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Large woody debris and river geomorphological pattern: examples from S.E. France and S. England

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Abstract

The study of accumulations of dead wood within the fluvial environment has been mainly undertaken in mountain streams and rivers within the Northwestern United States, and particularly in hydrosystems which have experienced little riparian vegetation cutting or disturbance by man. Appraisals of the spatial variability in the physical character of accumulations of dead wood has mainly highlighted the volumes of large woody debris (LWD) accumulations and the local channel morphological properties induced by their presence. The spatial variability in the accumulation and processing of organic material forms one of the central concepts of the River Continuum Concept, which characterises the occurrence and processing of organic material, of which LWD is an important component, according to a longitudinal gradient along a river's course. Some studies have extended the concept by illustrating the importance of the lateral dimension, particularly in large rivers with extensive floodplains, and by relating the occurrence of dead wood to fluvial morphodynamics. However, to date there has been no synthesis of the relationship between LWD and the geomorphic pattern of the river channel.

Although the research literature shows that the routine clearance of wood from water courses is not an environmentally-sympathetic strategy, within Europe LWD accumulations are usually seen as a river management problem and are routinely cleared from river channels.

This paper addresses these physical and applied aspects of the role of LWD. It presents an analysis based upon semi-natural hydrosystems in S.E. France and S. England. The forested corridors discussed are currently or have recently been maintained. They are essentially young and so produce relatively small amounts of woody debris in relatively small-sized individual pieces in comparison with the rivers studied in North America. Using observations from these example river corridors, the relationship between rivers of a particular size and geomorphic pattern and the dynamics of dead wood is described and evaluated. Major constrasts in the role of LWD are found between small, single thread rivers, and larger, piedmont, braided and wandering rivers. Some points of synthesis concerning the ecological, hydraulic and morphological impacts of dead wood are drawn from these examples, and are used as a basis for proposing some simple maintenance rules.

Keywords: large woody debris; river pattern; riparian zone management; European rivers

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1. Introduction

River valleys across much of the World were once extensively wooded with the consequence that fallen trees, branches and leaves formed a significant component of the river environment. Clearance of wood from rivers to maintain the capacity of the channel to transmit water and so to alleviate flooding; to avoid blockage and damage to structures such as bridges, piers and weirs; to improve navigation and; (mistakenly) to improve fish passage have led to far-reaching changes in the morphology, stability and ecology of river systems (e.g. Sedell and Froggatt, 1984). The adverse impact of woody debris clearance has been magnified by the widespread deforestation and drainage of floodplains and the engineering of river channels to completely new forms through straightening, dredging and bank stabilisation (Brookes, 1988; Petts, 1990).

In the United Kingdom, the long history of woody debris clearance from river channels is well illustrated by the reference to the routine clearance of weeds, trees and bushes in historical sources (e.g. Laws of Sewers, 1732). In France, since the floods of 1993, the authorities have clearly stressed their desire to manage riparian vegetation. The Barnier Law of 2 February 1995, which relates to the protection of the environment, reaffirms in article 23 that the riparian owner is required to undertake a regular clearing regime to reinstate the water course to its natural size and depth, to maintain banks by pruning woody vegetation, and to clear dams and debris, whether floating or not, in order to maintain the natural flow.

The analyses presented in this paper are based upon two premises:

First, it is already recognised within the international research literature, that the removal of debris dams is not consistent with the maintenance of a healthy aquatic ecosystem. Indeed, the contrary is true (Bisson et al., 1987; Piégay and Maridet, 1994; Gurnell et al., 1995). Whereas floodplain deforestation has a long history in Europe, tree and driftwood clearance has been more recent in the Pacific Northwest of the United States. Here settlement did not commence until the 19th century, and so the extensive research undertaken in this region has clearly documented the devastating impact of deforestation and driftwood clearance on the aquatic environment (Maser and Sedell, 1994). Very significant research programmes undertaken in this and other regions of North America over the last twenty years have provided the core of several recent reviews (e.g. Gurnell et al., 1995; Sedell et al., 1988; Sullivan et al., 1987). These reviews illustrate that the routine clearance of wood from water courses is no longer an environmentally-acceptable component of river management, but they also show that much research is required outside of North America if the management of wood in rivers is to be appropriate to local environmental conditions.

Second, the dynamics of large woody debris (LWD: defined as wood pieces greater than 10cm diameter and 1 m length, Platts et al., 1987) and its role in enhancing flood risk varies with the type of river, so influencing the assessment of the hazard. It also varies with the nature of human occupation of the floodplain, so impacting on the assessment of the risk. These varying aspects of both the hazard associated with LWD and the accompanying risks to floodplain occupants implies that a flexible approach to LWD management is required to maximise environmental benefit and minimise associated risks.

This paper contributes to the evaluation of the geomorphological significance of LWD in European rivers. It provides a context for this evaluation through an analysis of the international literature on LWD. The geomorphological significance and role of LWD within European rivers is then emphasised through the description of some case studies from S.E. France and S. England concerning rivers of different geomorphological pattern or type. Finally, some recommendations for management based upon geomorphological river types are presented.

2. Previous research

The emphasis of previous research on LWD can be illustrated by an analysis of the content of 104 research papers assembled by the present authors from the open literature. Of these 104 papers, only one was published before 1975, but there has been a steady rise in the number of publications since then.

There is a strong regional bias in the published studies. 23 are review papers which mainly focus on North American research, and of the remaining 81 papers concerning individual research programmes, 67 are based in North America of which 34 (50% of the North American research publications) are located in the Pacific Northwest or in Alaska. This not only indicates the North American bias in the published research but also the very strong regional focus within North America and the focus on catchments where much of the forest cover is relatively undisturbed.

The publications address a range of aspects of LWD character and impact. 49% provide details of the volume of LWD and the character and stability of debris accumulations. The impact of woody debris on physical habitat diversity and stability is also a major feature of the published case studies (47%). The influence of debris accumulations on sediment movement (27%), organic matter retention and decomposition (21%) and flow hydraulics (20%) relate to their significance in creating suitable habitat for fish (20%) and macroinvertebrate (10%) populations. Many studies consider the impact of forest management on debris accumulations through empirical analyses but the precise role of LWD is also investigated by debris addition or removal experiments in as many as 28% of the investigations. Whilst the general environmental significance of LWD is highlighted in virtually all of the studies, in 15% of the publications research has led to very specific recommendations about the management of in-channel debris and riparian vegetation.

In summary, the content of these 104 publications on LWD shows it to have at least three levels of impact on woodland river environments:

(1) LWD directly impinges upon the distribution of stream power, leading to influences on the hydraulics of in-channel flows and the distribution of overbank flows; and thus on the transport and storage of sediments and organic material within the river channel system and on the floodplain. Comparative studies between streams where debris has been retained or removed, suggest that as a result of removal, sediment yield can increase by an order of magnitude and sediment movement results in the development of bars and benches which partly replace the storage role of woody debris accumulations, although enhanced sediment yields persist because the bed material remains relatively more mobile than in channels where woody debris has been retained.

(2) Influences on flow hydraulics and sediment storage and transport lead to secondary impacts on the geomorphology of woodland river channels including the average condition and variance in channel dimensions; the magnitude and distribution of pools and riffles; and the overall increased stability of river channels.

(3) River channels containing accumulations of LWD are able to store and transmit sediments, including organic material, in a well-regulated manner; and they consist of channels which present a high physical habitat diversity both within and between debris accumulations. As a result there are major impacts of LWD accumulations on the ecology of woodland river channels. The storage, break-down and regulated release of organic matter provides temporally and spatially regulated food sources for aquatic biota. Furthermore, the complex physical structure of woodland river channels provides a variety of habitat patches which can support a wide variety of organisms at different stages of their life cycles. As a result, the abundance of LWD has been positively correlated with a high diversity in both macroinvertebrates and fish; and the removal of debris has caused a reduction in the diversity, density and/or biomass of invertebrates and fish.

However, the regional focus of much of the literature, has resulted in a large proportion of the research results reflecting mountain rivers where hydrosystems have experienced little riparian vegetation cutting or disturbance by man. Furthermore, although longitudinal gradients in the character of LWD accumulations have been identified, and their lateral role has also been recognised, the relationship between the character of accumulations and the geomorphological pattern of the river has not been evaluated. By focusing on some European examples, the emphasis presented in this paper is on semi-natural hydrosystems in forested corridors that are currently or have recently been maintained. The forests are frequently young and so produce relatively small amounts of debris in pieces which are individually of relatively small-size in comparison with the forested river corridors studied in North America.

3. The accumulation and transfer of LWD in rivers of different size and geomorphological pattern

A variety of factors govern the physical processes in rivers and thus their morphology. Primary factors are the volume and temporal distribution of water and sediment delivered to the channel and the nature of the materials through which the river flows. Secondary factors include the nature of the riparian vegetation, land use, and direct modification of the channel (Church, 1992). Since riparian vegetation and the associated supply of organic material to the river forms only a secondary factor influencing channel morphology, there is an enormous variety of river channel types within which the role of LWD should be evaluated.

Church (1992) provides a classification of river channel types within three groups: small, intermediate and large channels, where channel size reflects the ratio of channel to boundary particle size. "Large rivers are ones in which purely fluvial processes and geological constraints determine the morphology" and thus the primary factors are dominant, whereas within the range from intermediate to small channels, secondary factors, particularly individual roughness elements such as rocks and pieces of wood become increasingly important influences on channel morphodynamics. In particular, the size of the channel in comparison with the size of the organic debris delivered to it will have an important influence on the interaction between the two.

The subdivision of river types into three groups is mirrored by the River Continuum Concept (RCC, Vannote et al., 1980) which "provides a framework for integrating predictable and observable biological features of flowing water systems with the physical-geomorphic environment" (p. 135). The RCC is a concept developed mainly by biologists based on the energy equilibrium theory of geomorphologists (Vannote et al., 1980). It associates biological invertebrate strategies and coarse to fine organic matter dynamics with a hydrological and geomorphological continuum, and hypothesises analagous functioning of biological and physical systems in terms of energy utilisation. The authors argue that allocthonous supplies of coarse particulate matter including LWD are the main source of organic matter in small streams, whereas primary production characterises larger rivers located downstream. Thus, the RCC proposes some broad characteristics of lotic communities related to three groupings of stream size: headwaters (stream orders 1–3); medium-sized streams (orders 4–6) and larger rivers (order > 6).

The RCC is extended by Sedell et al. (1989) through the incorporation of the lateral dimension, particularly in the case of large rivers where the ratio of floodplain width to river channel width may be large, and where interaction between river and floodplain may be complex and both geomorphologically

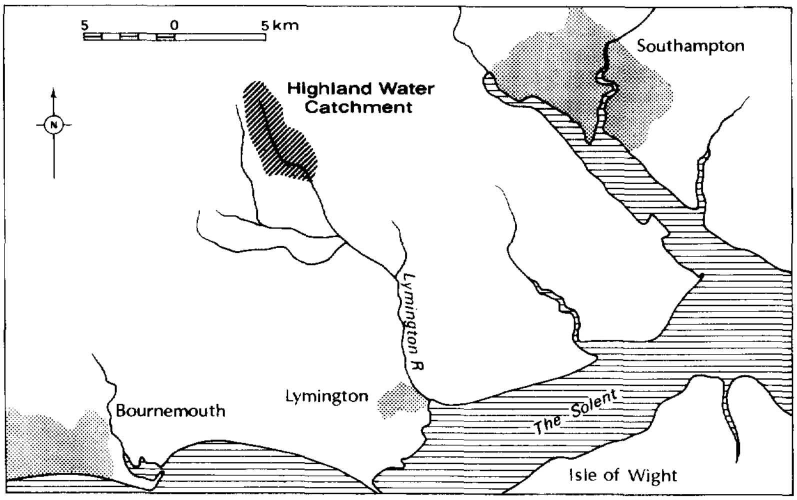

Fig. 1. Location of the Highland Water catchment.

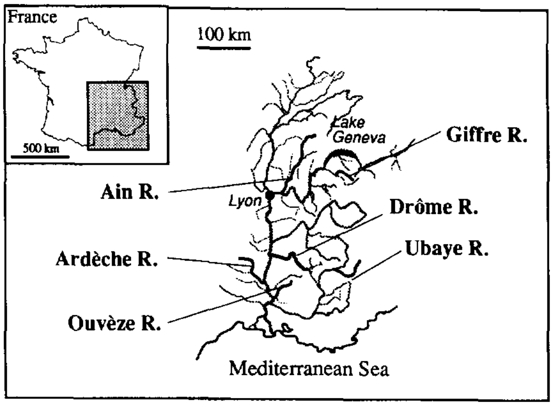

Fig. 2. Location of the large rivers studied.

and biologically significant. Sedell et al. (1989) emphasise the spatial variability in this interaction, so hinting at the significance of river channel and floodplain type in controlling the biological character of large rivers. "A framework which allows us to examine both the hydrologic and geomorphic settings of the individual reaches and their longitudinal arrangement will make it possible to distinguish the relative merit of viewing a particular river system as a continuum or as a series of independent reaches" (p. 53).

Church (1992) explicitly discusses the role of LWD in relation to the morphodynamics of small and intermediate channels. Furthermore, the great variety of river channel types defined by Church (1992) within his large channel category, and the variability in the nature and extent of channel morphodynamics within each type emphasises the importance of considering the geomorphological pattern of the river channel in relation to its biological character and specifically to the character and mobility of LWD.

A comprehensive review of the interaction between LWD and rivers of differing size and pattern is a major task, and at present there is insufficient field information to support such a review. We therefore concentrate on a restricted range of three river types for which European research studies are available: single thread small to medium-sized rivers (Highland Water, Fig. 1) and larger piedmont river systems with braided (Drôme, Giffre, Ubaye, Ouvèze) and wandering (Ain, Ardèche) channel patterns (Fig. 2).

4. Some European examples of the character of LWD accumulations within rivers of different geomorphological pattern

4.1. Small and medium-sized rivers

The character and dynamics of LWD in small and medium-sized rivers are represented here by the examples of the Bagshot Gutter and upper Highland Water (2.6 km and 3.5 km lengths, respectively, of channel of order 1 to 2) and a stretch of the main Highland Water (5.0 km length of order 3–4), located within the New Forest, Hampshire, Southern England (Fig. 1). These stretches are all bordered by relatively unmanaged, mainly mixed, woodland which extends to the edges of the active channel. Full details of the character of the Highland Water and enclosing Lymington River catchments are provided in a number of publications (e.g. Gregory and Davis, 1992, 1993; Gurnell and Gregory, 1995) and so are not included here. In brief, the channels are of low slope (the average slope of the 3–4 order channel is 0.0075), but are subject to a flashy hydrological regime as a result of the extensive areas of Eocene Barton clay underlying the lower hillslopes and floodplains within much of the catchment.

LWD accumulations resulting from the action of fluvial processes largely occur within the perennially-flowing river channels of these river stretches in the form of debris dams. The smaller channels (order 1–2) are not associated with significant floodplain development, but along the main Highland Water (order 3–4), there are some smaller dams of woody debris located within ephemerally-flowing flood channels on the surrounding floodplain. Nevertheless, in general the LWD accumulations occur as in-channel dams located approximately perpendicular to the direction of flow. This form of accumulation reflects the size of the trees in comparison with the size of the channel. For example, a survey of the main Highland Water in July 1990, identified 35 fallen trees located where they could influence fluvial processes in the main channel. The 10 largest trees had an average trunk diameter of 0.5 m and an average canopy height/length of 17 m compared with an average channel width of 3.2 m. Another illustration of the importance of tree/debris size in controlling the nature of woody debris accumulations

Fig. 3. Unstructured accumulation of LWD within the Upper Highland Water.

is a survey of the dimensions of the largest piece of debris present in the debris dams. In the summer of 1991, a survey of 76 dams within the same stretch of the Highland Water, revealed a mean length for the largest piece of wood within each dam as 5.3 m, a length which is significantly larger than the 3.2 m average channel width and which illustrates the way in which many LWD key pieces lie partly on the bank and partly in the channel.

Thus, in these small- to medium-sized channels, LWD accumulates largely in the form of transverse dams within or, in the case of some long pieces of debris, spanning the main channel. In smaller streams (e.g. order 1 to 2), the small width of the channel in comparison with the size of much of the debris and the low power of the flow, can lead to relatively unstructured, accumulations of LWD, with medium to large pieces of wood remaining where they fall (Fig. 3), although smaller debris pieces can move downstream and accumulate into quite compact, small dams (e.g. Fig. 4). In larger streams (e.g. order 3 to 4), larger wood pieces become mobile as a result of the larger channel size and the higher stream power. Under these conditions, quite large accumulations of LWD can develop (Fig. 5). Gregory et al. (1985) devised a simple classification of these transverse debris dams into three types: active dams (which present a complete barrier across the channel which induces a pronounced step in the water surface profile even at low flows); complete dams (which completely span the channel but do not induce a significant step at low to medium flows); and partial dams (which do not completely traverse the channel). Table 1 lists the frequency of the different dam types present in the example small and medium-sized channels during the summer of 1991.

Fig. 4. Compact accumulation of smaller debris pieces within the Upper Highland Water.

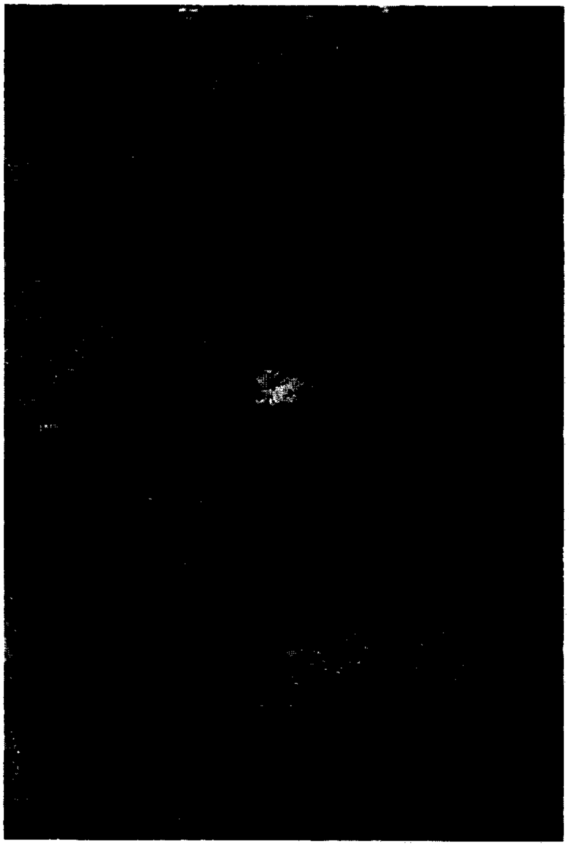

Fig. 5. An accumulation of LWD forming an active dam within the main Highland Water channel.

In the case of the main Highland Water, clearance of dams during January 1990 may have reduced the number below that which is representative of a period without significant dam management, and so frequencies for the same stretch in 1984 are included to represent a period of negligible dam management. The percentages of dams of the three types are similar for the two dates. The major contrast between the two small streams and the medium-sized stream is the larger proportion of complete dams in the former, representing the influence of the smaller channel size in proportion to tree size. There is little difference in the proportion of active dams between the streams of different size. Table 1 also lists estimates of the biomass of debris accumulations for the three sample stretches of river in summer 1991. The lower estimate for the main Highland Water in comparison with the smaller rivers may be influenced by an incomplete recovery from the debris clearance undertaken in January 1990.

Of particular significance for management is the mobility of debris dams within these small- to medium-sized rivers. Table 2 summarises the degree to which dams of different types mapped within 5.0 km of the main Highland Water in September/October 1982 persisted or changed according to a resurvey in January 1984. Table 2 lists changes in the frequency and type of debris dams identified within 50 100 m sections of the main Highland Water between 1982 and 1984. Although there was only a 8% increase in the total number of dams during this period, 33% of 1984 dams were newly created, 24% of dams had been removed, whereas 18% had changed type. Of the three different dam types, partial dams were the most unstable with a gain of 44% resulting from the creation of new dams, 40% resulting from dam removal, and only 13% and 9% gains and losses, respectively, resulting from a change of dam type. In contrast, active dams were the most stable with a gain of only 7% attributable to dam creation, a loss of only 11% attributable to dam removal, but 25% and 43% gains and losses, respectively, resulting from a change in dam type. This suggests that once major dams accumulate they are relatively stable, and may play an important role in regulating the movement of individual pieces of debris.

A further indication of the mobility of debris in this 5.0 km stretch of the main Highland Water is listed in Table 3, where the detailed recovery in the frequency of dams of different types is recorded from immediately after debris dam clearance (January 1990) over the following 16 months (to May 1991), in comparison with the condition of the dams after a long period without management (January 1984). The rate of recovery of the dams is rapid, although this recovery was undoubtedly accelerated by the major input of debris during the severe storm on 24 January 1990. The relatively large number of the partial and complete dams which developed immediately after clearance, also illustrates the mobility of LWD pieces when active dams are not there to trap them. Increased river flows during Autumn 1990 appear to have mobilised much of the LWD, reducing the number of partial and complete dams and relocating the debris within active dams. This pro-

Table 1
Frequency and biomass of debris dams in small and medium-sized rivers

River Stretch	Order	Biomass (kg · km^{-1}) [a]	Number (%) of different dam types			
			Partial	Complete	Active	Total
1984						
Main Highland Water	3–4	–	109 (64%)	41 (24%)	21 (12%)	171
1991						
Main Highland Water	3–4	5100	58 (61%)	23 (24%)	14 (15%)	95
Upper Highland Water	1–2	6500	7 (19%)	17 (46%)	13 (35%)	37
Bagshot Gutter	1–2	9800	0 (0%)	35 (85%)	6 (15%)	41

[a] Biomass is expressed to 2 significant figures.

vides further evidence for the importance of the more stable active dams in controlling overall debris mobility.

4.2. *Larger, alluvial rivers of mountain and piedmont zones*

The alluvial river channels of mountain and piedmont zones are characterised by high energy, strongly varying river flows, abundant coarse sediment load and wooded corridors whose ligneous biomass is frequently well developed. These forested hydrosystems are subject, according to their geomorphic patterns, to specific types of debris dynamics. Six water courses in South East France are taken as illustrative examples

4.2.1. *Braided river systems*

Braided rivers like the Giffre (Alpes du Nord), the Ubaye and the Drôme (Alpes du Sud) or the Ouvèze (piedmont of the Prealpes du Sud) (Fig. 2) have an approximately rectilinear active band. The riparian margins usually consist of pioneer vegetation which is restricted in its development by frequent floods. Thus, these hydrosystems are unable to supply large amounts of dead wood but more usually supply

Table 2
Changes in the frequency, location and character of debris dams in 100 m sections of a 5.0 km stretch of the main Highland Water, September/October 1982 to January 1984

Type of change observed in 100 m sections	Number of dams of different type [a]			
	Partial	Complete	Active	Total
1982 total	90	40	28	158
Dam Additions, 1982–84				
Changed dam type	12 (13)	10 (25)	7 (25)	29 (18)
Dams created	40 (44)	10 (25)	2 (7)	52 (33)
Total additions	52 (58)	20 (50)	9 (32)	81 (51)
Dam Losses, 1982–84				
Changed dam type	−8 (9)	−9 (23)	−12 (43)	−29 (18)
Dams removed	−28 (31)	−7 (18)	−3 (11)	−38 (24)
Total losses	−36 (40)	−17 (43)	−15 (53)	−68 (43)
Net change	+16 (18)	+3 (8)	−6 (21)	13 (8)
1984 total	106 (118)	43 (108)	22 (78)	171 (108)

[a] % of 1982 totals given in parentheses.

Table 3
Debris dam frequency at different dates along a 5.0 km stretch of the Highland Water

Date	Dam type			
	partial	complete	active	total
Autumn 1982	90	40	28	158
Jan. 1984	106	43	22	171
Jan. 1990	26	8	15	49
Jul. 1990	68	45	10	123
Nov. 1990	52	21	24	97
May 1991	58	23	14	95

pieces of flexible vegetation and small pieces of dead wood. They are also unable to retain those pieces of wood which are in transit because of the low trapping efficiency of the channel as a result of the low sinuosity, and the lack of secondary channels narrow enough to stop the transit of wood. Debris accumulations are extremely rare.

The deposits of LWD tend to accumulate preferentially in the braided zone and not in the forest fringe (Fig. 6). For example, isolated trunks are often deposited on gravel bars during the falling limb of floods (Fig. 7). The transfer time of wood is relatively short as a result of the relative rarity of potential depositional sites and the high energy of the river systems. Nevertheless, some of the wood may be transported only a short distance. For example, on the River Drôme there is a low but significant correlation between the number of logs located within a 500 m reach and the number of 500 m reaches in the 3 km stretch upstream that are characterised by an eroding wooded bank ($r^2 = 0.13$; $p < 0.0001$; Landon et al., 1995). Dead wood may also have a distinctive morphological role within the active band of the channel. Under certain circumstances it provides locations for sedimentation and thus the accumulation and stabilisation of gravel banks, as has been shown by Malanson and Butler (1990), Nakamura and Swanson (1993), Robison and Beschta (1990).

Contributions of dead wood have been observed to differ between intramontane and piedmont rivers. In intramontane rivers, the contributions of dead wood are primarily delivered from the numerous tributaries along the study reaches. The wood is often profoundly altered during transport so that it consists of torn and jagged pieces. In the piedmont rivers, the riparian zone can also act as a significant source of LWD. As a result, the logs are not so heavily altered and trees, complete with branches

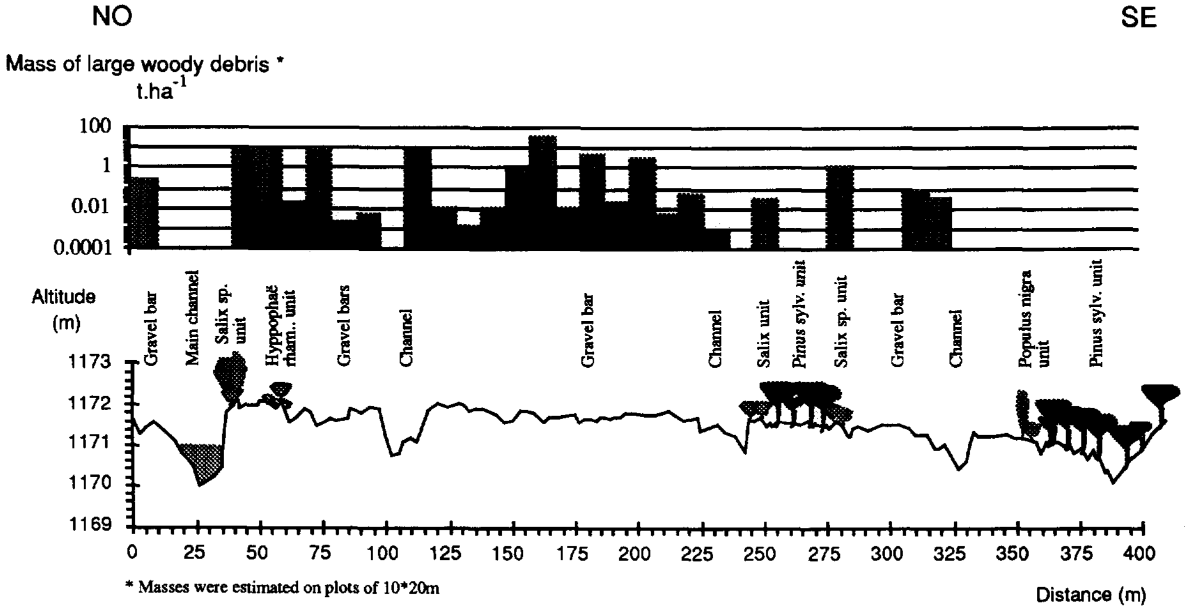

Fig. 6. Distribution of large woody debris along a cross-section of the River Ubaye at the Enchastrayes braided site.

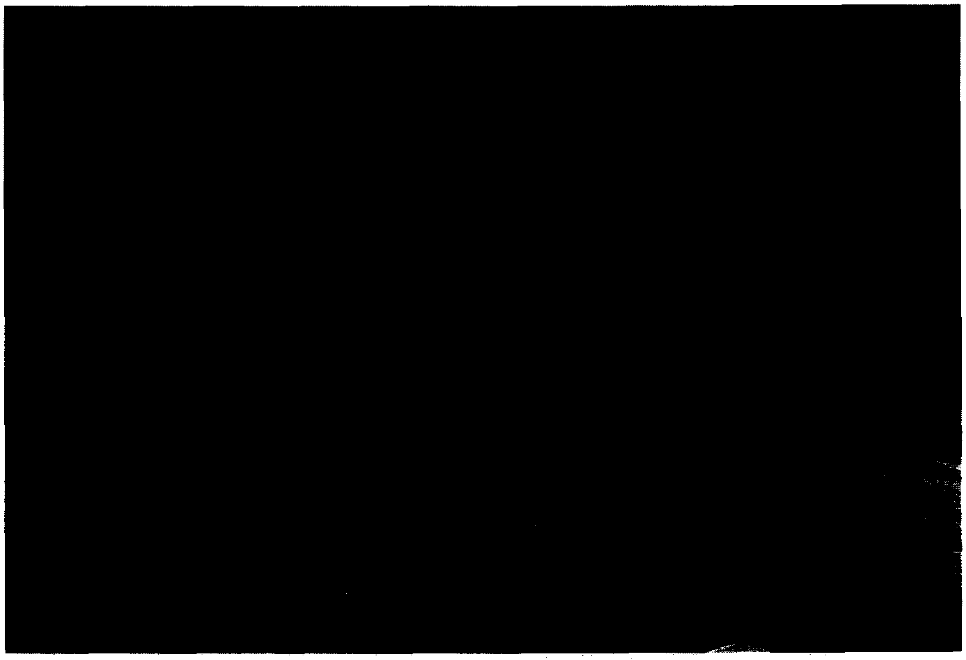

Fig. 7. Distribution of debris jams and floated-in logs on the gravel bars of the active band of the Drôme river, downstream of Crest.

and root systems, can sometimes be observed in the river. On the Drôme, two main types of dead wood have been observed: open accumulations of branches and broken or isolated logs on the active tract; and a discontinuous line of woody debris located on eroded, forested banks. The discontinuous line of debris is very different from that described below for wandering rivers. It exists only sporadically and comprises a

Table 4
Mass of LWD observed at seven sites on the Rivers Giffre, Ubaye and Ouvèze

River	Giffre		Ubaye			Ouvèze	
Study site	Verchaix	Millières	Champanastais	Meolans	Enchastrayes	Violes	Saint-Michel
Total area studied (m^2)	3600	2800	3800	6500	8000	1560	1320
Total LWD mass (t)	2.6	0.038	0.012	0.39	1.8	6.8	10.4
Total LWD mass (t · ha^{-1})	7.22	0.14	0.3	0.6	2.25	43.5	78.6
LWD location							
Active channel (% total mass)	99.0	73.0	0.0	48.0	93.3	0.0	0.0
Pioneer vegetation (% total mass)	1.0	0.0	0.0	43.0	6.7	0.0	–
Post-pioneer vegetation (% total mass)	–	25.0	100.0	2.5	0.0	–	100.0
Mature forest (% total mass)	0.0	2.5	0.0	6.5	0.1	100.0	–
Floodplain zone along the active channel (% total mass)	0.0	0.0	0.0	0.0	0.0	62.0	98.0
Locally-produced LWD (i.e. local blow-down not transported by river flows; % total mass)	0.0	25.5	100.0	9.0	0.1	8.0	0.0

relatively low mass of debris in comparison with the mass accumulated within the active tract of the channel.

Three main factors were found to influence the number of wood pieces (Y) located within 500 m lengths of the Drôme river bed: the braiding index (ratio of total wetted channel length to valley length, Leopold and Wolman, 1957) in the 500 m length (X_1); the number of wooded islands (X_2) in the 500 m length; and the number of 500 m lengths of eroding wooded banks in the 1 km section immediately upstream (X_3). The following multiple regression model illustrates the relationship between these variables:

$$Y = 11.99X_1 + 10.44X_2 + 6.21X_3 - 22.6$$

$$(r_2 = 0.31; \quad p < 0.0001; \quad n = 203)$$

X_1 and X_2 are indicators of the retentiveness of the reach, whereas X_3 is an indicator of the potential supply of wood to the reach.

The role of large floods is an important determining factor in controlling the spatial distribution and dynamics of debris. There is often a discontinuity between the timing of the supply of debris to the river and the occurence of rare floods which are able to transport the supplied wood, so influencing the nature and location of depositional sites. Whereas the active band of the channel is normally the main location of LWD, during large floods dead wood is deposited as a line of debris along the junction between the active band of the channel and the adjacent riparian shrub zones. This debris line can contain large masses of LWD. For example, on the River Ouvèze after a flood whose recurrence interval has been estimated to be greater than 1 in 100 years (Chastan et al., 1993), 4000–5000 t ha^{-1} of LWD were observed along the channel-riparian shrub contact zone compared with 5–40 t ha^{-1} within the forest. The mass and location of LWD differs to some extent between this river and other examples of

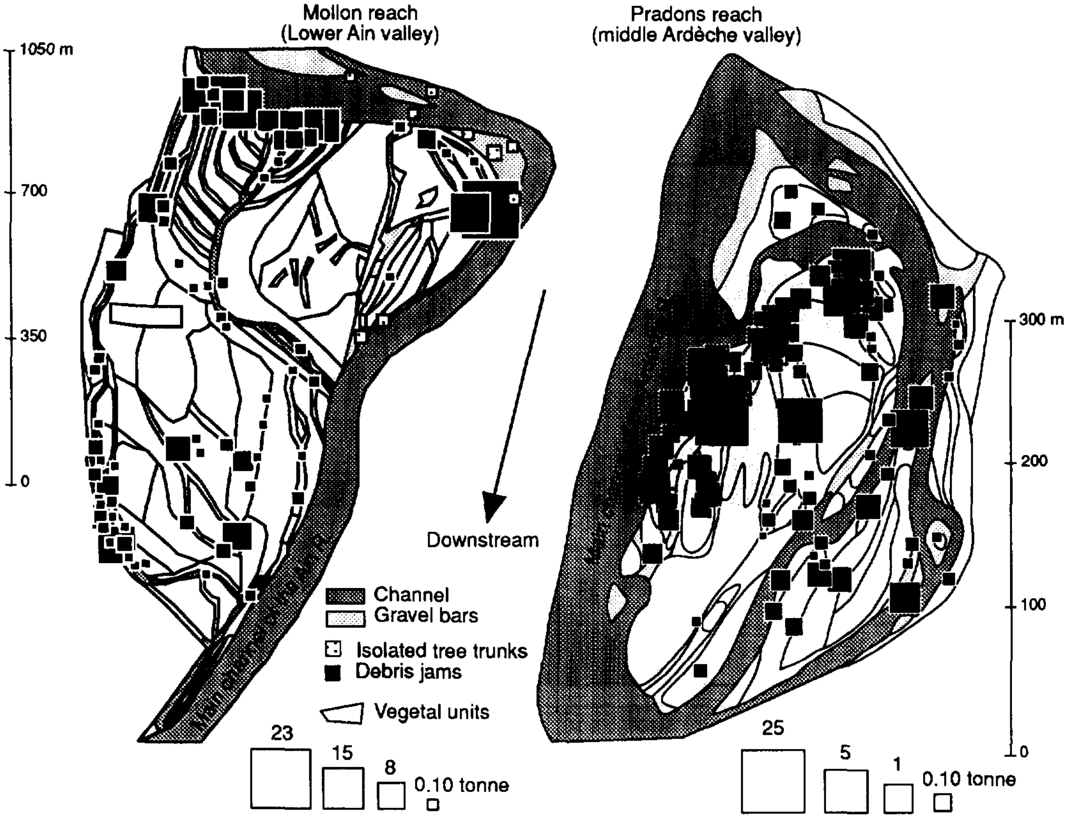

Fig. 8. Debris jam mass distribution in the meander peduncules of Mollon (Ain) and Chauzon (Ardèche).

Table 5
Mass of LWD observed at two sites on the Rivers Ain and Ardèche (see also Fig. 3)

	Mollon (Ain)	Chauzon (Ardèche)
Total area sampled (ha)	85.2	10.0
Total debris jam mass (t)	325.5	371.7
Total debris mass ($t \cdot ha^{-1}$)	3.8	37.1
Number of debris jams surveyed	93	110
Average debris jam size (t)	3.5	3.4
Smallest debris jam observed (t)	0.1	0.02
Largest debris jam observed (t)	23.0	59.0
% debris jam mass located on the channel banks (% total)	45.0	74.0
Debris line mass located on the channel bank (tonnes per linear metre of bank)	0.5	0.9

rivers of this geomorphic type (Table 4; Piégay and Bravard, 1997).

4.2.2. *Wandering rivers*

In wandering rivers the sites for preferential deposition of woody debris are not within the main channel, but are situated along the adjacent floodplain (Fig. 8, Table 5). The wood is deposited at the edges of the main channel and along axes of overbank flows within the forest (Piégay, 1993), the mass of LWD deposited being much larger in the former location. The LWD does not form a debris line along the axes of overbank flows, but is preferentially deposited along flow axis concavities.

Debris deposition occurs in the form of debris

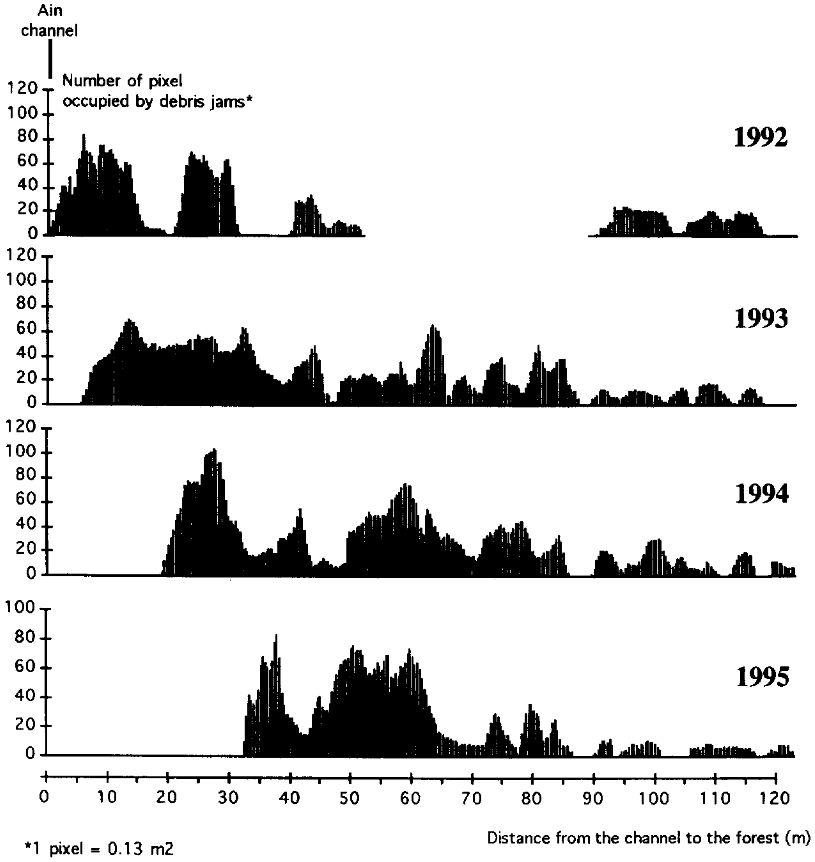

Fig. 9. Upstream – downstream distribution of the surface occupied by LWD in the Mollon plot at the edge of a meander bend on the Ain River in 1992, 1993, 1994 and 1995 (from a GIS-based analysis of raster data).

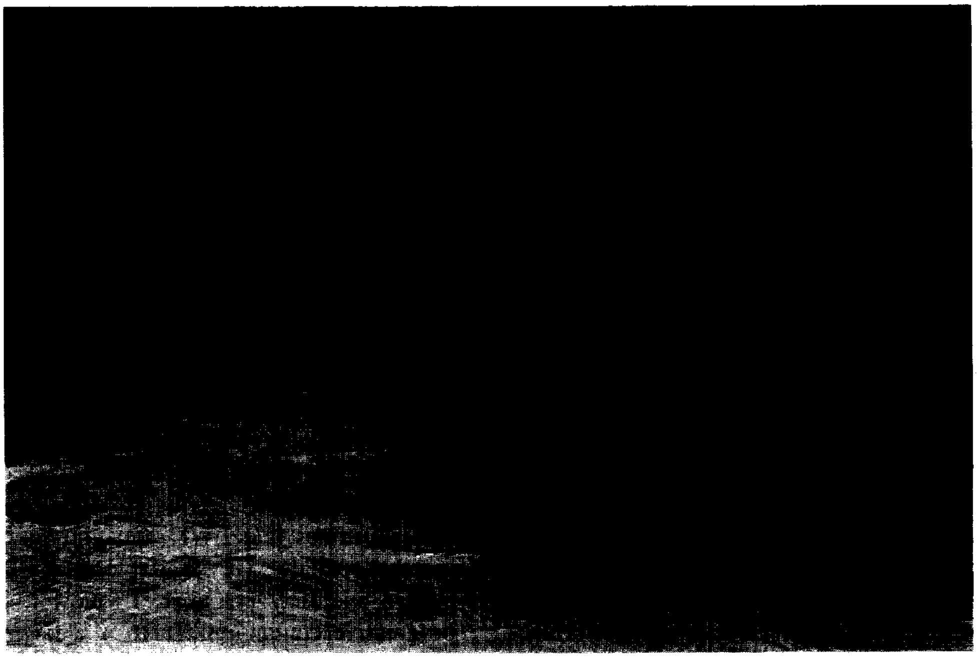

Fig. 10. Canalisation of overbank flow by the debris line on the edge of the Mollon meander bend, River Ain, during a 1 in 7 year flood.

accumulations or jams, that is heterogeneous accumulations of logs in transit, that progressively accumulate in response to debris inputs. These jams are not isolated but form a debris line which is more or less continuous according to the site. On the Chauzon and Mollon sites (located on the Rivers Ardèche and Ain), 74 and 45%, respectively, of the debris is located on the floodplain, amounting to 500 and 900 kg of debris per linear metre of channel.

The total mass of debris is considerably higher than that observed in braided river courses. However, the amount varies from one meander bend to the next. Three factors provide an explanation for this variability: the degree of connectivity between the main channel and the floodplain, the planform of the meander, and the availability of dead wood immediately upstream of the meander bend.

A four year study of a 4000 m^2 area at the edge of a meander bend on the Ain has shown that the mass of debris remained approximately constant from one year to the next although the bank receded by 15m each year (Fig. 9). The concave meander site was a preferential depositional zone but was equally a debris source since, on average, 20 trees disappeared each year. The lines of woody debris were mobile, progressing in proportion to the migration of the bank.

In these wandering systems, accumulations of dead wood have a morphological role. The distribution of debris is discontinuous and is canalised during overbank flows along preferential flow axes (Fig. 10). Marginal erosion occurs in these locations so that a single channel develops as a result of the coalescence of erosion scars. Dead wood, therefore, enhances the battering and erosion of the meanders of forested hydrosystems during overbank flows. These observations are different from those reported by Hickin (1984) and Keller and Swanson (1979), who worked on rivers of a similar geomorphic pattern. Hickin (1984) suggested that the debris line could stop the lateral migration of the channel, but we believe that the riparian morphodynamic reaction to LWD deposition depends on the supply rate, and thus human influence could explain the differences between our observations and those of Hickin. Keller and Swanson (1979) showed that an obstruction of the main channel could accelerate the process of cutoff. Such a process has not been observed on the River Ain, but the Ain is larger than the Squamish and is also probably subject to a more restricted supply of LWD. The supply of less LWD and the predominantly smaller piece sizes make obstruction of large channels by LWD very unlikely in the European context.

5. A relationship between the geomorphic pattern of the river and the character of dead wood accumulations

Our observations of the role of LWD on some European rivers illustrates that this role varies greatly between rivers of different size, power and geomorphic pattern.

The size of the river channel plays a major role in the rate and form of LWD retention and so influences the speed of migration of the material. The riparian forest has greatest influence on small rivers *firstly* because it supplies LWD to an aquatic surface of limited extent, and *secondly* because the size of the pieces of wood may exceed the channel width in some cases, so encouraging debris jams to develop. The interaction between LWD accumulation, decomposition and transfer and a downstream continuum of increasing channel width is the key underlying the River Continuum Concept (RCC; Vannote et al., 1980) and is confirmed by our observations of LWD accummulations in small and medium-sized European rivers. In the small rivers wood accumulates largely where it falls because the power of the river is rarely sufficient to move the debris and because a large proportion of the debris exceeds the river width, making it difficult for the river to transport it. In medium sized rivers the debris is more readily moved because of the relatively higher stream power and the greater proportion of debris pieces which are less than the channel width. Thus in the Highland Water catchment, the proportion of partial dams were observed to increase and complete dams decrease with increasing channel size.

In the larger European rivers studied, the small and restricted supply of debris pieces delivered from the riparian forests made complete obstruction of the channel by accumulations of LWD extremely unlikely. However, the location, structure and function of LWD accumulations associated with large rivers appears to be very variable and so does not always follow a simple longitudinal pattern as implied by the River Continuum Concept. This seems to reflect the retention capacity of the main channel rather than the size of standing trees and whether the trees are managed or unmanaged. It seems that wandering sections of river have a greater capacity to stop the migration of LWD than braided sections.

The variability in the role of LWD can be illustrated at a number of spatial scales. For example, an individual tree trunk within a dynamic meander may be localised in its influence, whereas downstream of a trunk within a braided channel considerable volumes of dead wood can be readily retained. At the scale of the entire channel cross section, the weak overall retention capacity of braided channels in comparison with wandering channels of similar size, also illustrates that LWD dynamics in large rivers can be spatially very variable according to river pattern and may not always follow a downstream progressive continuum. There is a longitudinal discontinuity in the retention capacity, the speed of debris transfer and the local volumes of debris delivered to the river system according to the geomorphic pattern of the river. Furthermore, the amount of wood can actually be much greater in large rivers than in smaller ones when the large rivers are characterised by high lateral channel mobility and thus by very significant local inputs of dead wood.

Based on our European examples, we have illustrated that in large piedmont rivers the functional and structural characteristics of dead wood differ according to the geomorphic pattern of the river. Distinct differences have been observed between braided and wandering river patterns and also between rivers of different power (specifically between intramontane and piedmont rivers). Importantly, the role of LWD in these larger European rivers has been noted to differ from that reported in North American studies. These differences are thought to be mainly attributable to the restricted supply rate and size of LWD pieces delivered from the managed riparian forests of the European rivers that have been investigated.

In greater detail, the geomorphic pattern of a river channel integrates a range of different controlling factors which operate in both longitudinal and lateral directions to control the LWD mass in a river cross section. Fig. 11 synthesises these different factors,

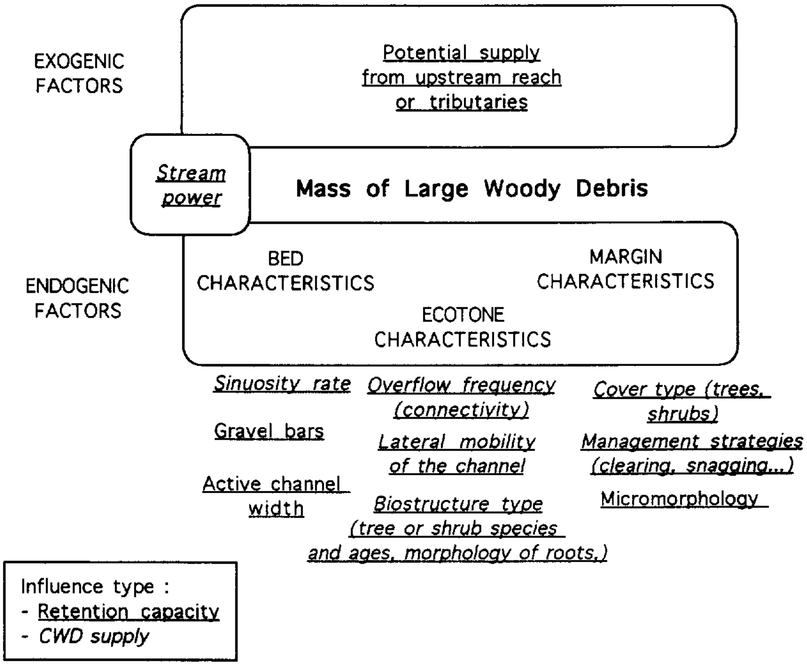

Fig. 11. Influences on the mass of LWD in river systems.

both endogenic and exogenic, and illustrates the importance of channel size, bed morphology, and bank and riparian zone character. Geomorphic pattern reflects stream power which depends on two closely interelated primary variables changing in a downstream direction, the bankfull flow and the slope. In addition, a variable and more subtle explanation is required to explain the spatial variability in the functional and structural character of dead wood. The character of the LWD depends on local biomorphological conditions associated with the vegetation (age, resistance of individual plants to flow and erosion) and the connectivity between the river and its floodplain which impacts upon the mobilisation and retention of wood and varies with geomorphic pattern of the river. The mobilisation of material is itself a function of the character of the riparian vegetation (age, degree of management) and the energy of the flow, which if it is strong is capable of fragmenting the vegetation mosaic and augmenting the input of wood.

It is, therefore, necessary to take into account the transverse dynamics and locally diverse character of stretches and of processes, if one wishes to understand the geographical diversity of the functional and structural characteristics of LWD.

6. What conclusions can be drawn for woody debris management?

LWD plays a critical geomorphological and ecological role in pristine temperate rivers flowing through forested river corridors (Triska, 1984; Sedell and Luschessa, 1982). It has also been shown to be important in arid (Minckley and Rinne, 1985) and tropical rainforest (Spencer et al., 1990) river systems. Therefore, the reappearance of LWD in heavily-modified European river systems can be seen as an indicator of the restoration of rivers to a more "natural" state. Indeed, agricultural change in Europe may lead to increased woodland cover along river corridors and thus an increase in the delivery of LWD to river systems. Environmentally-sensitive strategies are required for LWD management in European rivers.

Dead wood has long been recognised as a risk factor in the context of flooding and erosion along

Table 6
Ecological, hydraulic and morphological impacts [a] of LWD according to river size and pattern of European rivers (a qualitative and comparative assessment based upon the observations presented in this paper)

	Small–medium rivers	Large Piedmont rivers	
		braided	wandering
Creation of terrestrial habitat	−	+	+ +
Creation of aquatic habitat	+ +	+	+
Increase in inundation frequency	+	−	=
Diversification of the floodplain mosaic	=	−	+ +
Increase in bank erosion	− −	−	+ +
Increase in sedimentation	+	+ +	+

[a] Level of impact: + + very significant; + significant; = moderate; − weak; − − very weak.

man-modified river courses. Since the twelfth century, French legislation has recommended preservation of the free flow of water in river channels through the maintenance of riparian vegetation and river bed clearance. Similar long-term maintenance of rivers has also occurred in the United Kingdom (Brookes, 1988). However, as has been suggested for Danish rivers (Iversen et al., 1993), it is now necessary to redefine river maintenance strategies for both ecological and economic reasons, including the development of guidelines for the management of LWD.

Dead wood is associated with variable scenic/aesthetic, ecological and morphological impacts and differing hydraulic risk according to the geomorphic river type (Table 6). Maintenance decisions within a particular geomorphic type should be based on three groups of factors: erosion/flooding vulnerability; ecological criteria; and economic criteria. In general, the ecological gains represented by LWD retention (Table 6) and the significant costs involved in removal imply that minimal removal is the best strategy. Thus the fine-tuning of LWD management strategies is of considerable economic and ecological interest.

A primary intervention logic can be based upon river size, where maintenance is focused on small streams where the length of trunks is frequently greater than the channel width and thus the hydraulic impact of LWD is at its greatest. Here removal of large debris pieces at locations where flooding has significant economic consequences is highly cost-effective. However, retention of LWD debris elsewhere is not only of direct ecological and economic benefit, but it provides a buffer to slow movement of debris pieces rather than allowing them to move freely downstream to accumulate at more flood-sensitive sites. In larger rivers LWD is unlikely to create major obstructions to flow and so does not represent a significant influence on floodplain inundation frequency except where structures such as narrow bridge openings and weirs impede the transfer of the debris. At these locations removal is highly beneficial to

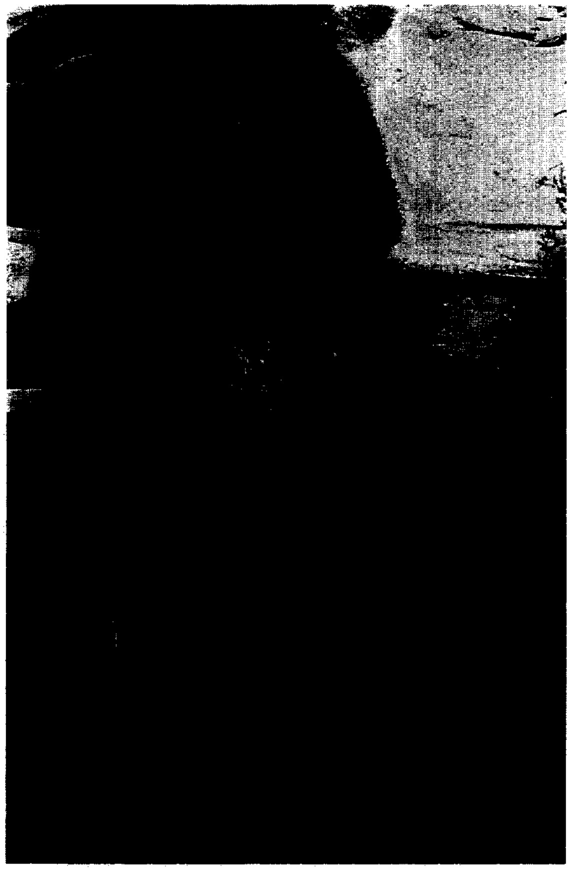

Fig. 12. Detail of a main debris jam located on the margin of the channel in the active band of the Drôme river, downstream of Crest.

flood alleviation, but elsewhere debris should be left because its environmental benefits and high removal costs heavily outweigh any small hydraulic benefits (Table 6). In particular, LWD has a very feeble hydraulic influence within braided systems but has considerable significance for both aquatic and terrestrial habitat diversity. For example, a vegetation maintenance strategy has been proposed recently on the Drôme River (Piégay and Landon, 1997). Three classes of reach have been distinguished based on a maintenance gradient from no intervention to riparian and bed clearing. The sectorisation takes into account potential risks and the ecological interest of each reach. In the most ecologically interesting reaches, it is proposed that debris jams are left in the channel (Fig. 12).

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