Freshwater Biology (2002) **47**, 601–619

Large wood and fluvial processes

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SUMMARY

1. Large wood forms an important component of woodland river ecosystems. The relationship between large wood and the physical characteristics of river systems varies greatly with changes in the tree species of the marginal woodland, the climatic and hydrological regime, the fluvial geomorphological setting and the river and woodland management context.
2. Research on large wood and fluvial processes over the last 25 years has focussed on three main themes: the effects of wood on flow hydraulics; on the transfer of mineral and organic sediment; and on the geomorphology of river channels.
3. Analogies between wood and mineral sediment transfer processes (supply, mobility and river characteristics that affect retention) are found useful as a framework for synthesising current knowledge on large wood in rivers.
4. An important property of wood is its size when scaled to the size of the river channel. 'Small' channels are defined as those whose width is less than the majority of wood pieces (e.g. width < median wood piece length). 'Medium' channels have widths greater than the size of most wood pieces (e.g. width < upper quartile wood piece length), and 'Large' channels are wider than the length of all of the wood pieces delivered to them.
5. A conceptual framework defined here for evaluating the storage and dynamics of wood in rivers ranks the relative importance of hydrological characteristics (flow regime, sediment transport regime), wood characteristics (piece size, buoyancy, morphological complexity) and geomorphological characteristics (channel width, geomorphological style) in 'Small', 'Medium' and 'Large' rivers.
6. Wood pieces are large in comparison with river size in 'small' rivers, therefore they tend to remain close to where they are delivered to the river and provide important structures in the stream, controlling rather than responding to the hydrological and sediment transfer characteristics of the river.
7. For 'Medium' rivers, the combination of wood length and form becomes critical to the stability of wood within the channel. Wood accumulations form as a result of smaller or more mobile wood pieces accumulating behind key pieces. Wood transport is governed mainly by the flow regime and the buoyancy of the wood. Even quite large wood pieces may require partial burial to give them stability, so enhancing the importance of the sediment transport regime.
8. Wood dynamics in 'Large' rivers vary with the geometry of the channel (slope and channel pattern), which controls the delivery, mobility and breakage of wood, and also the

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characteristics of the riparian zone, from where the greatest volume of wood is introduced. Wood retention depends on the channel pattern and the distribution of flow velocity. A large amount is stored at the channel margins. The greater the contact between the active channel and the forested floodplain and islands, the greater the quantity of wood that is stored.

Keywords: geomorphology, hydraulics, hydrology, large wood, sediment

Introduction

'Driftwood, wood carried by water from the forest to the sea … is both habitat and a source of food for a multitude of plants and animals, both aquatic and terrestrial. In addition, some driftwood controls stream velocities, stabilises stream banks, makes waterfalls and pools, and creates and protects fish spawning areas. Other driftwood protects the encroachment of vegetation on floodplains and allows forests to expand. In short, driftwood makes a vital contribution to the health of streams, rivers, estuaries and oceans …' (Maser & Sedell, 1994, pp. xi).

Research interest in the important role of wood within fluvial systems has developed largely within the last three decades. Before 1975, there was little reference to the subject in the scientific literature (Piégay & Gurnell, 1997), although important early papers relevant to woodland river research included Hack & Goodlett (1960) and Zimmerman, Goodlett & Comer (1967). Over the last 25 years, the role of wood in river ecosystems has become an increasingly important focus for research. This has been particularly true in the Pacific Northwest of the United States and in Alaska, where human impacts are relatively recent and so it has been possible to reconstruct the character of pristine woodland river systems.

Research on large wood and fluvial processes has been concerned with three main themes. The first of these is the impact of wood upon the hydraulics of flows within river channels. Wood pieces act as roughness elements whether they occur as isolated pieces or as wood accumulations. The quantity, position and orientation of the wood pieces within the river channel have differing impacts on flow resistance, flow patterns and the water surface profile (Young, 1991; Gippel, Finlayson & O'Neill, 1996a) but their gross effect, particularly in smaller rivers, is to increase flow complexity and water retention (Ehrman & Lamberti, 1992) and thus to attenuate small to medium flood peaks and increase flood peak travel times (Gregory, Gurnell & Hill, 1985). In many woodland streams, log steps and wood accumulations are the major control on the dissipation of the river's energy (Keller & Swanson, 1979) and on hydrological interactions between stream water and groundwater within channel banks and below the bed (White, 1990; Harvey & Bencala, 1993; Wondzell & Swanson, 1999). Mobile wood pieces can also interact strongly with river flows depending on their size and number and the degree to which the wood pieces move individually or as interacting clusters during transport (e.g. Braudrick *et al*., 1997; Johnson *et al*., 2000).

A second theme has been the impact of the above hydraulic characteristics on the transfer of solutes, mineral sediment and organic material within the river channel system and floodplain. Obstructions created by wood lead to enhanced mineral and organic sediment storage and nutrient retention within the channel (e.g. Anderson & Sedell, 1979; Keller & Swanson, 1979; Keller & Tally, 1979; Sullivan, Lisle & Dollof, 1987; Hedin, Mayer & Likens, 1988; Bilby & Ward, 1989; Thompson, 1994) and in the channel margins (Johnson *et al*., 2000), whereas wood removal leads to sediment scour, loss of organic matter and channel incision (Beschta, 1979; Klein, Sonnevil & Short, 1987; Smith, Sidle & Porter, 1993; Gurnell & Sweet, 1998).

The third theme is the geomorphological effect of hydraulic and sediment transfer patterns induced by wood accumulations. These include the accumulation, sorting and scouring of sediments and organic matter to create a variety of geomorphological features of varied form and sediment calibre. For example, Bisson *et al*. (1982, 1987) developed a classification of pools, riffles and glides found in woodland streams; and of the 10 pool types, six were associated with wood. Montgomery *et al*. (1995) and Gurnell & Sweet (1998) showed how pool frequency increased with the frequency of wood accumulations.

In general, the presence of wood accumulations has been found to increase channel stability. Wood dams provide sites for avulsion and the initiation of secondary channels (Hickin, 1984; Harwood & Brown, 1993), which on smaller streams can lead to the development of a fairly stable hierarchy of channels supporting flow for different proportions of the time (Gurnell, Gregory & Petts, 1995; Gurnell & Linstead, 1999). On larger rivers, wood can have important effects on the form and dynamics of river margins (e.g. Fetherston, Naiman & Bilby, 1995; Piégay, Citterio & Astrade, 1998; Piégay & Marston, 1998) and on the creation and maintenance of vegetated bars and islands (e.g. Abbe & Montgomery, 1996; Gurnell *et al.*, 2001; Gurnell & Petts, 2002).

These interactions between large wood and fluvial processes have important implications for the ecology of river systems that contain wood debris. The complex physical structure of woodland river channels and their wood pieces and accumulations provides a diversity of habitat patches which can support a wide range of organisms at different stages of their life cycles. Furthermore, wood accumulations may have an important role in regulating water quality and in sustaining refuge habitats to protect biota during pollution episodes and high flows. In addition, the storage, breakdown and regulated release of organic matter within wood accumulations provides temporally and spatially regulated food sources for aquatic biota (Gurnell *et al.*, 1995). As a result, large-wood management and restoration are attracting increasing attention from researchers and environmental managers (e.g. Bilby, 1984; Swanson *et al.*, 1984; Bisson *et al.*, 1987; Gregory & Davis, 1992; Gurnell *et al.*, 1995; Maridet *et al.*, 1996).

In this paper, we consider the role of wood as an important component of the load transported by rivers as well as a control on river morphology. We review the characteristics of wood that govern its dynamics and the characteristics of rivers that dictate the way in which wood is mobilised, transported and retained. In particular, we consider the relationship between large wood and fluvial processes within rivers of different size. By taking a broad geographical perspective, this review is not only differentiated from its predecessors by the analogies it draws between wood and sediment dynamics, but it also considers a wider range in biome type and river channel size.

Wood: an important element of a river's load

A sedimentological perspective

Wood forms one component of the total organic and mineral sediment load of woodland rivers. The study of wood in rivers is quite immature relative to the science of mineral sedimentary features and processes embodied in the field of sedimentology (see, for example, Hey, Bathurst & Thorne, 1982; Thorne, Bathurst & Hey, 1987; and references therein), and so it is instructive to consider the degree to which analogies can be drawn between the two.

Sediment transport involves the supply of sediment to channels, entrainment, transport and deposition of individual particles or groups of particles. Studies of sediment supply have revealed strong controls on transport and channel form, as exemplified by cases where exceptionally high levels of supply either in pulses or protracted periods have led to high rates of sediment transport and an evolution of river bedforms. Entrainment of mineral sediment particles is a very mature field of inquiry, with intensive work on roles of mechanisms of particle movement imposed by shear stress of flowing water leading to particle mobilisation by rolling, turning and impact of other particles. Braudrick *et al.* (1997) and Braudrick & Grant (2000) have begun analogous work on entrainment and transport of wood pieces by processes such as flotation and rolling.

Studies of both inorganic sediment and wood in rivers also include concern about loss of material to physical breakdown, such as abrasion during transport and biogeochemical breakdown while in storage through decomposition of wood and weathering of inorganic material. Abrasion of sediment particles has been extensively studied in both the field and laboratory with objectives of understanding distances of transport and development of particle form, but the role of weathering processes is less well understood. In the case of wood, breakdown as a result of biological processes is more fully studied than physical breakdown.

Sediment deposition and formation of arrangements of particles in imbricate fabric forming armour layers on the streambed has also been an important issue in sedimentology. In similar fashion, transported wood accumulates in depositional features with structures distinctive to the transport mechanism and depositional environment. Sedimentary features range across spatial scales from individual pieces, to small collections of pieces, to massive accumulations, to distributions of features of different types arrayed across a river reach or full network. In the case of gravel-sized sediment, these features scale from the single stone to pebble clusters, to gravel bars, to the form and spacing of a collection of gravel bars at reach and network scales. Research on wood in rivers contains a great deal of description of wood structures in some types of systems, particularly in small streams and intermediate-sized rivers of the Pacific Northwest of the United States typified by big trees and high-gradient, gravel-bed rivers. However, a systematic characterisation and classification system for wood structures that relates form to origin and function is currently lacking. For example, the distribution of wood and architecture of accumulations is known to differ among sites where different processes dominate (Swanson, 2002). In some sites, wood simply resides where it falls (pattern determined by tree fall processes); at others there are accumulations associated with individual large trees with rootwads; elsewhere collections of wood occur on the heads of islands and at the mouths of secondary channels; and in some locations large, tangled masses of wood are observed at the snouts of debris flow deposits.

Temporal and spatial patterns of wood in rivers may exhibit greater dynamics than sediment and its associated bedforms. The properties of wood in a particular reach of river are likely to reflect the recent history of wood input and redistribution – if a major redistribution event, such as a flood, occurred more recently than major input events, the signature of the redistribution event is likely to dominate the pattern of the wood in the reach. Many studies of fluvial geomorphology and sedimentology suggest that bedforms and channel planview pattern may change little through major floods, despite appreciable movement of coarse sediment over the bed.

Further comparative analysis of form and process governing wood and sediment in rivers is likely to be fruitful in developing a comprehensive understanding of river dynamics and ecosystems where wood is a significant component of the system. For example, the interaction between wood and large, inorganic particles (boulders) may be fundamental to wood retention in some river environments (J.M. Faustini & J.A. Jones, pers. comm.). In this paper, we make a simple attempt to adopt such a perspective by highlighting those factors that influence the dynamic properties of wood in rivers. Like any other load component, the transport of wood is dependent on the supply (quantity) and characteristics of the wood (size, shape, density) and on the characteristics of the river (channel dimensions, geomorphological characteristics and flow regime). The characteristics of the river, particularly channel size, flow regime, mineral sediment calibre and transport regime, and geomorphological style (meandering, braided, island braided, etc.), also influence the mobilisation, transport and deposition of wood pieces.

Wood supply

The quantity of wood supplied to a river provides an upper limit to wood storage and transport within the fluvial systems. Whilst toppling and wind throw can be an important local form of input (McDade *et al.*, 1990; van Sickle & Gregory, 1990), a range of geomorphological processes control wood delivery (Keller & Swanson, 1979). Bank erosion is an important process of wood supply (Murphy & Koski, 1989) through both the undercutting of living trees (e.g. Piégay, Thévenet & Citterio, 1999) and the remobilisation of wood stored on the floodplain (e.g. Piégay *et al.*, 1998). Wood can be delivered from more distant sources through flotation and wood torrents along tributary streams, and through slope processes such as landslides and avalanches (Wondzell & Swanson, 1999; Johnson *et al.*, 2000; Nakamura, Swanson & Wondzell, 2000). These processes link to form a spatially and temporally complex disturbance cascade (Nakamura *et al.*, 2000), which not only delivers, stores and remobilises wood and sediment within the fluvial system, but also structures a 'shifting mosaic of disturbance patches – linear zones of disturbance created by the cascading geomorphological processes' (Nakamura *et al.*, 2000, p. 2849). Geomorphology, both form and process, favours some processes and suppresses others; hence spatial variation in dominant processes is substantial (e.g. Martin & Benda, 2001). This spatial dimension is developed further later in this paper.

There is little quantitative information on wood supply rates to river systems. Johnson *et al.* (2000) combined field survey with analysis of air photographs to estimate the extent of riparian forest disturbance by floods and Piégay *et al.* (1999) also analysed air photographs to estimate wood delivery to the Drôme River by bank erosion between 1948 and 1991. Geomorphological style, which is largely a product of the river flow and sediment transport regimes, is an important control on both wood input and storage. The highest wood inputs occur on free-meandering piedmont rivers, where bank erosion is relatively high and vegetation turn over is relatively slow in comparison with braided rivers. In such rivers, erosion usually occurs on concave banks and encroaches on older forested units. Although braided rivers erode their floodplains, the turn over of the vegetation is much higher because the floodplain margin is continuously renewed forming a buffer zone on which, the trees rarely attain maturity. A. Citterio (pers. comm.) compared the Ain River, France, a free meandering piedmont river, with the Drôme, a braided river, and showed that the former supplied almost 40 t $year^{-1}$ of wood per km of river length whereas the latter only supplied 12 t $year^{-1}$. Free-meandering lowland rivers supply much less wood than their piedmont counterparts because the erosion rate is very low, often only reaching a few cm per year on concave banks.

Wood supply is also highly temporally variable. During a period without floods, B. Moulin (pers. comm.) observed that wood output from the Upper Rhône catchment averaged 0.8 t km^{-2} catchment area, whereas during a single flood of 1100 $m^3 s^{-1}$ (Q_{2-5}), the output was 6 t of wood per km^2. One study that has produced detailed information on interannual variations in wood input and movements has been undertaken along Mack Creek, Oregon, U.S.A., a third-order stream flowing through a 500-year-old-coniferous forest dominated by Douglas fir (*Pseudotsuga taxifolia* Britton), western hemlock [*Tsuga heterophylla* (Raf.) Sars.], and western red cedar (*Thuja plicata* D. Don) within the H.J. Andrews Long-Term Ecological Research site (Harmon *et al.*, 1986; Lienkaemper & Swanson, 1987; Van Sickle & Gregory, 1990). Inputs and storage of wood can be extremely high in such rivers, which drain catchments covered by relatively pristine forests (Harmon *et al.*, 1986; Bilby & Ward, 1989), where the late-successional stands contain large trees (1–2 m diameter, 60–90 m height). Wood input rates have been observed to be highly variable (Fig. 1a), ranging from large wood pieces 100 m^{-1} $year^{-1}$ to more than 59 pieces 100 m^{-1} $year^{-1}$,

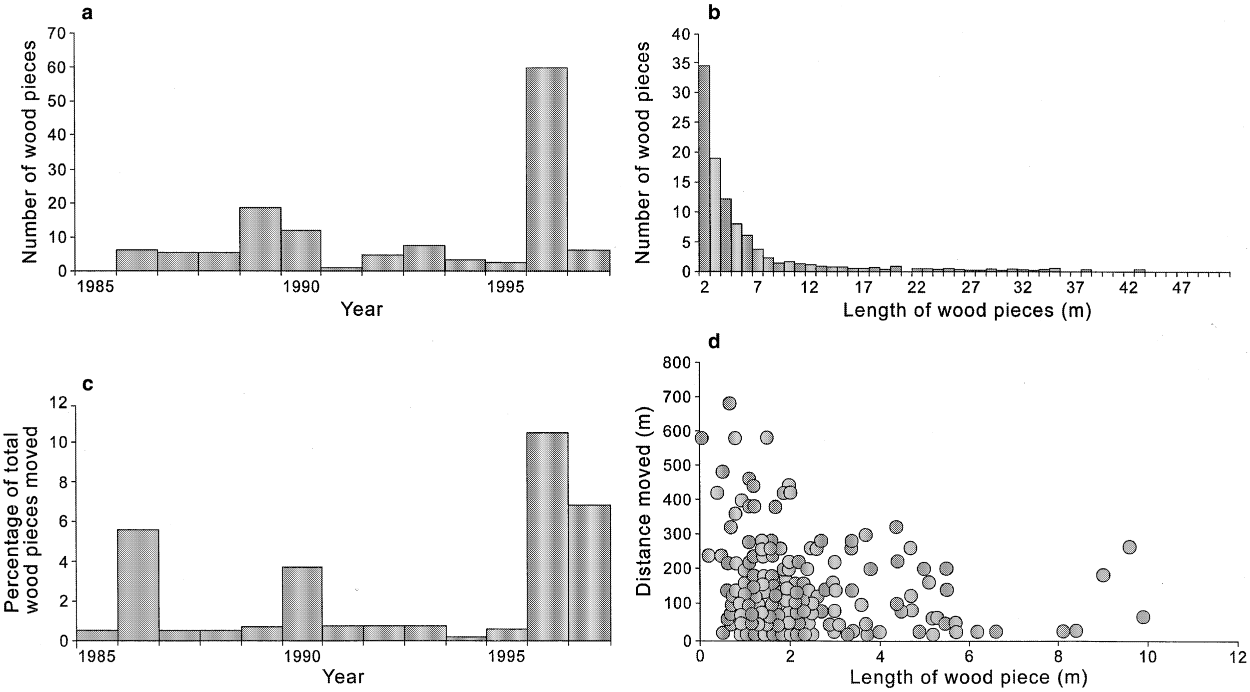

Fig. 1 Wood size and dynamics in an old growth reach of Mack Creek, Oregon: (a) number of new large wood pieces delivered annually per 100 m of channel; (b) size class distribution of large wood; (c) percentage of wood pieces moved annually and (d) distance of wood piece movement versus length of wood piece.

and are related to both climatic events (e.g. wind storms, snow storms) and discharge events (e.g. floods, mass failures). For example, in 1995–96, an average of almost 60 pieces of wood per 100 m entered the channel, largely as a result of a wet snowpack in December 1995, which caused large numbers of trees to fall over.

Wood storage within the fluvial corridor, although not an accurate surrogate for wood supply, is more widely estimated and provides a basis for drawing comparisons between river systems as an indicator of relative wood availability. Gurnell (2002) analysed published information on wood storage within the channel of 152 river reaches. These analyses provide baseline estimates of typical wood volumes stored within the river channels of unmanaged or lightly managed river corridors. When dummy variables were introduced to represent four broad woodland types, a significant but weak regression relationship between $\log_{10}$ (wood volume) and $\log_{10}$ (channel width) was reduced to four significantly different ($P < 0.05$) constant values according to woodland type (red woods = 1000 $m^3.ha^{-1}$; other conifers = 240 $m^3.ha^{-1}$; hardwoods or mixed conifers and hardwoods = 110 $m^3.ha^{-1}$; deciduous softwoods = 33 $m^3.ha^{-1}$). These estimates were thought to be a genuine reflection of the type of woodland, but the relatively small sample size and the characteristics of the sample sites suggested that the estimates might be partly confounded by woodland age; climatic, hydrological and sediment transport regimes; catchment topography; and level and type of woodland and river management, even though relatively unmanaged sites were selected. In addition to such within-channel storage, large quantities of wood may be stored along the river margin and on the flood plain (Piégay & Gurnell, 1997). However, such marginal wood only becomes part of the total wood supply to the river when it moves into the active channel.

Wood piece characteristics

Various characteristics of individual wood pieces affect their potential to be mobilised and transported or to be retained. Three particularly important properties are size, shape and density.

Wood piece size is important for two main reasons. First it is an important control on whether the wood is likely to become jammed within the river channel, lodged against trees or stabilised by significant overlap of the channel margin and floodplain. All of these situations reduce or prevent wood movement downstream. In these cases, the critical dimension is the length of the wood piece in relation to the size of the river channel. This factor is discussed below under the heading of river size. Second, wood piece size dictates the depth of flow required to initiate movement (Braudrick & Grant, 2000). In this case the critical dimension is the diameter of the wood piece, although the water depth required to mobilise the wood also depends upon the density of the wood. Wood piece size reflects both tree species and age. For any particular species and environmental context there is an upper limit to tree size and thus to the size of the largest wood pieces, but smaller pieces are supplied through the undermining of younger trees, through pieces of wood breaking off trees, and through the break up of wood pieces in transport. Some tree species are particularly susceptible to breakage or to decay, both of which lead to many small wood pieces being delivered to the river. Other species are more susceptible to toppling so that entire trees enter the river. The age of the trees is another important control on wood piece size, as older trees of most species shed diseased or decaying branches.

The growth habit of the tree affects the form of the wood pieces in the river. This is another important control on wood dynamics, as irregularly shaped wood pieces are more likely to become trapped or snagged within river channels or in exposed roots and overhanging vegetation canopies than more streamlined wood pieces of a similar size. For example, a simple contrast can be drawn between many conifers, which are dominated by their more cylindrical trunk, branch and canopy forms, in contrast with the more open, varied, branching structure of many deciduous species. Conifers also usually possess a higher proportion of wood mass in their trunk in comparison with many deciduous species. This contrast results in a tendency for conifers to shatter and scatter branches when they fall, producing many near-cylindrical pieces, whereas the branch-dominated forms of many deciduous trees may buffer tree impact with the ground, yielding more complex and open-structured wood pieces.

Wood density controls whether and how well wood pieces float and also the energy required to mobilise the wood. Wood density varies with tree species, age and degree of waterlogging and decay. Undecayed wood density typically varies between of 0.3–0.7 Mg m^{-3} (Harmon *et al*., 1986), but some species have densities well outside this range. For example, Rutherfurd *et al*. (2000) quote densities ranging from 0.8 to 1.3 Mg m^{-3} for 15 Australian tree species, implying that the wood from most of these species will not float in fresh water. Therefore, whereas most wood species float to some degree and so, where the water depth is sufficient, the wood pieces will move in suspension, denser wood pieces may settle on the bed of the river, probably moving relatively little and in a manner analogous to bedload. Waterlogging of wood increases its density if it is initially less dense than water whereas decay tends to decrease wood density (e.g. Thévenet, Citterio & Piégay, 1998). The residence time of wood in a channel is reflected in the state of decomposition of the wood and thus its density. Less managed woodland rivers may therefore contain a mix of wood pieces of contrasting density, even when there is a single dominant tree species. For example, in a survey of Mack Creek, Oregon, most large wood pieces (51%) were in an intermediate stage of decay (decay class 3). Only 19% were fresh logs with intact bark and 20% were firm logs without bark. Logs with extensive decay made up only 10% of the total number of logs, and no logs were found as fragments of well-decayed wood (decay class 5). Flows within the active channel and across the floodplain tend to destroy accumulations of decayed wood, eliminating the extensively decayed wood pieces. Indeed, the presence of large amounts of decayed wood in streams is an indication of a relatively subdued flow regime, whereas streams that experience large floods would be expected to have little decayed wood.

The above characteristics reflect not only the riparian tree species, but also the age and management regime applied to riparian woodland and to the wood pieces that are delivered to the river systems.

A final characteristic of wood, which does not affect its initial transport but which may be important in its longer-term retention once it has been deposited, is whether it is 'dead' or 'alive'. Many riparian tree species reproduce vegetatively as well as sexually. Indeed, some species are able to sprout and produce numerous new trees from a single original tree. Species that reproduce in this way can anchor themselves to alluvial sediments by producing adventitious roots, particularly where they track a falling water table in the alluvial sediments after deposition. Poplar (*Populus*) and willow (*Salix*) species are obligate phreatophytes, which track falling water tables rather than utilising soil moisture in the unsaturated zone (Hughes, 1997). In experiments conducted by Barsoum & Hughes (1998) on seedlings and cuttings of black poplar (*Populus nigra* L.) grown in sediments of differing calibre and subject to different water table regimes, cuttings developed both roots and shoots more rapidly than seedlings, regardless of the experimental treatment. Edwards *et al*. (1999) and Gurnell *et al*. (2001) suggest that shoot and root development from uprooted *P. nigra* trees deposited on gravel bars is a process that supports pioneer island development along the Tagliamento River, Italy.

River channel size

Another important factor affecting wood retention is the size of the river channel. This is partly because wood pieces can become jammed within smaller channels but also because the flow within small channels may be insufficient to transport larger pieces of wood. Church (1992) defined three sizes of channel (small, intermediate and large) in relation to channel morphology and typology, based upon channel dimensions scaled mainly by bed material size. Gurnell (2002) proposed that for rivers influenced by wood, the wood pieces form such important roughness elements, influencing both geomorphology and ecological pattern and process, that channel size should be scaled according to wood piece size. For example, 'small' channels might be those whose channel width is less than the median wood piece length; 'medium' channels might be those with channel width less than the upper quartile wood piece length; and 'large' channels might be those where the channel width is greater than the length of all of the wood pieces delivered to them. Although these suggested thresholds of wood piece size are imprecise, they are indicative of the proportion of the total wood pieces that are likely to become jammed within the channel. Channels where wood mobility is likely to be very limited ('small' channels), are separated from those where wood is likely to move and accumulate behind a few key pieces that span the channel ('medium' channels), and from those where all wood pieces are mobile unless they become anchored to a roughness element within or at the margin of the channel or the wood supply is so great that complex accumulations of many wood pieces can develop to span the channel ('large' channels).

Based on the ratio of typical tree height to river width (rather than wood piece size for which information is more difficult to obtain for large rivers), research on the following rivers provide invaluable perspectives on wood in larger river systems and the significance of the relationship between wood and channel size: the Queets River, Washington state (ratio of tree height to river width approximately 1.2–2.3; Abbe & Montgomery, 1996), the McKenzie River, Oregon (1.5; Keller & Swanson, 1979), the Drôme, France, and the Tagliamento, Italy (both 0.07–0.10 Piégay *et al*., 1999; Gurnell *et al*., 2000). These rivers have similar catchment areas (respectively, 1164, 1024, 1620 and 2500 km^2) but the first two rivers drain basins with substantial areas of old-growth forests of Douglas-fir (*P. taxifolia*) where the trees are commonly taller than 60 m, whereas the last two drain riparian corridors that are frequently rejuvenated by channel shifting and colonised by pioneer species where the tallest trees [e.g. black poplar (*P. nigra*), ash (*F excelsior* L.), grey alder (*Alnus incana* (L.) Moench), common alder (*Alnus glutinosa* (L.) Gaertn)] rarely exceed 15 m. Although many larger rivers, such as the Willamette (catchment area 29 138 km^2) and Red River (236 000 km^2) in the United States no longer store much wood within their channels, prior to human impacts (particularly cleaning to support navigation during the 19th century), they retained so much wood that they were locally completely spanned by wood accumulations despite their considerable width (respectively, 108 and 215–365 m; Sedell & Froggatt, 1984; Triska, 1984).

Thus, channel size in relation to wood dynamics becomes a function of tree size, age, species and management as these are the four main controls on the piece sizes of wood entering a river.

Flow and sediment transport regimes

Whilst the channel size can be an important influence on the trapping of wood, the flow regime influences the potential for wood pieces to be transported. The river's flow regime controls the degree and frequency with which various wood sources can be tapped by flotation or erosion and also the depth and power of flows that are available to mobilise and transport the wood. The quantity and calibre of sediment mobilised, transported and deposited by the river influences the degree to which wood pieces can become undermined or alternatively anchored by complete or partial burial. In the case of living wood, the quantity and calibre of sediment deposited with the wood can have an important influence on whether it is able to sprout and grow.

The interaction between wood, flow and sediment is extremely important in affecting sediment storage in river channels. In small to medium river channels, wood accumulations that extend across the entire width of the active channel have been shown to be important sites for sediment accumulation. For example, Keller & Tally (1979) estimated that 30% and 40% of the channel area in Prairie Creek and Little Lost Man Creek, CA, U.S.A., were zones of wood-controlled sediment storage. Megahan (1982) estimated that 49% of the total sediment stored in seven Idaho streams was related to wood debris. Keller & Swanson (1979) noted how wood-associated sediment storage on low gradient, meandering streams was often in the form of bars downstream of wood-controlled plunge pools, whereas on steep-gradient streams the stepped longitudinal profile reflected the deposition of sediment upstream of wood accumulations. As a result of wood-associated sediment storage, sediment is rapidly mobilised when wood accumulations are removed from river channels, leading to major increases in sediment transport (Beschta, 1979; Klein *et al*., 1987; MacDonald & Keller, 1987; Smith *et al*., 1993). Furthermore, the role of wood accumulations as natural check dams is illustrated by the channel incision that can result when wood is removed (Gurnell & Sweet, 1998). In larger rivers, wood can also be an important influence on sediment storage by encouraging scroll bar formation (e.g. Nanson, 1981; Gurnell *et al*., 2001), by accelerating bar surface accretion (Gurnell & Petts, 2002) and by playing a significant role in island development (e.g. Abbe & Montgomery, 1996). Furthermore, buried wood has been seen to be associated with bar and riffle development within braid channels along the Tagliamento River, Italy (A.M. Gurnell, pers. obs.).

Interactions between flow, sediment and wood can also be important in influencing the amount of wood stored within a river. Buried or partially-buried wood is more stable than exposed wood (particularly where the wood is of low density) and also wood decay rates may be significantly reduced by burial and strongly influenced by the frequency and duration of wetting and drying. In addition, water depth and velocity can be important influences on the break-up of wood pieces. For example, shallow, high velocity flows, where the wood is abraded by the flows and transported sediments, can result in high rates of mechanical breakdown of wood.

Geomorphological style

Geomorphological style has already been referred to but it is important to identify it here as a significant influence on wood retention. The planform pattern and relative relief of the river channel becomes a particularly important influence on wood retention once channels are 'large'. Geomorphological style influences the availability of locations for large wood retention (Piégay & Gurnell, 1997), and the vegetation itself can impact on geomorphological style, the relative relief of the river's active zone, and the level and patchiness of vegetation roughness (Gurnell & Petts, 2002). All of these factors influence the degree to which wood is retained within or transported through river reaches.

Fig. 2 draws together some of the issues raised in this section and provides a context for the following section, by presenting an overview of the *relative* importance of wood, geomorphological and hydrological characteristics within rivers of different size in influencing wood dynamics and the quantity, nature and locations of wood storage.

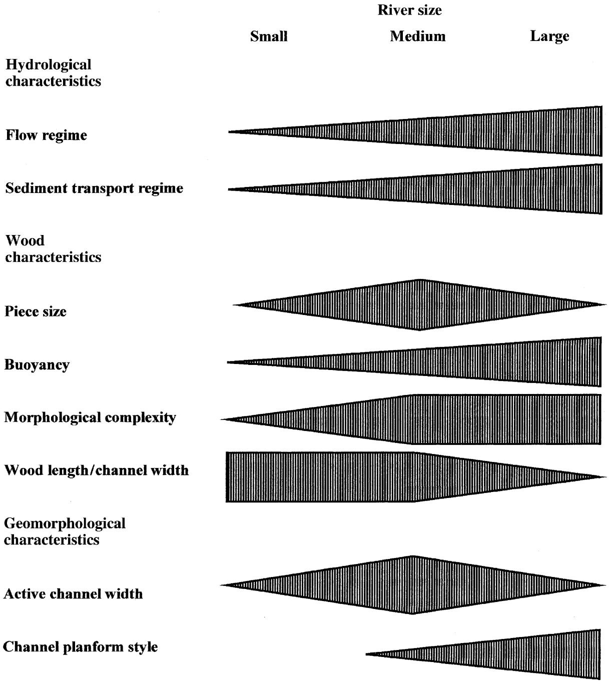

Fig. 2 The relative importance of wood, geomorphological and hydrological characteristics in influencing the retention of wood in rivers of different size.

Wood in rivers of different size

This section considers the way in which large wood interacts with fluvial processes in different environments and in rivers of different size. Table 1 provides summary data from rivers studied by the authors that will be used to illustrate some of the issues that have been raised and to amplify some of the trends suggested in Fig. 2. The rivers in Table 1 represent cool temperate, alpine and mediterranean climatic regimes; coniferous, temperate deciduous hardwood and deciduous softwood-dominated marginal woodland; and meandering, wandering and braided channel patterns. As the studies presented in Table 1 were undertaken by different researchers using different sampling approaches, comparisons between the study results should be drawn with caution. The study sites in Table 1 are presented in order (left to right) of the ratio of tree height to channel width rather than the ratio of wood D_{75} (i.e. 75th percentile of wood length) to channel width, because of the different wood piece sampling frameworks that underpin the wood size distributions for each site (see footnotes on Table 1 and comments in the following text). An important contrast can be drawn between the characteristics exhibited by the old-growth environment of Mack Creek, where the size of the trees and the quantities of wood input to and stored within the river are far higher than the more disturbed environments of the other example rivers. As a result, this study site has greater similarity to the order 1 and 2 Highland Water streams than the order 4 stream once the data are scaled for wood and tree size, despite the fact that the absolute channel size of Mack Creek is larger than all of the Highland Water study sites.

The transition from small to medium rivers

The most important characteristic of small rivers is the wood piece length in relation to channel size. In the

Table 1 Summary river channel, wood and tree characteristics within selected rivers of different size

	Small to medium rivers				Large Rivers		
Characteristics of Surveyed reaches	Highland Water, U.K., Order 1	Highland Water, U.K., Order 2	Mack Creek Oregon, U.S.A.	Highland Water, U.K., Order 4	Ain River, France	Drôme River, France	Tagliamento River, Italy
River characteristics							
Channel (bankfull or active zone) width (m)	1.2	1.8	9.1	4.9	100–150	150–200	140–890
Channel (bankfull) depth (m)	0.3	0.5	1.4	1.1	2–3	1.5–2	2.6–3.0
Valley slope	0.0125	0.0107	0.100	0.005	0.0013	0.003–0.008	0.0032–0.0187
Planform	Low-sinuosity single thread	Meandering	Low-sinuosity single thread	Meandering	Meandering	Braided	Island braided reaches only
Tree characteristics							
Forest type	Deciduous hardwood	Deciduous hardwood	Coniferous	Deciduous hardwood	Deciduous hardwood and softwood	Deciduous hardwood and softwood	Deciduous softwood
Typical height of largest trees (m)	20–30	20–30	60–90	20–30	12–18	12–18	10–16
Wood characteristics							
Wood volume in channel/ active zone (m3ha–1 channel)	76	44	812	88	< 10**	20–60	40–60**
D_{50} piece length (m)	2.3*	3.1*	4–5	4.7*	–	–	–
D_{75} piece length (m)	5.2*	4.6*	9–10	7.9*	–	–	–
Average distance between accumulations (m)	12	21	90	42	NA	NA	NA
Average distance between accumulations (channel widths)	10	12	10	9	NA	NA	NA
D_{75} piece length: channel width	4.3	2.6	1.1	1.6	–	–	–
Typical tree height: channel width	< 25	< 17	< 10	< 6	< 0.1–< 0.15	< 0.07–< 0.1	< 0.01–< 0.07

*These estimates are derived from measures of the three largest large-wood pieces in each wood accumulation. The average number of large wood pieces in each accumulation was 1, 2 and 6, respectively, for order 1, 2 and 4 streams, and so these estimates are probably too large for the order 4 streams, where considerably less than the entire population of large wood pieces was sampled).

**Wood is mainly stored within the floodplain woodland on these rivers, reaching loadings up to approximately 115 m^3 ha^{-1} along the Ain and 160 m^3 ha^{-1} along the Tagliamento; –, no data, NA: not applicable.

following discussion, we adopt the widely accepted definition of large wood as wood pieces greater than 1 m in length and 10 cm in diameter. Because in small rivers the wood pieces are large in comparison with the river size, their actual size is not critical and they tend to remain close to where they are supplied to the river. Thus wood mobility is relatively low and wood pieces provide important structures in the river controlling rather than responding to the hydrological and sediment transfer characteristics of the river. As the ratio of wood piece length to channel width reduces, significant interactions begin to occur between the wood and fluvial processes (e.g. Lienkaemper & Swanson, 1987; Montgomery *et al.*, 1996). For medium rivers, the wood piece size and its morphological complexity are very important, because the length of many wood pieces is close to or less than the channel width and so the combination of wood length and form becomes critical to the stability of wood within the channel. Wood accumulations form as a result of smaller or more mobile wood pieces accumulating upstream of key pieces. Wood transport is governed mainly by the flow regime and the buoyancy of the wood, and even quite large wood pieces may require partial burial to give them stability, so enhancing the importance of the sediment transport regime. Therefore, wood buoyancy and the flow and sediment transport regime become important secondary factors in affecting the nature of wood dynamics and storage in medium rivers.

Data from Mack Creek illustrate the high wood storage and stability of wood pieces in a river that can be categorised as on the small to medium threshold based on its wood piece size distribution (Fig. 1b, Table 1). The quantity of large wood pieces in the channel and floodplain of Mack Creek in 1998 was 239 pieces per 100 m (Swanson & Gregory, unpubl. data). Size class distributions (e.g. Fig. 1b) reflected the large size of trees in the riparian forest, with more than 65% of the pieces of wood less than 5 m in length, but some pieces as long as 45 m. The larger pieces create important physical structures that serve as the framework for major wood accumulations. Rootwads can be particularly important in anchoring pieces of wood, making wood more resistant to transport (Bisson *et al.*, 1987), although in Mack Creek only 6% of the surveyed wood pieces had a rootwad connected. Most of the wood was found in jams and accumulations rather than as single pieces, with almost 80% of the pieces in an accumulation of three pieces or more. Most logs that were considered to be stable (40% of the total number of pieces) were stabilised by other logs. Other features such as boulders and trees were less frequent agents of stabilisation, accounting for only 25% of the stabilised pieces. Fig. 1c shows the proportion of large wood pieces that moved within Mack Creek during each year of a record from 1985 to 1997. Less than 1% of the logs in Mack Creek moved in most years and most movements are probably attributable to floods. A major flood occurred in February 1996 (approximately 25-year return period), inducing peak water levels of more than 1.5 m above the active channel. However, even during this major flood, 89% of wood pieces remained in their original positions, and only 11% of the pieces moved more than 10 m. All pieces of wood that moved during the 14-year record were less than the width of the active channel, and most pieces that moved more than 300 m were less than 2 m in length (Fig. 1d).

Data from streams of different order within the Highland Water, U.K., illustrate changes in the character of wood pieces and accumulations across the transition from small to medium rivers. Although the Highland Water river channels are quite small in absolute size (maximum width 7 m), the wood pieces delivered to the river are also small, generating wood size to channel size ratios that are not dissimilar to Mack Creek (Table 1). Fig. 3 illustrates the size distribution, ratio of wood piece length to stream width, and orientation of large wood pieces within over 300 wood accumulations along the surveyed channels. The three graphs to the left of Fig. 3 show the increasing number of pieces of large wood present within dams in larger channels. The central three graphs show that although the number of large wood pieces within each dam increases with increasing channel size, the ratio of the length of the key wood piece to the channel width decreases. The three graphs to the right of Fig. 3 highlight the way in which wood is predominantly aligned across the channel perpendicular to the stream centre line in the smallest streams, but as the channel size increases, the wood becomes increasingly oriented parallel to the channel centre line and thus the flow direction. The nature of the wood accumulations also changes with increasing channel size. Whilst 75% of the accumulations extend across the entire bed of the

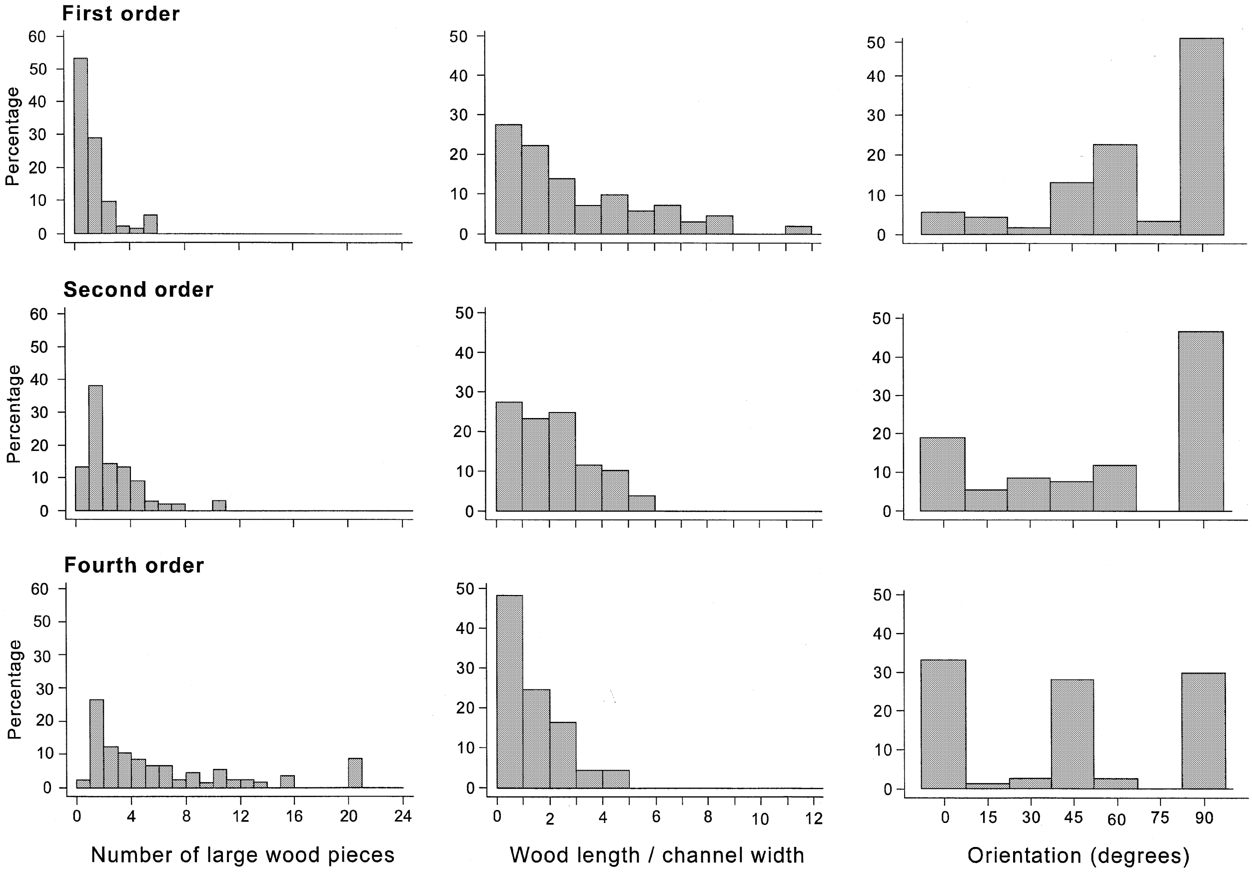

Fig. 3 Characteristics of wood pieces within wood accumulations in the Highland Water, New Forest, U.K. Left: Percentage frequency of the number of large wood pieces in dams surveyed in first (top), second (middle) and fourth (bottom) order reaches (for the number of wood pieces read the value to the left edge of each bar). Centre: Percentage frequency distribution of the ratio of key wood piece length to channel width in first (top), second (middle), and fourth (bottom) order reaches. Right: Percentage frequency in the horizontal orientation in degrees from the channel centre line in first (top), second (middle), and fourth (bottom) order reaches.

active channel in the first order stream, this reduces to 46% in the second order stream and 37% in the fourth order stream. This reflects the decreasing relative size and changing orientation of the key pieces within the accumulations.

Within small to medium sized rivers, wood pieces and accumulations frequently extend across a significant proportion of the channel width, even if they do not completely span the channel. The impact of such structures on flow hydraulics and thus sediment deposition, storage and scour is considerable and is illustrated by the fact that 87% of the in-channel wood accumulations surveyed within the Highland Water have one or more pools that are, at least in part, within one channel width of the accumulation and 48 and 34%, respectively, have at least one bar or riffle in similar proximity. In general, smaller than average riffle-pool spacings have been reported for unmanaged channels as a result of the influence of large organic debris (Gregory *et al.*, 1994). This is confirmed by the analysis of small to medium forested channels in Alaska and Washington, U.S.A., by Montgomery *et al.* (1995), who noted that pool spacing within mountain forest channels is controlled by wood loading, channel type and width, and slope; and that, as a result of flow convergence and channel bed scour, the mean pool spacing in forest pool-riffle channels is less than expected for free-formed pool-riffle reaches. This close association between large wood and pools helps to explain why Wood-Smith & Buffington (1996) found pool spacing and pool depth to be the two best geomorphological discriminators between pristine forest streams and streams influenced by timber harvesting in Alaska.

With increasing channel width, the change in the relative importance of the factors that influence wood dynamics and storage not only influence the nature of wood storage but also the quantity of wood that is retained. Examination of storage of large wood in mature to late-successional forests of the Pacific North-west of the United States demonstrates a decreasing volume of wood (weight per unit area of channel) with increasing stream width. This pattern of wood storage within the river network has been observed in several major regions of the Pacific Northwest (Harmon *et al.*, 1986; Bilby & Ward, 1989; Montgomery *et al.*, 1996) and has been attributed to mechanisms including: (1) an increasing ability to transport wood as the ratio of piece length to channel width decreases, (2) the simple distribution of equal lateral inputs of wood to the channel over an increasing area of channel bed as width increases, and (3) downstream shifts toward lateral or floodplain storage rather than storage within the active channel.

Large rivers

There have been few studies of wood dynamics in large rivers (Piégay, 2002), but those that have been undertaken illustrate that once the channel width exceeds the size of the wood pieces within a river, other factors dominate the storage and dynamics of the wood. Fig. 2 suggests that the flow and sediment transport regimes, wood buoyancy and form complexity, and channel platform style are all extremely important controlling factors.

In pristine conditions, large rivers of the temperate zone drained forested corridors and were affected by large quantities of wood and such high hydrological connectivity between the channel and the floodplain that it was often difficult to distinguish the boundaries between these landforms. Large lowland rivers, such as the Red River (Triska, 1984), provided important areas of wood storage because flow velocities were low and so there was little wood breakage or removal, and also because the wood was commonly stored under water (in floodplain wetlands and side channels, anchored to the banks or within the main channel) so that rates of wood decay were slow. Whereas the Drôme or Tagliamento channels commonly store less than 10 t ha^{-1} of wood, rivers such as the Ogeechee (East US coastal plain) or Thompson (Australia) can store, respectively, 90 (Wallace & Benke, 1984) and 110 t ha^{-1} (Gippel *et al.*, 1996a). Moreover, Shields & Smith (1992) in the context of channel degradation and widening on the South Fork Obion (a lowland river), observed sites where wood storage averaged 260–540 t ha^{-1}.

Wood dynamics in large rivers varies with the geometry of the channel (slope and channel pattern), which controls the delivery, mobility and breakage of wood and also the characteristics of the riparian zone and thus the volume of wood that is available. The majority of wood is introduced from local riparian areas (through bank erosion and the action of meteorological agents such as snow, wind and ice storms), because the wood delivered from upstream is rapidly broken up during transport (e.g. Gippel *et al.*, 1996b; B. Moulin, pers. comm.).

Wood retention is associated with the channel pattern of large rivers and with the distribution of flow velocity. A large amount of wood is stored at the channel margins, for example on concave banks, the edges of vegetated islands and bordering secondary channels. The greater the contact between the active channel and the forested floodplain and islands, the greater the quantity of wood that is stored. Gurnell *et al.*, 2000) showed that island braided areas stored much more wood than bar braided areas because of the high wood retention around and on islands. Whereas the gravel bar surfaces stored 1–6 t ha^{-1} of wood, some vegetated patches stored more than 1000 t ha^{-1}. Detailed mapping of wood accumulations on the braided River Drôme, France (Fig. 4), showed that accumulations were randomly distributed on bar surfaces, and, in the studied areas, were mainly jams of wood pieces and rarely individual whole trees, indicating the physical fragmentation of wood during transport in the shallow water of the river. Only 20% of accumulations were crescent-shaped, whereas 80% formed straight deposits (including all the observed trunks but also some jams), suggesting wood deposition on bar surfaces during relatively gentle, falling river stages. This contrasted with wood deposition at the channel – floodplain forest boundary, where crescent-shaped accumulations were often formed, illustrating the force of the water against the wood structure. The deposited trunks and the shrubs were usually oriented parallel to the axis of the braided channel or active zone (not the low flow channel), whereas the jams were perpendicular. The accumulations formed in lines on open gravel areas, often

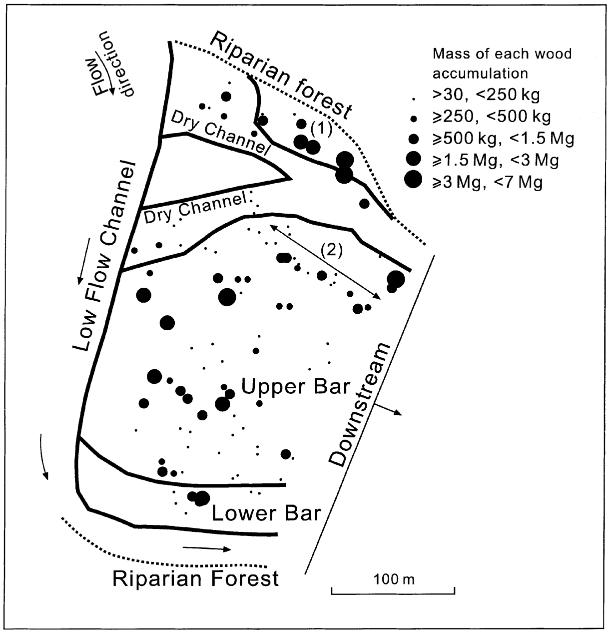

Fig. 4 Distribution and mass of wood pieces and accumulations deposited in the braided reach of 'Les Ramières' on the River Drôme. Wood accumulations form lines on open gravel, often corresponding to areas of preferential flow across low areas of bars [e.g. (1)] or the upper parts of bars [e.g. (2)].

corresponding to the low areas of preferential flow across the bars [e.g. (1) on Fig. 4] or to the upper parts of bars [e.g. (2) on Fig. 4], with smaller numbers and sizes of accumulations corresponding to the areas between axes of preferential flow. Lower areas within the active zone (e.g. the lower parts of bars and secondary channels) had fewer and smaller accumulations. This reflects the discontinuous nature of wood input and the importance of the flow regime. Large floods (e.g. > Q_5) can erode the floodplain forest and can occupy the entire width of the braided channel, depositing wood widely during subsequent falling stages, whereas small floods do not extend to the floodplain forest margin and so achieve little bank erosion to supply wood, but are capable of removing wood deposited within the lower levels of the active zone by previous larger floods. As a consequence, the amount of wood stored within the braided channel decreases with increasing time from the last large flood.

Fig. 5 illustrates the different types and positions of wood accumulation within large meandering or braided rivers. Wood has various effects on river morphology. Most wood pieces accumulate in heterogeneous accumulations, called jams (Fig. 5, A), which are mainly distributed in association with roughness structures, such as the edges of vegetated islands. Locally, jams can form as continuous walls or 'debris lines' (Hickin, 1984; Piégay 1993) along concave banks during overbank flows (B). Other jams can establish on the concave banks of secondary channels or overbank flow channels (C). Individual trees and logs are frequently deposited on bars (D) and are usually oriented parallel to the flow. In the former case, the tree's trunk and root wad usually points upstream. In higher energy situations, such deposits can have a significant morphological impact. Pools form at the upstream end of deposited trees in response to flow diversion imposed by the root wad (Fetherston *et al.*, 1995; Abbe & Montgomery, 1996; Edwards *et al.*, 1999) and fine sediment often accumulates downstream along the trunk, frequently providing suitable conditions for pioneer vegetation establishment. The deposition of isolated trees or logs is very common on point bars of meandering piedmont rivers (E) (e.g. Fetherston *et al.*, 1995), inducing the above morphological changes and sometimes leading to scroll bar development (Nanson, 1981; Gurnell *et al.*, 2001). Wood deposited on bars may have little morphological effect when the pieces have been broken, simply forming a strand line (F), although subsequent shooting and growth of the wood pieces may form vegetation lines which can provide a core for sedimentation and ridge formation (McKenney, Jacobson & Wertheimer, 1995). On lowland, low-energy rivers, weak wood transport results in most of the wood pieces being isolated, positioned close to the bank and often still anchored in it (G). Other wood pieces form 'snags' within the channel (H). B and E are typical of meandering piedmont rivers but can also be observed on braided channels. The degree to which these morphological adjustments are found on any particular river system depends not only upon the wood supply but also on the power of the river flows to erode, transport and deposit sediment and the quantity and calibre of sediment that is available for transport.

Whilst the above description illustrates that the geomorphological effect of the wood is easily recognised at the microscale (fluvial facies), more research is needed to understand its role at the reach scale in large rivers. Historical studies show that above a threshold of wood input and storage in a channel reach, wood has significant effects on

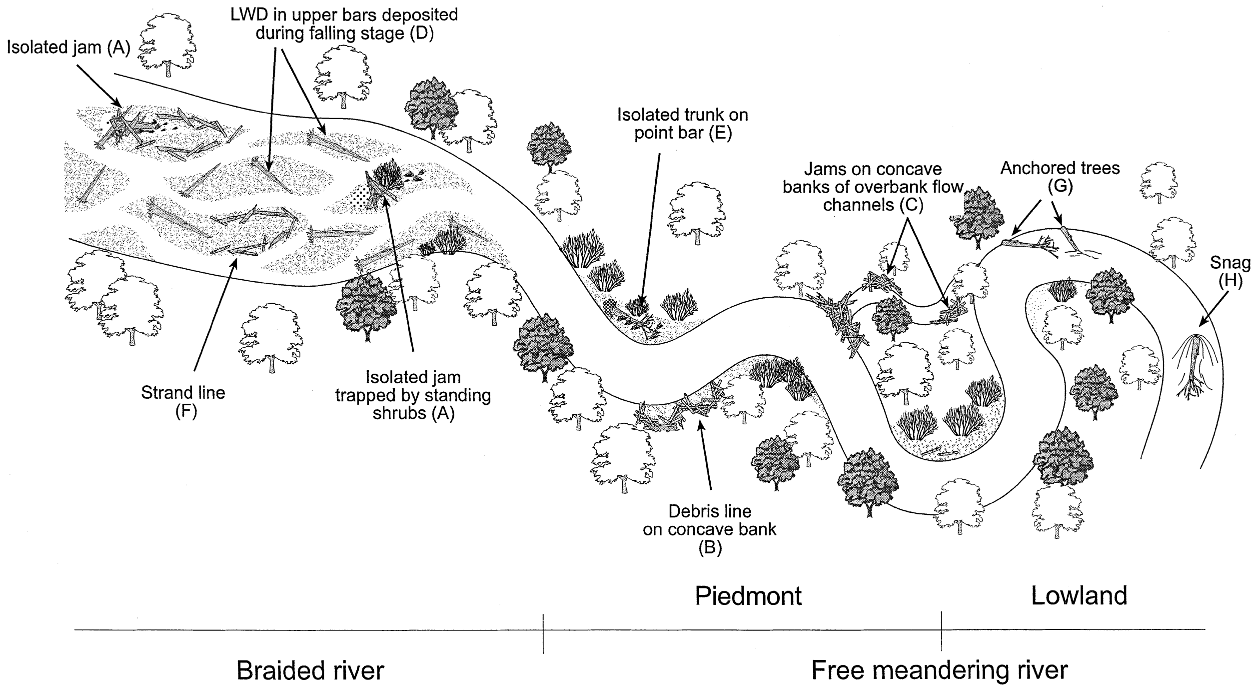

Fig. 5 Typology of large wood accumulations observed in large rivers from upland braided systems to meandering lowland ones.

channel and floodplain processes and connectivity (Triska, 1984). Wood favours forest establishment and actively participates in the development of island-braided and anastomosing systems (Gurnell & Petts, 2002). In many circumstances wood can protect sedimentary structures against imposed shear stresses but in other cases it can accelerate erosion by diverting flows. Fetherston *et al.* (1995) suggested that successional stages of vegetation within a riparian forest are associated with the incorporation and coalescence of forested islands largely initiated behind wood accumulations. Furthermore, within individual islands, they observed that the age of vegetation decreased from upstream to downstream reflecting the direction of island growth behind wood accumulations. Moreover, where the deposited wood remains alive, island development can become accelerated (e.g. Edwards *et al.*, 1999; Gurnell *et al.*, 2001). Vegetated islands can also establish independently of wood deposits, because on any given area of the channel the shear stress can change over time with bar formation, flow diffluence and channel shifting. Vegetated islands can also act as trapping structures that cause wood deposition and so wood presence may be a cause or a consequence of vegetation encroachment. The efficiency of wood as an agent of vegetation encroachment is controlled by factors such as the size of the wood compared with the channel size (which controls its stability), the capacity of the wood to sprout (which depends upon the tree species, the calibre and moisture regime of the local substrate, the rate of sediment accumulation around the establishing vegetation) and the frequency and magnitude of flood disturbance (Gurnell *et al.*, 2000). All of these factors contribute to the dynamics of islands within large river systems (Gurnell *et al.*, 2001; Gurnell & Petts, 2002). Wood can also have a significant impact on meander chute cut-off. In large rivers such as the Ain River, France, wood that accumulates in the form of a debris line protects the floodplain forest from erosion and slows the cut-off processes. However, if wood blocks the channel (a typical process in medium rivers, that can also occur in large rivers where the wood load is very high), it can favour cut-off development.

Whilst Fig. 2 explicitly considers the relative importance of the natural controls on wood storage and dynamics, it implicitly includes man's influence through the consideration of hydrological and wood characteristics. Natural processes of wood dynamics are far from being well-understood, particularly in large rivers, because of the frequently high impact of human activity. This has modified (i) the volume of wood input (riparian trees are usually smaller now than they were before human settlement, bank erosion rates have been reduced by various engineered structures, and beaver populations have been reduced even to extinction), (ii) the volume of stored wood (much wood has been removed from rivers to maintain navigation and control floods), and (iii) the longitudinal connectivity underpinning wood transfer (dams and weirs trap wood coming from upstream and other structures limit landslides and debris flows in upland areas).

Furthermore, river flow and sediment transport regimes not only reflect natural processes within the catchment but also management impacts such as flow augmentation or regulation and artificial controls on sediment release and transport. Such management practices affect both channel size and geomorphological style, and they are significant for the interactions between flow, sediment and wood. Changes in water level regime can also induce changes in wood decay patterns and rates. As a consequence, studies of wood dynamics, particularly in large rivers, illustrate anthropogenic systems more than natural systems, even if the landscape of the river appears to be relatively natural. In such contexts, questions about restoration strategies are complex and often exceed the time scales usually considered within restoration projects. For example, even if it were possible to mitigate human effects on wood input and storage, the restoration of an ecosystem within which the wood fully influences habitat creation and diversity is extremely unlikely because it requires a long period (decades to centuries) of riparian vegetation recovery to re-establish mature riparian forests of mixed, including senescent, stages. This is inconsistent with restoration projects for which managers want to measure effects in the few years following interventions. Conservation measures are therefore essential to save reaches where the natural structural conditions of the riparian forests are still well preserved and within which it is still possible to observe wood-related processes over a shorter timescale.

Conclusion

Early in this paper, analogies were drawn between wood and mineral sediment as important elements of a river's load. In drawing these analogies, issues of supply, entrainment, weathering or decomposition, deposition, accumulation, temporal variability and the nature and the potential for a typology of wood architecture were raised. Whilst all of these require deeper discussion, the present review has sought to indicate how these factors may vary with river size. Importantly, key properties of wood pieces (length, diameter, form, buoyancy, ability to sprout), which reflect their species, age and susceptibility to decay, have been shown to influence wood dynamics and storage. Wood supply is also important, because it influences the degree to which pieces may interact, break up, or become entangled during transport and deposition. However, the dynamics and storage of wood are also highly dependent upon fluvial processes. The river's flow regime and slope (which provide its power), the moisture regime of exposed sediments, the quantity and calibre of the sediment that is available for transport and deposition, the water depth in comparison with the wood piece diameter (which control wood mobility and abrasion), all moderate the role of wood within fluvial systems.

Acknowledgments

The authors wish to thank colleagues and students who have participated in studies of wood in France (L. Maridet, A. Thévenet, A. Citterio, B. Moulin) and Italy (D.M. Hannah, A.J.G. Gerrard, G.E. Petts, B.P.G. Smith). A.M. Gurnell and G.E. Petts acknowledge grants GR9/3249 and NER/B/S/2000/00298 from the U.K. Natural Environment Research Council, which funded research in Italy. F.J. Swanson and S. Gregory thank the National Science Foundation for funding for the Andrews Forest Long-Term Ecological Research program and the U.S. Forest Service for support of long-term watershed studies. Finally, we thank A. Citterio who drew Fig. 5 and K. Burkill and A. Ankcorn who drew Figs 1, 3 and 4.

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(Manuscript accepted 5 November 2001)