the LW frequency with a concentration of 21.5 log jams/km. Mass wasting is the dominant bank erosion process (80%). The furthest downstream reach, reach 4, is significantly different from the upstream reaches owing to its sea level elevation and wind tide processes. Channel morphology is characterized by the lack of a defined bank, low gradient, low sinuosity, and low *W*:*D* ratios. Log jams make up 16% of the entire LW population with a low concentration of 9.92 log jams/km. Fluvial erosion is dominant in this reach. Thus, an increase in log jam concentrations may be associated with decreases in *W*:*D* ratio and bank height that occur with increases in sinuosity and channel gradient. Log jam concentration is also the highest where bank mass wasting is dominant.

Comparison of log jam distribution to log jam size and snag distribution

The four largest log jams occurred between river km 70 and 115 (log jam reaches 1 and 2). Two of the log jams were caused by a bridge crossing where there is an accumulation between a bridge pier and the bank, and another on a sand bar formed immediately downstream from the eddies created by the upstream log jam. The other two large jams were located near each other and located at or near meander bends. These jams are large (mean 64.5 pieces/jam, std. dev. 9.5), especially compared with the 10 next largest jams (mean 27.6 pieces/jam, std. dev. 3.6). Nine of the 10 next largest jams are clustered in a sinuous reach extending from river km 133 to 157 (mostly in log jam reach 3 with one jam in reach 4). We also determined a significant relationship between log jam concentration and the amount of wood trapped in jams by km (a function of log jam size; ANOVA, $P<0.001$, $n=200$). Thirteen of the 14 largest jams are located in or near mean low-water, indicating that they are readily available as aquatic habitat, have an influence on channel hydraulics, even at low flow, and are readily available as a source of LW for downstream transport.

Log jam concentration is correlated with the presence and concentration of snags by river km (ANOVA, $P<0.001$, $n=200$). However, the reach with the highest concentration of snags (log jam reach 4) does not have the highest concentration of log jams (Figure 10).

Discussion

The lower Roanoke River contains the largest contiguous hardwood forest on the eastern coast of the USA. LW from the majority of this forested wetland is unavailable for transport and deposition in the active channel due to the extent of the floodplain (usually several kilometers wide) relative to channel size and also human modifications to the landscape. Dam regulation prevents large floods with significant flow over the levees. Moderate floods enter the floodplain through levee cuts and crevasses providing only localized access for LW to enter the channel from the interior areas during flow recession. The landscape has also been altered by floodplain deposition of several meters of post-colonial legacy sediment from upstream agricultural erosion primarily in the 18th and 19th centuries. This sediment has created abnormally high banks in the upstream section of the study area that attenuate downstream toward the Albemarle Sound (Hupp *et al*., 2009). Both human modifications, dams and the legacy of European colonization, negatively impact the amount of wood available to the system. The modifications should not, however, be seen as unique to the Roanoke River as dams and legacy sediment occur on most large eastern US rivers.

Present and future LW spatial frequency

Results along 177 river km provide an unprecedented view of LW characteristics and distribution on large coastal plain rivers of the eastern USA. The LW population is dominated by available for transport material, either in the form of log jams or detached individual LW. Over 75% of the population is available for transport with the remainder consisting of future recruitment as either snags or dead standing trees. This is similar to the results of a previous study on the gravel bed Drôme River in France, where the ratio of in-channel LW was 1.3 to 3.1 times greater than the annual recruitment of new LW (Piégay *et al*., 1999). Approximately 73% of the LW still retains roots, indicating that the majority of the LW available for transport is produced by bank erosion rather than logging or fragmentation from decay. The amount of wood stored as either types of LW available for transport is approximately equal to only 18% of the total detached individual LW located near or at the low-water level, while the majority of log jams were either at water level or low on the bank. Log jams appear to be more important than detached individual LW in terms of both aquatic habitat and risks for human activities.

LW lifecycle and residence time

Biomorphological characteristics of LW, such as the bark, branch, and rootball condition can provide hints to the history

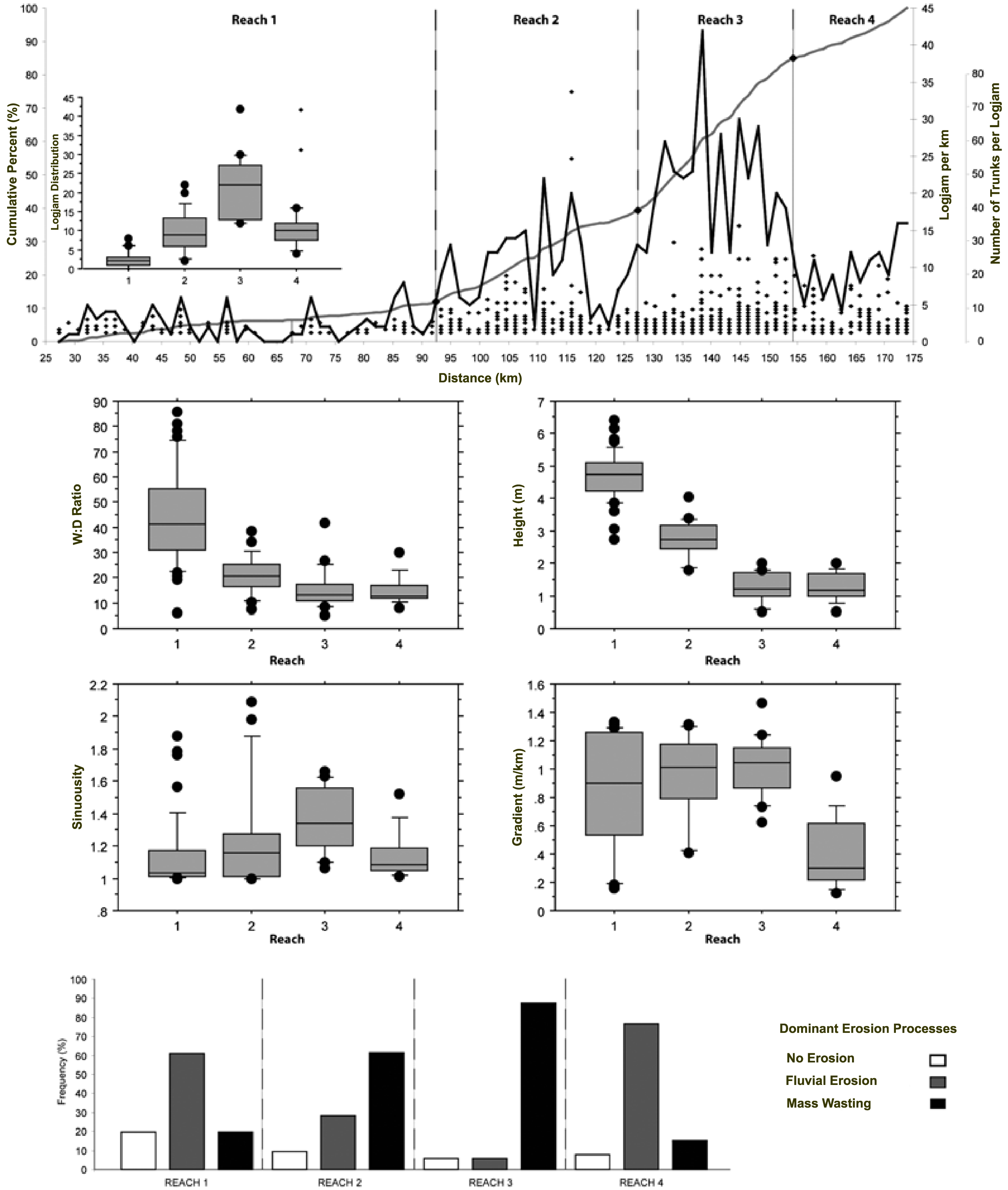

Figure 9. Distribution of log jams by river kms, and by statistically determined river reach using the Pettit Test. The solid gray line is the cumulative percent of log jams, the solid black line is the concentration of log jams, and the black points represent LW in individual log jams. Geomorphic information, in terms of *W*:*D* ratio, bank height (m), sinuosity, and channel gradient, are provided as boxplots separated by statistical reach (resolution = 1 measurement/1.6 river km. Bank erosion index developed to measure mass wasting. A higher index value indicates a greater frequency of mass wasting. Detailed methods of both fluvial erosion monitoring and the bank erosion index are provided in Hupp *et al.* (2009).

of individual pieces of LW. Wood that still retains fragments of bark, branches, and their roots indicate that the tree entered the channel in its entirety instead of as a fragment from *in situ* decay. LW decay can then progress either biologically or physically from the abrasive effect of in-channel transport. Physical abrasion becomes less of a factor as the river increases in width and depth Piégay (2003). The state of decay and the morphology of LW on the Roanoke River confirm Piégay's observations and suggest a low rate of movement and a high residence time. Most of the bank erosion derived LW is in an advanced state of decay with no bark (class 1, 55%), whereas some (class 2, 15%) are probably new recruitment with half of the wood also orientated perpendicular to the bank. Only 23% of the detached individual LW was produced by mechanisms other than bank erosion (class 3, detached LW). Classes 2 and 3 are situated on the mid and upper banks and probably either

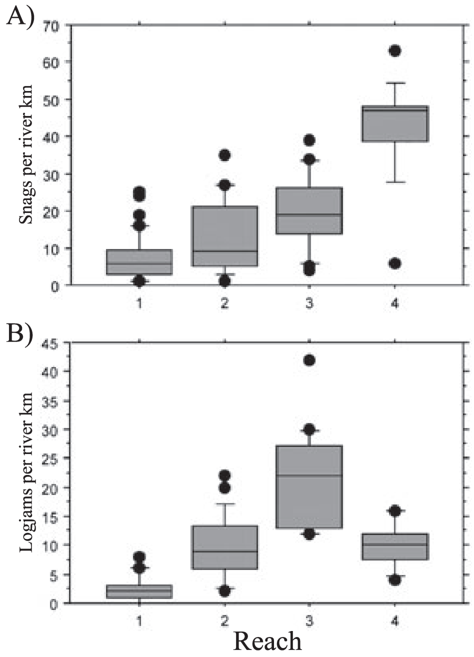

Figure 10. (0A) Snag distribution by Pettit Test derived homogeneous reach determined for log jams frequency. (B) Log jam distribution by homogeneous reach.

rarely or never moved during floods. Degradation is a function of a long residence time and short travel time. The majority of the individual LW (73.5%) have rootballs positioned upstream indicating that they pivoted during high flow and had a short travel time (Braudrick *et al.*, 1997; Braudrick and Grant, 2001). This is similar to a previous study on the lowland Thompson River in Australia where 83% of the detached LW had rootballs oriented upstream (Gippel *et al.*, 1994). The state of decay displayed through the condition of the bark and branches, indicates a long residence time for the majority of the individual LW. Qualitatively, many of the individual LW measured in the field were in an advanced state of decay with some form of root structure or branches, indicating that they probably have not been transported far from their initial point of entry.

The large amount of decayed and transported LW on the Roanoke River indicates a long residence time. A qualitative assessment of individual LW from field reconnaissance confirms that the overwhelming majority of the LW is in an advanced state of decay. Much of the floating LW found during flood events was also highly decayed; not only is LW recruitment slow, and residence times long, but newly recruited LW may remain on the bank until partially decayed before having the proper buoyancy to be transported in this dam regulated system. The long residence time is probably due to the dam regulation limiting high flows and providing consistent flood events of limited duration and magnitude. LW recruitment was probably higher before dam regulation, while residence time may have been lower.

LW abundance and biomass

The Roanoke River has a low amount of LW compared with the mean abundance found in other LW studies (Table II). Our results fall in the lower range given by Cordova *et al.* (2007) for eastern streams, but similar to 15 low-gradient streams draining previously logged watersheds in the Upper Peninsula of Michigan, with a stream bankfull width that ranged from 2–12 m. The Roanoke River may appear to have less LW than other studies due to differences in the lower detection limit for LW. We focused on LW larger than 3 m length and 0.2 m diameter whereas some of the field based studies were able to detect LW as small as 1 m length and 0.1 m diameter. Despite the differences in study design, large rivers like the Roanoke generally produce relatively small amounts of LW relative to discharge and associated channel width.

The lower Roanoke River also contains relatively low amounts of LW biomass in comparison wuith other rivers. Bilby (1984) has shown that watershed size is not a good indicator of LW biomass. The lower Roanoke River is affected by dams that effectively cut off LW available for transport from the upstream watershed. Flow regulation further reduces in-channel LW by limiting the frequency and magnitude of flooding that may transport wood from interior floodplain locations.

Unfortunately, the majority of LW studies report abundance in terms of watershed area instead of concentration per river km, making it difficult to compare our results on a flow-regulated system with more natural systems, or high-gradient systems with much smaller watersheds. The fate of most interior floodplain wood appears to be decomposition and fragmentation, rather than exportation to the river channel. Biomass and abundance is thus negatively affected by the upstream dam. All or most of the LW observed in this analysis originated from banks or floodplain surfaces adjacent to the channel; there is no possibility of upstream inputs. Regardless, the abundance and stability of woody debris in the main channel provides aquatic habitat for both riverine invertebrates and fishes.

LW longitudinal distribution patterns

Our results suggest that snags play a significant role in trapping LW and creating log jams (Figure 10). The size of individual log jams increases as the concentration of log jams increases; the third log jam river reach (Figure 10), therefore, has the highest trapping efficiency. Trapping efficiency is determined partly by snag density, but also local wood recruitment rates, distance from dominant wood recruitment zones, and bank roughness. Our results suggest that bank roughness in fine-grained river systems, such as the Roanoke River, is determined by bank snag concentration, existing LW accumulation, and channel geometry. Geometry variables include channel sinuosity, width, gradient, and bank height. The hydrologic regime of the system, including flood frequency and intensity can influence the importance of channel geometry on LW distribution.

River reach 3 (Figure 9), for log jams, had the highest concentration of jams and the greatest bank roughness. Bank roughness was high, as defined by a narrow channel, and high sinuosity, gradient, and snag densities. Bank height also contributed to roughness, the lower banks in reach 3 allow flow in the channel to come into contact with woody features of the riparian forest (rootballs, fallen branches, shrubs) that may increase trapping efficiency. The reach is actively eroding, as indicated by a high bank-erosion index and a high concentration of recent mass wasting events including rotational failures (Figure 9). High rates of bank erosion may substantially affect LW recruitment and local distribution. Upstream reaches have higher banks isolating the flow to relatively low on the bank slopes and away from the riparian forest, whereas the lowermost reaches have low to no banks and large mudflats. During low flow most roughness is derived from the mudflat itself, during a high flow event with high tides the trees at the bottomland swamp edge may trap LW, especially where mudflats are limited.

Table II. Large wood (LW) abundance and concentrations by site, watershed size, and stream order

Reference	Site	Watershed (km^2)	Stream order	Biomass Mg/ha	LW (pieces/ river km)
Cordova *et al.*, 2007	USA, Michigan	NA	NA		98.4
Cordova *et al.*, 2007	USA, headwaters				
	pacific NW	NA	NA		362
	midwestern	NA	NA		362
	eastern	NA	NA		61 – 131
Bryant, 1983	USA, Alaska	-	1–2	15 – 582	
Keller and MacDonald, 1995	USA, California, Redwood Creek	0.7 – 27.2	2–4	125 – 2180	
Comiti *et al.*, 2006	Italy, Dolomites	2.2 – 51	NA		130 – 320
Richmond and Faush, 1995	USA, Colorado	2.4 – 29.1	1–3	46 – 127	
Lisle, 1995	USA, Washington	9.3 – 32.7	NA	140 – 325	
Magilligan *et al.*, 2008	USA, Maine	20 – 280		5 – 10	15 – 50
Baillie *et al.*, 2008	New Zealand Whirinaki River	73	4	106	660
Hauer, 1989	USA, Meyer Creek GA	91	NA	55	
Marcus *et al.*, 2002	USA, Yellowstone	NA	2–6		6.8 – 209
Hedman *et al.*, 1996	USA, Appalachian streams	NA	3–4	45 – 130	
Chen *et al.*, 2006	USA, British Columbia	675 – 1162	NA	2.65 – 6.51	
Shield and Smith, 1992	USA, Tennessee	927	NA	215 – 470	35 – 58
			NA	45 – 165	6 – 58
Keller and Swanson, 1979	USA, Mc Kenzie River,	1024	NA	6	
Piégay *et al.*, 1999	France, Drôme River	1620	NA	8 – 32	
Gurnell *et al.*, 2000	Italy, Tagliamento, open gravel surface	2500	NA	1 – 21	
	islands		NA	24 – 186	
	pioneer islands		NA	293 – 1664	
Van der Nat *et al.*, 2003	Italy, Tagliamento,	2500	NA	43 – 121	
This study	USA Roanoke River, all LW	2747		0.0415	158.2
	Wood in log jams			0.016	59.6
	Detached individual LW			0.0146	55.4
Gippel *et al.*, 1996	Australia, Thompson River	3540	NA	86	
Piégay and Marston, 1988	France, Ain River	3630	NA	16 to 19	
Wallace and Benke, 1984	USA, Ogeechee R, GA	7000	NA	90 to 110	148
Curran, 2010	USA, San Antonio R., TX	5473	NA		1.0–2.1 jams/km
Angradi *et al.*, 2010	USA, Mississippi R., Missouri R., and Ohio R.	0.49, 1.37, 0.53 million	10, 9, 9		42 to 52

LW recruitment is low in the furthest downstream reaches where there are low or non-existent banks that are separated from the active channel by mudflats. A conceptual river evolution model (Simon and Hupp, 1992) for the Roanoke River (Hupp *et al.*, 2009) predicts our result of low amounts of bank erosion downstream as sites approach sea level and are increasingly distant from the attenuating impacts of the upstream dam. However, adjustment to dam regulation as evidenced by high rates of mass wasting (bank destabilization) continues presently in the middle reaches of the river (Hupp *et al.*, 2009). Banks are least stable in the presence of mass wasting in response to high bank heights and steep bank-slope angles that develop during channel incision (in this case following legacy colonial-era sedimentation and dam operations). Ultimately, mass wasting returns the banks toward a dynamic equilibrium after the hydrologic regime shift associated with channel incision and subsequent recovery (Hupp, 1992; Simon and Hupp, 1992). Mass wasting loads the river not only with sediment, but with large wood from the riparian zone that is carried down into the channel with the failed bank material (Hupp, 1992; Piégay, 2003). Along the lower Roanoke River, changes in channel geometry downstream (no/low banks), woody riparian species (fringing bottomland hardwoods to bald cypress/tupelo gum swamp forest), and recruitment may explain the decrease in log jam LW storage and abundance, even though downstream high snag concentrations could act as a trapping mechanism. The downstream-most reaches may function as a final resting place for LW, because of shallow near-bank conditions and a general lack of stream competence that impedes further LW transport.

Results are consistent with the observation that some river systems are composed of a mosaic of functional units rather than a gradient of gradually changing conditions from small to larger streams, as shown by Golladay *et al.* (2007). Local geomorphic patterns may largely control the trapping efficiency and LW recruitment within specific reaches (Wallerstein and Thorne, 2004). The high concentration of LW between Hamilton and Williamston, NC (Figure 3) corresponds to the actively migrating (upstream to downstream) channel degradation detailed in Hupp *et al.* (2009). Future LW distributions will likely follow the bank erosion impetus downstream, with higher LW concentrations occurring in the areas with the most active channel widening.

Worldwide, LW distribution patterns differ by channel type (braided, meandering, etc.) and in this case, on an incised sand-bed river (Piégay, 2003). Channel pattern and dynamics determine LW storage and recruitment (Lassettre *et al.*, 2007) in a sand bed river like Roanoke. Snags also play a large role in LW dynamics, especially log jam distribution. Snags provide an anchoring point for log jams that consequently simultaneously facilitate LW trapping, and provide a source for individual LW; a process that appears fundamental in sand-bed systems (Piégay, 2003).

Individual LW distribution appears to be controlled by flow velocity and flood hydroperiod. Our results are similar to those of Gippel *et al.* (1994) where they demonstrated that along low-gradient rivers flow velocity is not sufficiently high to dislodge and transport individual LW. Floods are also controlled and of short duration. Individual LW is therefore randomly, or nearly randomly, distributed along the longitudinal profile and is often stored on the bank, confirming our result that suggests many of the individual LW fragments are of local origin. The other component of LW available for transport, log jams, likely represents the majority of the actively transported LW on the river due to the impact of dam regulation on individual LW.

These results show that log jams account for approximately half of the LW available for transport on the Roanoke River. Previous research indicates that the relative occurrence of wood accumulation decreases as the river becomes larger (Bilby, 1984); however, the overall volume of wood increases (Montgomery *et al.*, 2003). Log jam concentration on the Roanoke River is variable throughout the river with increasing presence in the middle and downstream reaches, as previously noted; however, the size of the log jams remains relatively constant. This trend is counter to the results of both Montgomery *et al.* (2003) and Bilby (1984) for other low-gradient rivers. The largest jams on the Roanoke River occur on bridge pilings, suggesting that persistent hard points within the channel, on an otherwise relatively soft substrate system, serve as long-term LW collection points.

We have shown that LW distribution and dynamics are controlled by a mosaic of factors ranging from the geomorphic features/processes defined by longitudinal channel evolution following dam regulation (Hupp, *et al.*, 2009) to the dam-regulated hydrological regime itself. Cumulative processes such as snag and log jam concentrations, while also a result of geomorphic and hydrological factors, may synergistically act as factors themselves for LW accumulation. Ultimately the upstream dam operations may control LW dynamics, by creating the current hydrological regime and thus modifying geomorphic parameters, including the lack of bank complexity due to uniform high and low flows (decreasing LW accumulation, Gurnell, 2003) and the high rates of mass wasting (increasing LW loading and accumulation). Flow regulation, and the attenuation of flood peaks in particular, directly modifies the river's capacity to mobilize, transport, and trap LW (Gurnell, 2003), including decreasing the power to laterally transport wood into and out of the adjacent floodplain (Benke and Wallace, 1989, 2003).

Conclusion

The study of in-channel LW has accelerated in the last three decades, expanding beyond original research in the Pacific North-west to encompass rivers and streams throughout the world. Our study is one of the first on a low-gradient, large river in the eastern USA. The aerial census of 177 river kms of the dam-regulated lower Roanoke River allowed us to study the entire population of LW on the north shore. With a concentration of 55 individual LW per river km and 60 pieces of LW in log jams per river km, the river has a higher concentration of LW than mid-continent large rivers, but a lower concentration than smaller high gradient streams.

The majority (>70%) of the LW on the river was produced by bank erosion. Individual LW appears to be mostly pieces that have not moved at high flows. This is indicated by their position high on the bank (only 18% near the water at mean low water levels) and their seemingly random longitudinal distribution. Slightly more than half of the individuals are decayed or weathered with no remaining bark, indicating long residence times and low transport rate. Conversely, 52% of the LW available for transport is stored in log jams.

Log jams as a product of transport are often found in or near the water making them excellent aquatic habitat and providing bank roughness in an otherwise largely homogenous fine-grained channel. We found the majority of the log jams in areas of high trapping efficiency, that is, areas with high snag densities, bank roughness, and local wood recruitment rates. Bank roughness was highest where the river was narrowest, had high sinuosity, relatively high snag density, and low to intermediate bank heights. Low bank heights allow for greater interaction between the channel and the floodplain forest at high flows, leading to a high trapping efficiency. Log jam frequency decreased along the downstream-most reaches, despite an increase in snag density. We attribute the decrease in log jam concentration to the lack of bank development, a decrease in stream competence as the river reaches sea level, and the existence of extensive mudflats isolating the floodplain forest from the active channel.

Substantial LW occurs on the low-gradient, dam-regulated river, providing aquatic habitat and risks to human interests primarily in the form of log jams. Generally, individual LW is unavailable as habitat or as a human risk, owing to its common location high on the bank and related lack of transport. Ongoing research on the Roanoke River is focused on the determination of transport sources, catalysts, and dynamics using radio tags on a small sample (< 300) of both individual and log jam LW.

Acknowledgements—We would like to thank Cary Gordon and Bridget Lins for their months of work reviewing video and creating the LW database. We also thank Jean Richter (USFWS) for her invaluable support both in the office and the field. The manuscript was greatly improved with the thoughtful reviews of Herve Piégay, Katherine Skalak, and anonymous reviewers on behalf of the journal. Funding for this project was provided by the US Geological Survey and the US Fish and Wildlife Service.

References

Abbe TB, Montgomery DR. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers Research and Management* **12**: 201–221.

Angradi TR, Taylor DL, Jicha TM, Bolgrien DW, Pearson MS, Hill BH. 2010. Littoral and shoreline wood in mid-continent great rivers (USA). *River Research and Applications* **26**: 261–278.

Baillie BR, Garret LG, Evanson AW. 2008. Spatial distribution and influence of LWD in an old-growth forest river system, New Zealand. *Forest Ecology and Management* **256**: 20–27.

Benke AC, Wallace JB. 1989. Wood dynamics in the coastal plain blackwater streams. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 92–99.

Benke AC, Wallace JB. 2003. Influence of wood on invertebrate communities in streams and rivers. *American Fisheries Society Symposium* **37**: 149–177.

Bilby RE. 1984. Removal of organic debris may affect stream channel stability. *Journal of Forestry* **82**: 609–613.

Bilby RE. 2003. Decomposition and nutrient dynamics of wood in streams and rivers. *American Fisheries Society Symposium* **37**: 135–147.

Bilby RE, Ward JW. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* **118**(4): 368–378.

Bilby RE, Ward JW. 1991. Characteristics and function of LWD in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences* **48**: 2499–2508.

Bisson PA, Bilby RE, Bryant MD, Dolloff CA, Grette GB, House RA, Murphy ML, Kosky KV, Sedell JR. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present and future. In *Streamside Management: Forestry and Fishery Interactions*, Salo EO, Cundy TW (eds). College of Forest Resources: University of Washington, Seattle; 143–190.

Bisson PA, Wondzell SM, Reeves GH, Gregory SV. 2003. Trends in using wood to restore aquatic habitats and fish communities in Western North American rivers. *American Fisheries Society Symposium* **37**: 391–406.

Braudrick CA, Grant GE. 2001. Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology* **41**(4): 263–283.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: A flume experiment. *Earth Surface Processes and Landforms* **22**(7): 669–683.

Bryant MD. 1983. The role and management of woody debris in west coast salmonid nursery stream. *North American Journal of Fishery Management* **3**(3): 322–330.

Chen XY, Wei XH, Scherer R, Luider C, Darlington W. 2006. A watershed scale assessment of in-stream large woody debris patterns in the southern interior of British Columbia. *Forest Ecology and Management* **229**: 50–62.

Comiti F, Andreoli A, Lenzi MA, Mao L. 2006. Spatial density and characteristics of woody debris in five mountain rivers of the Dolomites (Italian Alps). *Geomorphology* **78**(1-2): 44–63.

Cordova JM, Rosi-Marshall EJ, Yamamuro AM, Lamberti GA. 2007. Quantity, controls and function of LWD in Midwestern USA streams. *River Research Applications* **23**: 21–33.

Curran JC. 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology* **116**(3-4): 320–329.

Daniels MD. 2006. Distribution and dynamics of LWD and organic matter in a low-energy meandering stream. *Geomorphology* **77**: 286–298.

Diehl TH. 1997. Potential drift accumulations at bridges. US Department of Transportation, Federal Highway Transportation, FHWA-RD-97-028.

Dollof CA, Warren ML Jr. 2003. Fish relationships with large wood in small streams. *American Fisheries Society Symposium* **37**: 179–193.

Fetherson KL, Naiman RJ, Bilby RE. 1995. Large woody debris, physical process, and riparian forest development in montane river network of the Pacific Northwest. *Geomorphology* **13**: 133–144.

Gippel CJ. 1995. Environmental hydraulics of large woody debris in streams and rivers. *Journal of Environmental Engineering* **121**(5): 388–395.

Gippel CJ, Finlayson BL, O'Neil IC. 1996. Distribution and hydraulic significance of large woody debris in a lowland Australian rivers. *Hydrobiologia* **318**: 179–194.

Gippel CJ, O'Neil IC, Finlayson BL, Schnatz I. 1994. Hydraulic guidelines for the reintroduction and management of LWD in degraded lowland rivers. In *N.I.O.T SINTHEF-NHL, 1st International Symposium on Habitat Hydraulics*. The Norwegian Institute of Technology, Trondheim, Norway; 225–238.

Golladay SW, Battle JM, Palik BJ. 2007. Large wood debris recruitment on differing riparian landforms along a gulf Coastal Plain (USA) stream: a comparison of large floods and average flows. *River Research and Applications* **23**(4): 391–405.

Gregory KJ, Davis RJ. 1993. The perception of riverscape aesthetics an example from two Hampshire rivers. *Journal of Environmental Management* **39**: 171–185.

Gregory SV, Boyer KL, Gurnell AM (eds). 2003. The ecology and management of wood in world rivers. *American Fisheries Society Symposium* **37**: 431.

Gurnell AM. 2003. Wood storage and mobility. *American Fisheries Society Symposium* **37**: 75–91.

Gurnell AM, Petts GE, Harris N, Ward JV, Tockner K, Edwards PJ, Kollman J. 2000. Large wood retention in river channels: the case of the Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms* **25**: 255–275.

Gurnell AM, Piegay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47**: 601–619.

Gurnell AM, Sweet R. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* **23**(12): 1101–1121.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. In *Advances in Ecological Research*, MacFadayen A, Ford ED (eds). Academic Press: London; 133–302.

Hauer FR. 1989. Organic matter transport and retention in a blackwater stream recovering from flow augmentation and thermal discharge. *Regulated Rivers: Research and Management* **4**: 371–380.

Hedman CW, Van Lear DH, Swank WT. 1996. In-stream LWD loading and riparian forest serial stage associations in the southern Appalachian Mountains. *Canadian Journal of Forest Research* **26**(7): 1218–1227.

Hogan DL. 1986. Channel morphology of unlogged, logged and debris torrented streams in the Queen Charlotte Islands. British Columbia Ministry of Forests and Lands. *Land Management Report* **49**: 94.

Hupp CR. 1992. Riparian vegetation recovery patterns following stream channelization: a geomorphic perspective. *Ecology* **73**: 1209–1226.

Hupp CR. 2000. Hydrology, geomorphology and vegetation of Coastal Plain rivers in the south-eastern USA. *Hydrological Processes* **14**(16-17): 2991–2301.

Hupp CR, Schenk ER, Richter JM, Peet RK, Townsend PA. 2009. Bank erosion along the dam-regulated lower Roanoke River, North Carolina. In *Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts*, James LA, Rathburn SL, Whittecar GR (eds). Geological Society of America Special Paper 451; 97–108.

Hygelund B, Manga M. 2003. Field measurements of drag coefficients for model LWD. *Geomorphology* **51**(3): 175–185.

Keller EA, MacDonald A. 1995. River channel change: the role of large woody debris. In *Changing River Channels*, Gurnell A, Petts G (eds). John Wiley and Sons, Chichester; 217–235.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* **4**(4): 361–380.

Kothyari UC, Ranga Raju KG. 2001. Scour around spur dikes and bridge abutments. *Journal of Hydraulic Research* **39**(4): 367–374.

Lassettre N, Piégay H, Dufour S, Rollet AJ. 2007. Decadal changes in distribution and frequency of wood in a free meandering river, the Ain River, France. *Earth Surface Processes and Landforms* **33**(7): 1098 – 1112.

Lienkaemper GW, Swanson FJ. 1987. Dynamics of large woody debris in streams in old-growth douglas-fir forests. *Canadian Journal of Forest Research* **17**(2): 150–156.

Likens GE, Bilby RE. 1982. Development, maintenance, and role of organic debris dams in New England streams, USDA Forest Service, General Technical Report PNW-GTR 141.

Lisle TE. 1995. Effects of CWD and its removal on a channel affected by the 1980 eruption of Mount St Helen, Washington. *Water Resources Research* **31**: 1791–1808.

MacVicar BJ, Piégay H, Henderson A, Comiti F, Oberlin C, Pecorari E. 2009. Quantifying the temporal dynamics of wood in large rivers: field trials of wood surveying, dating, tracking and monitoring techniques. *Earth Surface Processes and Landforms* **34**: 2031–2046.

Magilligan FJ, Nislow KH, Fisher GB, Wright J, Mackey G, Laser M. 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology* **97**(3-4): 467–482.

Manners RB, Doyle MW, Small MJ. 2007. Structure and hydraulics of natural woody debris jams. *Water Resources Research* **43**: 1–17.

Marcus WA, Marston RA, Colvard CR, Gray RD. 2002. Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology* **44**: 323–335.

Maridet L. 1994. La végétation rivulaire, facteur de contrôle du fonctionnement écologique des cours d'eau : influence sur les communautés benthiques et hyporhéiques et sur les peuplements de poissons dans trois cours d'eau du Massif Central. Thèse de doctorat, CEMAGREF, Div. Bio. Des Ecosystèmes Aquatiques, Université Lyon I.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. *American Fisheries Society Symposium* **37**: 21–47.

Mosley MP. 1981. The influence of organic debris on a channel morphology and bedload transport in a New Zealand forest stream. *Earth Surface Processes and Landforms* **6**: 571–579.

Moulin B, Piegay H. 2004. Characteristics and temporal variability of large woody debris trapped in a reservoir on the River Rhone

(Rhone): implications for river basin management. *River Research and Applications* **20**: 79–97.

Nakamura F, Swanson FJ. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. *Earth Surface Processes and Landforms* **18**(1): 43–61.

Pettit AN. 1979. A non-parametric approach to the change-point problem. *Applied Statistics* **28**: 126–135.

Pettit NE, Naiman RJ, Rogers KH, Little JE. 2004. Post-flooding distribution and characteristics of large woody debris piles along the semi-arid Sabie River, South Africa. *River Research and Applications* **20**: 1–12.

Piégay H. 2003. Dynamics of wood in large rivers. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). *American Fisheries Society Symposium* **37**: 109–134.

Piégay H, Gurnell AM. 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology* **19**: 99–116.

Piégay H, Marston RA. 1998. Distribution of coarse woody debris along the concave bank of a meandering river (the Ain river, France). *Physical Geography* **19**(4): 318–340.

Piégay H, Thevenet A, Citterio A. 1999. Input, storage and distribution of LWD along a mountain river continuum, the Drôme river, France. *Catena* **35**: 19–39.

Richmond AD, Faush KD. 1995. Characteristics and function of LWD in subalpine Rocky Mountains streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* **52**: 1789–1802.

Robinson EG, Beschta RL. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 1684–1693.

Sedell JR, Bisson PA, Swanson FJ, Gregory SV. 1988. What we know about large trees that fall into streams and rivers. In *From the Forest to the Sea : a Story of Fallen Trees*, Maser C, Tarrant RF, Trae JM, Franklin JF (eds). USDA Forest Service, General Technical Report PNW-GTR 229.

Shield FD, Smith RH. 1992. Effects of large woody debris removal on physical characteristics of a sand-bed river. *Aquatic Conservation: Marine and Freshwater Ecosystems* **2**: 145–163.

Simon A, Hupp CR. 1992. Geomorphic and vegetative recovery processes along modified stream channels of West Tennessee. US Geological Survey Open-file Report 91-502.

Skalak K, Pizzuto J. 2010. The distribution and residence time of suspended sediment stored within the channel margins of a gravel-bed bedrock river. *Earth Surface Processes and Landforms* **35**(4): 435–446. DOI: 10.1002/esp.1926

Smith LA, Sidle RC, Porter PE, Noël JR. 1993. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel bed stream. *Journal of Hydrobiology* **152**: 153–178.

Smock LA, Metzler GM, Gladden JE. 1989. The role of organic debris dams in the structuring and functioning of low gradient headwater streams. *Ecology* **70**: 764–775.

Steel EA, Richards WH, Kelsy KA. 2003. Wood and wildlife: benefits of river wood to terrestrial and aquatic vertebrates. *American Fisheries Society Symposium* **37**: 235–247.

Swanson FJ, Lienkaemper GW. 1982. Interactions among fluvial processes, forest vegetation and aquatic ecosystems, South Fork Hoh River, Olympic National Park. In *Ecological Research in National Parks of the Pacific Northwest*, Franklin JF, Starkey EE, Matthews JE (eds). Oregon State University; 30–34.

Thevenet A. 1998. Intérêt des débris ligneux grossiers pour les poissons dans les grands cours d'eau, pour une prise en compte de la dimensions écologique des débris ligneux grossiers dans la gestion des cours d'eau. Thèse de doctorat, Université Claude Bernard Lyon I.

Townsend PA. 2001. Mapping seasonal flooding in forested wetlands using multi-temporal Radarsat SAR. *Photogrammetric Engineering and Remote Sensing* **67**: 857–864.

Triska FJ. 1984. Role of woody debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study. *Verhandlung Internationale Vereinigung Limnologie* **22**: 1876–1892.

Van der Nat D, Tockner K, Edwards PJ, Ward JV. 2003. Large wood dynamics of complex Alpine river floodplains. *Journal of the North American Benthological Society* **22**(1): 35–50.

Wallace JB, Benke AC. 1984. Quantification of wood habitat in subtropical coastal plain streams. *Canadian Journal of Fisheries and Aquatic Sciences* **41**: 1643–1652.

Wallerstein NP. 1998. Impact of LWD on fluvial processes and channel geomorphology in unstable sand bed rivers. Unpublished PhD thesis, University of Nottingham, UK.

Wallerstein NP, Thorne CR. 2004. Influence of large woody debris on morphological evolution of incised, sand-bed channels. *Geomorphology* **57**: 53– 73.

Zalewski M, Lapinska M, Bayley PB. 2003. Fish relationships with wood in large rivers. *American Fisheries Society Symposium* **37**: 195–211.