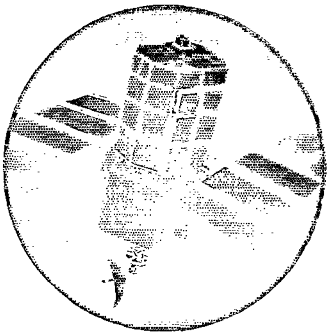
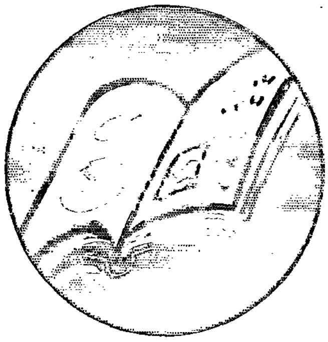
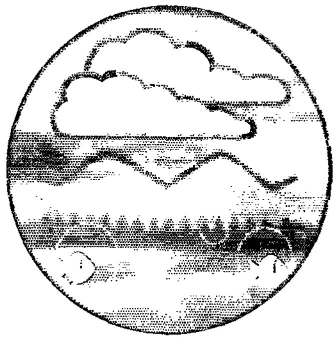
Large Woody Debris in British Headwater Rivers
Physical Habitat Role and Management Guidelines







Research and Development

Technical Report
W181

ENVIRONMENT AGENCY

Large Woody Debris in British Headwater Rivers
Physical Habitat Role and Management Guidelines

R&D Technical Report W181

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Statement of use
This Technical Report (Main Report) describes a study to assess the ecological value of large woody debris in rivers in order to identify the consequences for river management. It provides the detailed information to support the associated Technical Report (Main Report) W185. It will mainly be of interest to Conservation and Flood Defence staff involved in the management of river catchment headwaters.

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CONTENTS

EXECUTIVE SUMMARY

1. 'CWD' (coarse woody debris), 'LOD' (large organic debris) and, more recently 'LWD' (large woody debris) or simply 'large wood' have been the terms applied to pieces of dead wood of a variety of sizes, but now generally accepted to be pieces large than 0.1m diameter and 1.0m length. Since 'LWD' or 'large wood' are the terms used in the most recent literature, these terms are used throughout this report to refer to the entire trees, root boles, trunks, logs, branches and other large pieces of wood that can accumulate within river systems.

2. In unmanaged small streams, wood is distributed in a near-random pattern, reflecting where it enters the channel. With increasing stream size, debris dams become the characteristic form of debris accumulation. In larger river systems the geomorphology of the river channel controls the locations of large wood retention. Wood is retained locally in side streams; in floodplain woodland; on vegetated islands, where large wood pieces can brace against their upstream margins or can accumulate in their lee; and in association with features within the active channel where wood can be braced or deposited.

3. **This report focuses on headwater streams, where debris dams are the characteristic form of LWD accumulation.** The routine removal of LWD from many British rivers for flood defence purposes means that little is found in rivers wider than ca.10m. For the purposes of this report, a 10m channel width is taken to define the upper width limit for British headwater rivers.

4. **The main conclusions regarding the role of LWD in British headwater rivers,** based upon observations at locations where LWD is relatively unmanaged, are as follows:

Hydraulic impact:

- LWD accumulations cause an increase in the flow resistance of river channels. At low flows this increase in flow resistance may be considerable, but the contrast in Mannings n between channels with and without LWD accumulations converges with increasing discharge.
- The increased flow resistance induced by LWD accumulations leads to an increase in reach mean flow depth and velocity and also an increase in the variability or diversity of flow depth and velocity within the reach.
- Reaches containing LWD accumulations are more retentive than debris-free reaches, exhibiting a higher dispersive fraction.
- These complex hydraulic effects of LWD dams have important geomorphological and ecological consequences. Therefore, a simple classification of LWD accumulations in headwater streams which reflects their gross hydraulic impact, is used throughout this report:

  'partial dams' - only extend across a part of the channel width.

  'complete dams' - extend across the complete channel width, but consist of a sufficiently leaky structure, that they have no significant impact on the water surface profile at low flows.

'active dams' - extend across the complete channel width and induce a step in the water surface profile at all flows.

Geomorphological impact:

- The hydraulic changes induced by LWD accumulations result in changes in the morphology of the channel. LWD accumulations in headwater streams are associated with a range of types of pool which play an important role in retention of water, sediment, solutes and organic matter. Upstream (dammed) pools and downstream (plunge) pools are particularly common in association with active and complete dams. Pools may occur as frequently as every 2 channel widths where LWD accumulations are unmanaged.
- Dammed pools appear to be particularly important sites for organic and mineral sediment retention, so attenuating its transfer downstream.
- Dammed pools behind major, hydraulically-active dams also serve as locations of flow avulsion during high flows. Ephemerally- and intermittently-flowing channels may establish, linked to the location of major active dams. If the dams persist for long enough, this may lead to a change in the position of the main, perennially-flowing channel.

Physical habitat:

- LWD accumulations support complex suites of hydraulic and physical conditions which promote high within-dam habitat diversity. They also induce increases in the variety and complexity of habitat in the surrounding river channel and floodplain.
- The increased diversity in flow depths and velocities within reaches containing LWD accumulations lead to an increase in hydraulic habitat diversity.
- The morphological changes induced by the hydraulic effects of LWD accumulations provide high physical habitat diversity in the form of pools of different size, riffles, and marginal benches within the channel, and the development of perennial, intermittent and ephemeral channels across the adjacent floodplain surface. The plunge and dammed pools associated with many LWD accumulations also form important refuges for aquatic fauna during low flows.
- The application of the physical habitat simulation model PHABSIM has demonstrated that the removal of LWD dams reduces both habitat quantity and quality for juvenile and adult brown trout. Proportionately greater adult habitat was lost or reduced in quality.

Stability:

- Active dams form the most stable dam type, persisting for many years at the same location, and trapping and storing mobile debris pieces. The overall stability of LWD within headwater river channels appears to be closely linked to the presence of active dams. Active dams take the longest time to re-establish after disturbance.
- Although active dams have a major hydraulic effect, they rarely cause a rigid barrier within the river. Even if the dam is braced by an entire tree which is essentially immobile, smaller wood pieces within the structure will shift with variations in river flow. Thus, although the LWD structure settles to pond back water at low flows, water (and fish) can readily pass through it at higher flows.

5. The research results summarised above suggest that **LWD accumulations have enormous importance for the structure and diversity of physical habitat, water quality and temperature, and substrate conditions within British headwater rivers.**

Active dams are particularly important in this regard, and also in stabilising and trapping LWD and sediment movement within headwater river systems. **Removal of major, active LWD dams destabilises the LWD that remains and results in the mobilisation of sediment, the incision of the channel bed and a reduction in habitat diversity.** These effects not only reflect a reduction in physical habitat diversity at the sites of LWD dam removal but also have consequences for downstream channels which will receive larger inputs of LWD and sediment.

6. **LWD accumulations also have benefits in relation to the control of runoff at the catchment scale.** Reaches containing LWD accumulations have a higher flow resistance than LWD-free reaches, although the values of Manning's n converge with increasing discharge. The hydraulic effect of LWD accumulations causes geomorphological adjustments, which result in increased within-channel and floodplain water storage. Although these effects may be relatively small when only a single LWD accumulation is considered, their aggregate effect may be very significant. LWD accumulations in headwater streams provide a potentially significant contribution to flood attenuation at the catchment scale because they help to desynchronise headwater and downstream-generated flood peaks by attenuating upstream-generated floods and increasing flow travel times from the headwaters. Similar desynchronisation of floods draining from different headwater catchments would result from contrasting land uses and thus differing amounts of LWD. Such flood attenuation advantages are at best free and at worst inexpensive if the management guidelines suggested below are implemented.

7. **River and riparian management has important effects on the distribution and character of dead wood accumulations within river systems:**

- Riparian woodland management controls the species and age of trees which input LWD to the river system.
- The harvesting of trees reduces the input of the very largest pieces of wood, which would normally form the key wood pieces in stable debris dams.
- Hydrological management involves changes in the river flow regime, which changes the frequency and distance of transport of wood pieces of different sizes.
- Channel management to increase flow conveyance involves both the reduction of the river channel's wood retention capacity and the active removal of wood from the river channel.
- In general, the impact of these types of management is to reduce the size of the wood pieces that enter and are stored within the channel system, reduce the wood retention capacity of the channel and reduce the stability of debris dams. The combined effect is that the mobility of wood increases and blockages of structures such as channel constrictions, bridge arches and weirs becomes more likely.
- These adverse on-site and downstream effects give support to the view of Benke et. al. (1985) that 'Although there are certain situations that may require wood removal to eliminate stream blockage, the wisest management practice is no management'.

8. **Recommendations for reach scale LWD management.** Points (i) to (viii) below build from simple recommendations about LWD removal, through guidelines on emplacement of debris and the development of a self-sustaining system of natural debris supply.

(i) In headwater rivers, indiscriminate removal of LWD should be avoided, particularly in wooded and tree-lined reaches where LWD accumulations are a natural feature of the channel.

(ii) Some removal of LWD may be necessary under certain circumstances as indicated in Figure 4.1 by the arrow of increasing economic cost of flooding. Figure 4.1 considers reaches and their riparian land use in isolation, but there are additional advantages of considering reaches within their catchment context. For example, an increase in in-channel water storage, flow avulsion, overflow channels and flooding associated with LWD dams in areas of low economic cost and high environmental benefit, such as in semi-natural woodland areas, would have a beneficial flood-attenuation impact for downstream higher-risk areas.

(iii) Where LWD blockage of man-made structures forms a flood management problem in headwater streams, complete removal of LWD may be necessary. However, this should only be undertaken along a restricted length of the upstream river channel. Such focused removal of LWD is highly cost-effective and maximises management benefits.

(iv) Where flooding is a less severe and localised problem, selective removal of debris within affected reaches is preferable to complete removal since the major environmental benefits of LWD dams are retained when the most stable pieces of wood are not disturbed (see (vi) below)

(v) Inputs of large quantities of small wood pieces (e.g. small branches, twigs and leaves) from riparian management and forestry operations can cause excessive sealing of active dams, making them too effective a barrier to fish movement. Such wood input should be avoided or selectively (see (vi) below) rather than completely removed.

(vi) The following selective removal guidelines are applicable where there is a need to increase the conveyance of a reach but where complete clearance of debris is unnecessary. Remove debris that is:

- not anchored or buried in the stream bed or bank at one or both ends or along the upstream face;
- or is not longer than the channel width;
- unless it is LWD (i.e. longer than 1m and wider than 10 cm) which is braced on the downstream side by boulders, bedrock outcrops, riparian trees, or by pieces of large wood that are stable because they do not fall into the first two categories.

(vii) The addition of LWD improves physical habitat and counteracts stream incision, particularly where LWD has previously been cleared or where, as a result of the age structure of riparian trees, the LWD supply to the river channel is low. The introduced wood pieces should be capable of forming the key pieces in stable debris accumulations. They should be at least as long as the channel width with a diameter of at least 0.1 m or 0.05 channel width, whichever is larger. In order to increase the potential for wood to form stable structures, the spacing of the introduced pieces should reflect natural spacings of LWD accumulations (i.e. 7 to 10 channel widths). Wood pieces should be introduced into stable positions (e.g. upstream of channel constrictions or braced by boulders, bedrock outcrops, or riparian trees).

(viii) Riparian woodland is the natural source of LWD. Tree clearance and pruning close to the river channel disrupt the supply of wood. Therefore, riparian tree management should be minimised within a buffer strip along the river margin, particularly in reaches bordered by natural or semi-natural woodland. Ideally this buffer strip should be 20m wide and should consist of trees of mixed age. A 20m buffer strip is ideal because it approximates the height of mature native tree species and thus it ensures that wood delivery to the river, for example by wind throw of entire trees, simulates the rate that might be expected from a more extensive woodland cover. Some initial active management of trees within the buffer zone may accelerate the development of a strip of mixed age and species, which will provide a good LWD supply to the river.

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Tables 1.3 and 3.1, and Figures 3.10 and 3.12 were originally published as Tables 2 and 4, and Figures 3 and 4 in A.M. Gurnell and C. Linstead (1998) Interactions between large woody debris accumulations, hydrological processes and channel morphology in British headwater rivers. In: H. Wheater and C. Kirby (Eds) *Hydrology in a Changing World,* Vol 1, 381-395, Wiley Chichester. Figures 3.13, 3.14, 3.15 and 3.16 were originally published as Figures 3, 4, 6 and 7 in A.M. Gurnell and R. Sweet (1998) The distribution and magnitude of large woody debris accumulations and pools in relation to woodland stream management in a small low-gradient stream. *Earth Surface Processes and Landforms*, 23, 1101-1121. All of the above Tables and Figures are reproduced with permission from John Wiley and Sons Ltd.

Table 3.3 was originally published as Table 2 in H. Piégay and A.M. Gurnell (1997) Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology*, 19, 99-116. This Table is reproduced with the permission of Elsevier Science.

KEYWORDS
Large woody debris, headwater rivers, in-stream habitat, dead wood management

1. CONTEXT

1.1 Introduction

The view is often expressed that there is little to be gained in undertaking research on large woody debris within the United Kingdom or, indeed, the rest of Europe, because the subject has already been studied in more than sufficient detail in North America. A very significant conclusion that can be drawn from this report is that such a view is incorrect. The report provides an overview of the dynamics and role of large woody debris in river systems; some research results from relatively unmanaged British headwater rivers; and it makes some management recommendations for LWD in British headwater rivers.

Because of the fundamental nature of the research that has been undertaken, this report inevitably includes some detailed research findings. However, the report is structured so that readers wanting to extract the key findings without being immersed in the scientific detail can easily do so by reading the summary bullet points at the ends of sections 1 to 3 (i.e. 1.6, 2.3, 3.6), followed by the overview and management recommendations of section 4. The report contains four sections:

Section 1 defines large woody debris (1.2); describes how large wood pieces are retained in river systems, with particular emphasis on the characteristic way in which wood is retained as debris dams in headwater rivers (1.3); outlines the key North American research results concerning the role of woody debris in headwater rivers (1.4); and describes some major contrasts in the quantity, wood piece size and spacing of debris dams in North American and British unmanaged headwater rivers (1.5). All of this information provides a context for the research that is described in sections 2 and 3.

Section 2 presents an analysis of information drawn from the River Habitat Survey database. The analysis provides baseline information on LWD in British headwater rivers as a whole. It shows that virtually all river channels containing extensive large woody debris and debris dams are less than 10m wide and that the presence of woody debris and debris dams is strongly associated with riparian land use and tree density...

Section 3 presents field observations and experimental results from some relatively unmanaged woodland headwater streams in the Forest of Dean, Gloucestershire and the New Forest, Hampshire. These sites were chosen to indicate the potential benefits for British headwater rivers if there was less management of woody debris. Research results are presented on the hydraulic effects of debris dams (3.2); the ecological significance of these hydraulic effects (3.3); and the impact of debris dams on river channel geomorphology, its hydrological and ecological significance (3.4). Finally, a rather complex, but important case study is described (3.5), which illustrates how debris dam removal can actually increase the mobility of wood within the river channel and can cause a severe reduction in physical habitat diversity through the sedimentation of pools.

Section 4 draws together the research results to propose some management recommendations for large woody debris in British headwater rivers.

1.2 What is Large Woody Debris?

The role of large wood in river channels has been the subject of much research over the last 30 years, particularly within certain regions of the USA (e.g. Alaska, Pacific Northwest, Florida, California and N. Carolina). Over this period, different abbreviations have been used to refer to the woody debris 'primarily in the form of standing dead trees and downed boles and branches, (which are) abundant in many natural forest and stream ecosystems, forming major structural features with many crucial ecological functions - as habitat for organisms, in energy flow and nutrient cycling, and by influencing soil and sediment transport and storage' (Harmon et al., 1986, p133). 'CWD' (coarse woody debris), 'LOD' (large organic debris) and, more recently 'LWD' (large woody debris) or simply 'large wood' have been the terms applied to pieces of dead wood of a variety of sizes, but now generally accepted to be pieces large than 0.1m diameter and 1.0m length. Since 'LWD' or 'large wood' are the terms used in the most recent literature, these will be used throughout this report to refer to the entire trees, root boles, trunks, logs, branches and other large pieces of wood that can accumulate within river systems.

1.3 Retention of Large Woody Debris in River Systems

Within a river system, the controls on the retention of large wood fall into four categories: forest character (tree sizes/ages, species and density); hydrological processes (both river discharge and sediment transport regimes); geomorphology (river corridor width, slope and form; river channel bank and bed sediment calibre; river channel size, style/pattern and dynamics); and management as it affects the above three groups of factors.

In less-managed systems, where river channels have a natural form and are bordered by riparian forest and woodland throughout their length, the relative importance of forest character, hydrological processes and geomorphology changes in a downstream direction.

In very small headwater streams, the character of the forest is of over riding importance. Many wood pieces are large enough to span the channel width, even being supported above the channel by the valley sides in very narrow river corridors. Once they have fallen into the river channel, large wood pieces are relatively immobile because stream discharges are not sufficiently powerful to move them. The result is an apparently random distribution of wood pieces within and across the channel governed largely by the locations of wood input to the channel and the rate of wood decay. Therefore, input mechanisms such as local tree fall as a result of bank undercutting and blow down and, in very steep terrain, processes such as mass failures of hillslopes and debris torrents, dictate the distribution of large wood within the stream system.

As streams increase in size, large wood pieces are less likely to be long enough to span or jam across the channel and are more easily moved by the increasingly powerful stream discharges. As a result, other controls begin to have a significant influence on the retention of large wood. Whilst stream discharges may not be able to move the largest pieces of wood, intermediate-sized pieces can only be retained within the river channel if structures are present to brace them against the flow. Such retention structures include the very largest wood pieces, riparian vegetation (particularly the trunks and exposed roots of riparian trees), other large roughness elements within the channel such as boulders, constrictions in the width of the channel and irregularities in the channel's planform. The result is the development of accumulations or dams of wood which are braced by a few larger 'key' pieces of wood, but which then build by trapping mobile wood pieces of all sizes. The dominant control category here is the hydrological or river flow regime, since this drives the periodic movement of wood pieces during high flows and controls the size of wood pieces that move.

Once the river channel becomes so wide that it is no longer possible for large pieces of wood to span the channel, and the discharge is sufficient to transport wood pieces of all sizes during high flows, then river geomorphology becomes the most important control on the retention of wood. In particular, the geomorphological style of river channel (meandering, braided, island braided etc.) dictates the number and type of locations for large wood retention.

Thus in unmanaged small streams, wood is distributed in a near-random pattern reflecting where it enters the channel. With increasing stream size, debris dams become the characteristic form of debris accumulation, although smaller debris washed out of the channel during floods may form accumulations around the upstream sides of individual trees and ribbon-like trash lines close to the channel margin. In larger river systems, the geomorphology of the river channel controls the locations of large wood retention. Sites where wood is retained within large rivers include: (i) side streams that are sufficiently narrow for the formation of debris dams similar to those found on small streams; (ii) floodplain woodland which can trap debris in ribbons parallel to the channel margin or as patches of debris around individual trees; (iii) vegetated islands, where large wood pieces can brace against their upstream margins or can accumulate in sheltered areas along the sides and in the lee of islands; and (iv) features within the active channel where wood can be braced, such as at the apex of bars, or where wood can be deposited, such as on benches along sheltered channel margins.

Management impacts on the above groups of factors and so has important effects on the distribution and character of dead wood accumulations within river systems.

- Riparian woodland management controls the species and age of trees which input LWD to the river system. In particular, tree thinning and felling can lead to the introduction of many small pieces of wood, which are easily moved by the river and, if trapped by debris dams, can clog them and so increase their flow resistance.
- The harvesting of trees reduces the input of the very largest pieces of wood, which would normally form the key wood pieces in stable debris dams.
- Hydrological management involves changes in the river flow regime, which changes the frequency and distance of transport of wood pieces of different sizes.
- Channel management, which often involves techniques to increase the flow conveyance of river channels, involves both the reduction of the river channel's wood retention capacity and the active removal of wood from the river channel.

- In general, the impact of the above types of management is to reduce the size of the wood pieces that enter and are stored within the channel system, reduce the wood retention capacity of the channel and reduce the stability of debris dams. The combined effect is that the mobility of wood increases and blockages of structures such as channel constrictions, bridge arches and weirs becomes more likely.

Although large wood plays an important geomorphological and ecological role in rivers of all sizes, its routine removal from many British rivers for flood defence purposes means that little is found in rivers wider than ca.10m and that the LWD that remains is more mobile than would be the case in less-managed systems. It is in the headwater rivers that the greatest benefits of wood retention can accrue with minimum risk of adverse consequences. This report is concerned solely with British headwater rivers; the small- and medium-sized systems discussed above, where the dominant mode of wood accumulation is the debris dam.

1.4 The Role of Large Woody Debris in Headwater Rivers: Results from North American Research

In headwater rivers, many pieces of LWD are large enough to span the river channel. Many other wood pieces, although only partly spanning the channel, have sufficient mass to remain quite stable even during high flows. The presence of these stable 'key' pieces of LWD can lead to the development of the accumulations or dams of LWD, which are so characteristic of woodland streams where routine wood debris clearance is not practised. A great deal of research undertaken in North America over the last twenty years has shown that LWD accumulations or dams are of great importance for woodland river environments; enhancing biological diversity and productivity, regulating flows and water quality, and increasing the range of habitats within and along the river. Specifically, LWD dams affect woodland river environments in four main ways.

- First, LWD accumulations directly impact upon the hydraulics of flows within the river channel. Debris dams also increase hydrological interactions between the river channel and its floodplain by controlling the local distribution and intensity of overbank flows and by enhancing flows through the river channel bed and bank sediments around the site of the debris dam.
- Second, these hydrological and hydraulic effects of LWD accumulations enhance the storage and attenuate the transport of solutes, sediments and organic material within the river channel system and floodplain.
- Third, the influences on flow hydraulics and sediment movement affect the geomorphology of woodland river channels, resulting in an increased variability in channel size; an increase in the size, amplitude and number of pools and riffles; and an increase in overall channel stability. As a result, woodland rivers affected by LWD accumulations present a higher physical habitat diversity than those where debris dams are removed.
- Fourth, the complex physical structure of woodland river channels and their LWD accumulations provides a diversity of habitat patches which can support a wide range of organisms at different stages of their life cycles. Furthermore, LWD 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 LWD accumulations provides temporally and spatially regulated food sources for aquatic biota.

These far-reaching effects of LWD dams are a direct consequence of their impact on flow hydraulics. As a result, a simple and useful classification of debris accumulations in headwater streams, which reflects their gross hydraulic impact will be used throughout this report:

'partial dams' - only extend across a part of the channel width.
'complete dams' - extend across the complete channel width, but consist of a sufficiently leaky structure, that they have no significant impact on the water surface profile at low flows.
'active dams' - extend across the complete channel width and induce a step in the water surface profile at all flows

1.5 Contrasts in Large Woody Debris in North American and British Headwater Rivers

North American research results, summarised in section 1.4, have shown that accumulations of LWD have a fundamental influence on headwater stream ecosystems within natural forest catchments. In North America, these research results have been adopted by river managers. Wood is deliberately placed in some streams and active management of streamside woodland buffer strips is encouraged to supply plenty of woody debris pieces of all sizes to river systems. The underlying rationale of this type of management is to provide environmental conditions that can support both a high diversity and healthy populations of aquatic biota.

Little research has been undertaken on the role of LWD in British headwater rivers. It is tempting to assume that LWD has identical influences on British as it has on North American headwater river systems and that similar management practices should be implemented. However, the few British studies that have been undertaken demonstrate subtle differences in the nature and role of LWD. These differences result from contrasts in climate; contrasts in tree species; and, most importantly, differences in the degree and nature of forest and riparian woodland management practices, and in the scale and mode of management of river systems.

There are no headwater rivers in Britain where LWD is truly unmanaged, but there are locations where wood is relatively lightly managed. The New Forest, Hampshire, is one such location, and is used in here to highlight the contrasts in LWD between a relatively unmanaged British woodland environment and the old growth river systems studied in North America.

The influence of LWD on the geomorphology and ecology of headwater streams is fundamentally influenced by the amount of wood and the number of debris accumulations that are present. Table 1.1 compares the amount of LWD (i.e. the debris loading) reported for rivers draining old growth forests in the United States with observations on the Highland Water, New Forest, Hampshire. The table illustrates that virtually all of the tree species studied are conifers, and so little information is available for deciduous woodland, which is characteristic of many lowland British river corridors. Furthermore, the debris loading in all North American sites is very high in comparison with the New Forest, which has the highest stream debris loadings of any British sites known to the authors. Table 1.2 presents debris dam spacings quoted in the literature in comparison with spacings observed in the Highland Water, New Forest. Whilst there is some similarity in the spacings observed in third order streams, the New Forest appears to have a lower debris dam frequency in first and second order streams than have been observed in North American studies. Another contrast between LWD accumulations or dams in the Highland Water and those described in many North American studies, is the quantity and size distribution of the wood pieces making up these structures. Table 1.3 shows the median size of LWD pieces within streams in the Cascade Range of Oregon and Washington, and the Coast Range of Oregon (McDade et al., 1990), in comparison with the median of the largest individual debris pieces in New Forest LWD accumulations. The median piece sizes listed for the North American sites are considerably larger than the largest individual wood pieces recorded in each of the New Forest LWD accumulations. Indeed the largest piece recorded in any of the dams surveyed in the New Forest (14m length and 0.8m diameter) is scarcely as large as the median piece sizes in the North American studies.

This brief comparison of observations from North American old-growth forest streams with observations drawn from the Highland Water, New Forest, indicates that even in a relatively unmanaged British woodland catchment LWD loadings are lower; LWD pieces are smaller; and LWD dams are more widely spaced, particularly in the smallest (lowest order) streams. Whatever the causes of these differences, they undoubtedly affect the environmental role of LWD accumulations, including their influence on flow hydraulics, channel geomorphology and ecology.

1.6 Summary

This section has described the ways in which LWD is retained in rivers of different size, illustrating the importance of LWD accumulations or dams in headwater rivers.

- The routine removal of LWD from many British rivers for flood defence purposes means that little is found in rivers wider than ca.10m (section 2.2.2). For the purposes of this report, a 10m channel width is taken to define the upper limit for British headwater rivers.
- Research undertaken in North America has clearly shown that accumulations of LWD have a fundamental influence on headwater stream ecosystems within natural forest catchments. This reflects the complex impact of LWD dams on the hydraulics, hydrology, water quality, sediment and organic matter transfer and storage, and geomorphology of woodland headwater river systems.
- Because these complex effects of LWD dams are a direct consequence of their impact on flow hydraulics, a simple and useful classification of debris accumulations in headwater streams which reflects their gross hydraulic impact, will be used throughout this report:
  'partial dams' - only extend across a part of the channel width.

'complete dams' - extend across the complete channel width, but consist of a sufficiently leaky structure, that they have no significant impact on the water surface profile at low flows.

'active dams' - extend across the complete channel width and induce a step in the water surface profile at all flows

- In North America, research results have been adopted by river managers. Wood is deliberately placed in some streams and active management of streamside woodland buffer strips is encouraged to supply plenty of woody debris pieces of all sizes to river systems. The underlying rationale of this type of management is to provide environmental conditions that can support both a high diversity and healthy populations of aquatic biota.
- It is tempting to assume that LWD has identical influences on British as it has on North American headwater river systems and that similar management practices should be implemented. However, the few studies that have been undertaken demonstrate subtle differences in the nature and role of LWD in British headwater rivers. These differences result from contrasts in climate; contrasts in tree species; and, most importantly, differences in the degree and nature of forest and riparian woodland management practices, and in the scale and mode of management of river systems. Some of these differences are illustrated in sections 2 and 3.
- A comparison of observations from North American old-growth forest streams with observations drawn from Highland Water, New Forest, indicates that even in a relatively unmanaged British woodland catchment LWD loadings are lower; LWD pieces are smaller; and LWD dams are more widely spaced, particularly in the smallest (lowest order) streams. Whatever the causes of these differences, they undoubtedly affect the environmental role of LWD accumulations, including their influence on flow hydraulics, channel geomorphology and ecology.

Table 1.1 Observations of the biomass of large woody debris in streams draining old growth forests (developed from Gurnell et al, 1995)

Dominant tree species	Location	Mean biomass ($kg.m^{-2}$)	Source
CR	California	85.0	Keller et al., 1985*
CR	California	74.0	MacDonald et al, 1982
CR	California	63.3	Keller and Tally, 1979
CR	California	52.5	Swanson, unpubl.*
DF	Oregon	42.5	Luchessa, unpubl.*
SS, WH	British Columbia	39.7	Toews and Moore, 1982*
SR	California	38.8	Luchessa, unpubl.*
DF	Oregon	33.4	Froelich, 1973*
Pine-hemlock	New Hampshire	27.5	Swanson and Sedell, unpubl.*
SS, WH	British Columbia	26.5	Hogan, 1986
DF	Oregon	24.4	Keller and Swanson, 1979
DF	Oregon	23.9	Lienkaemper and Swanson, 1987
DF	Oregon	22.6	Lienkaemper, unpubl.*
ES, WF, DF, WL, PY	Washington	19.0	Carlson et al., 1990
DF	California	14.1	Lehre, unpubl.*
DF, PP, WL	Montana	14.1	Potts and Anderson, 1990
Mixed Deciduous	**New Forest**	**10.4-1.7**	**Field surveys by the authors and colleagues**
SS, WH	Alaska	10.0	Swanson et al, 1984
SS, WH, RA	Alaska	9.8	Robison and Beschta, 1990a,b
Pine-SF	Tennessee	9.0	Gregory and Lienkaemper, unpubl.*
SS, WH	Alaska	8.2	Smith et al., 1993
SS, WH	Alaska	6.5	Bryant, 1983
Hardwood	Tennessee	6.3	Gregory and Lienkaemper, unpubl.*
DF, WH	Oregon	6.0	Ward and Aumen, 1986
Pine	Idaho	6.8	Lienkaemper, unpubl.*
ES	Idaho	3.5	Lienkaemper, unpubl.*

* cited in Harmon et al. (1986).
CR - coastal redwood; DF - Douglas fir; SS - Sitka spruce; WH - western hemlock; SR - Sierra redwood; ES - Englemann spruce; WF - white fir; WL - western larch; PY - Pacific yew; PP - Ponderosa pine; RA - red alder; SF - silver fir.

Table 1.2 Density of debris dams per unit stream length (developed from Gregory et al, 1993)

Dam density (dams/100m)	Stream / forest character	Location	Source
0-32		Colorado/Arizona	Heede, 1981
2-8		Washington	Sedell et al., 1988
13		New Hampshire	Hedin et al., 1988
0-10	Aspen forest	New Mexico	Trotter, 1990
50	Coniferous forest	New Mexico	Trotter, 1990
4		**New Forest**	**Field Survey, 1996**
20-40	1st order streams	New England	Bilby, 1979*
34	1st order streams	New Hampshire	Bilby and Likens, 1980
17	1st order streams	Montana	Potts and Anderson, 1990
8-13	1st order streams	Virginia	Smock et al, 1989
7	**1st order streams**	**New Forest**	**Field Survey, 1996**
10-15	2nd order streams	New England	Bilby, 1979*
14	2nd order streams	New Hampshire	Bilby and Likens, 1980
13	2nd order streams	Montana	Potts and Anderson, 1990
5	**2nd order streams**	**New Forest**	**Field Survey, 1996**
1-6	3rd order streams	New England	Bilby, 1979*
3	3rd order streams	New Hampshire	Bilby and Likens, 1980
4	3rd order streams	Montana	Potts and Anderson, 1990
4	**3rd order streams**	**New Forest**	**Field Survey, 1996**

* - cited in Likens and Bilby, 1982

Table 1.3 A comparison of LWD piece sizes in streams in Oregon and Washington, USA and the largest pieces of LWD in individual debris dams in the New Forest, UK (from Gurnell and Linstead, 1998)

	Sample Size	Length (m)	Diameter (m)
Oregon / Washington, USA			
Old-growth conifer	619	20.7	0.45
Mature conifer	551	15.9	0.35
Mature hardwood	86	11.4	0.32
First order streams	423	16.9	0.42
Second order streams	450	16.6	0.46
Third order streams	383	20.0	0.53
New Forest, UK			
First order	77	2.0	0.12
Second order	54	4.0	0.20

US data derived from McDade et al. (1990)

2. LWD IN BRITISH HEADWATER RIVERS

2.1 Introduction

This section presents information on LWD in British catchments by analysing data from the Environment Agency's River Habitat Survey (RHS) database. Analyses of this dataset provide baseline information on LWD in British headwater rivers as a whole.

The River Habitat Survey (RHS) has been developed by the Environment Agency to create a classification of rivers that is nationally applicable, based on their habitat quality (Raven *et al.*, 1997). LWD is recorded in the RHS within the sweep up as a feature associated with trees, and debris dams are recorded as a feature of special interest. Raven *et al.* (1998) state that, although LWD and debris dams provide a 'wild' character and habitat diversity, relatively few RHS sites have these features as a result of channel management for drainage, flood defence and fisheries. Although no size definition is given for LWD or debris dams in the RHS, descriptive definitions are provided. LWD is defined as 'trees, large branches, etc., swept downstream and temporarily occupying part of the channel' and a debris dams is defined as a 'log jam of woody debris creating an obstruction across the channel and ponding back water' (RHS 1997 Field Survey Guidance Manual). This latter definition is equivalent to the active dam type used elsewhere in this report. LWD and debris dams are recorded in the RHS as being either absent, present or extensive in each 500m RHS site, where extensive indicates that they are present on ≥33% of the site length.

2.2 LWD and the River Habitat Survey

Raven *et al.* (1998) includes data derived from the RHS database on the extent of LWD both by region and for four example river types. Table 2.1 shows the percentage of upland and lowland sites in the UK with LWD, debris dams, fallen trees and at least one bank with trees. For Scotland and England and Wales there is a greater percentage of lowland sites with LWD and extensive LWD than upland sites, reflecting the greater percentage of lowland sites with trees on either bank. Debris dams, however, occur in approximately the same percentages of upland and lowland sites for both Scotland and England and Wales although they occur about twice as frequently in England and Wales as in Scotland. This indicates that, although there is a greater occurrence of LWD in lowland sites there is a smaller tendency for it to form debris dams than in upland sites.

Table 2.2 presents data from Raven *et al.* (1998) on LWD and fallen trees from four distinct river types: steep streams; mountain valley rivers; chalk rivers; and small, lowland, riffle dominated rivers. Together, these four types represent 21% of RHS reference sites. For steep streams, LWD and fallen trees are not as abundant on semi-natural sites as on other sites, reflecting the smaller number of semi-natural sites with riparian trees. For the other three river types LWD is more extensive on semi-natural sites. In this case it is probably due to less management and a greater abundance of riparian trees on semi-natural sites for these stream types.

Table 2.1 Occurrence of LWD, debris dams and fallen trees as a percentage of sites (after Raven *et al.*, 1998)

Feature	UK and Isle of Man		England and Wales		Scotland		N. Ireland
	Upland	Lowland	Upland	Lowland	Upland	Lowland	Lowland
LWD	35.7	51.6	42.3	52.7	22.5	43.8	52.3
Extensive LWD	1.9	3.1	2	3.4	1.6	2.7	0.4
Debris dams*	17	18.6	22	21	9.9	11	12
Fallen trees	31.1	36.8	34.4	36.8	24.7	37.2	35.7
Extensive fallen trees	1.5	1.3	1.2	1.3	2.2	1.5	0
Trees on either bank	67.5	91.2	71.0	93.3	61.0	78.1	88.4

*1995 and 1996 only

Table 2.2 Percentage occurrence of LWD and fallen trees by stream classification (after Raven *et al.*, 1998)

	Percentage Occurrence LWD		Percentage Occurrence Fallen Trees	
	Semi-natural sites	Other sites	Semi-natural sites	Other sites
Steep streams	41.7	60.1	41.4	55.3
Mountain valley rivers	50.0	46.8	46.1	31.9
Chalk rivers	50.0	35.7	38.2	22.7
Small, lowland, riffle dominated rivers	78.4	68.8	71.9	52.2

Further analysis of information from the RHS data base was undertaken for this report to establish the frequency of occurrence of LWD, and the degree to which the presence of LWD and of LWD dams is associated with channels of a particular size, with specific types of adjacent land use, and with the density of riparian trees.

2.2.1 Frequency of Occurrence of LWD

Of the 4518 RHS sites in England and Wales analysed during the research for this report, 47.8% had no LWD, 48.9% had LWD present and 3.3% had extensive LWD. Information on debris dams was recorded for 3030 sites. Of these, debris dams were absent for 81.7% of sites, present for 18.3% and extensive for 0.06%. 36.1% of sites with LWD present or extensive had one or more debris dams.

2.2.2 Influence of Channel Size

Figure 2.1 shows the cumulative frequency of sites with LWD absent, present and extensive in relation to banktop channel width. The cumulative frequency of channel widths for all data is also shown. Channels with extensive LWD tend to be smaller than channels where LWD is present, which are in turn smaller than channels containing no LWD. Figure 2.2 shows the cumulative frequency distribution of channel widths for all sites and for sites with debris dams absent and present. Debris dams tend to occur in channels with smaller than average width. This decreasing abundance of debris dams and LWD with increasing channel size is consistent with the downstream decrease in retentiveness of streams for LWD, which was discussed in section 1.3. It also probably reflects more thorough removal of LWD from larger British river channels. Figures 2.1 and 2.2 clearly illustrate that virtually all river channels with extensive LWD or debris dams are less than 10m wide.

2.2.3 Influence of land use

Riparian land use can have an important influence on LWD and debris dams as riparian vegetation acts as the local source of LWD. Figure 2.3 (upper graphs) shows the proportions of sites with LWD absent, present and extensive for different land use types according to whether the land use is present (upper left graph) or extensive (upper right graph) on both banks. LWD is most abundant for sites with broadleaf/mixed woodland, followed by sites with coniferous plantation. The discrimination in LWD abundance between each land use is greater for extensive land use types (upper right graph), reflecting the importance of particular land use categories as sources of LWD when they are sufficiently extensive. Figure 2.3 (lower graphs) also shows the proportion of sites with debris dams absent, present and extensive in association with each land use type, according to whether the land use is present (lower left graph) or extensive (lower right graph) on both banks. Scrub, coniferous plantation and broadleaf/mixed woodland are associated with the highest abundance of debris dams. The difference in LWD dam abundance between each land use is greater for extensive land use types, again reflecting the importance of particular land use categories as sources of LWD when they are sufficiently extensive.

2.2.4 Influence of tree density

The association between land use and the abundance of sites containing LWD and debris dams is likely to be largely a reflection of the density of riparian trees. Figure 2.4 shows the proportion of sites with LWD absent, present and extensive for differing densities of riparian trees on both banks. There is a clear trend of decreasing LWD abundance with decreasing riparian tree density. The proportion of sites with LWD extensive or present ranges from 83.8% for sites with continuous trees to 5% for sites with no trees. A similar pattern emerges when debris dams are considered. Figure 2.5 shows the proportion of sites with debris dams absent and present for each riparian tree density class. Sites with higher tree densities have a higher abundance of debris dams. For example, sites with semi-continuous trees on both banks have debris dams present on 27.3% of sites whereas sites with no trees have debris dams present for only 1.3% of sites.

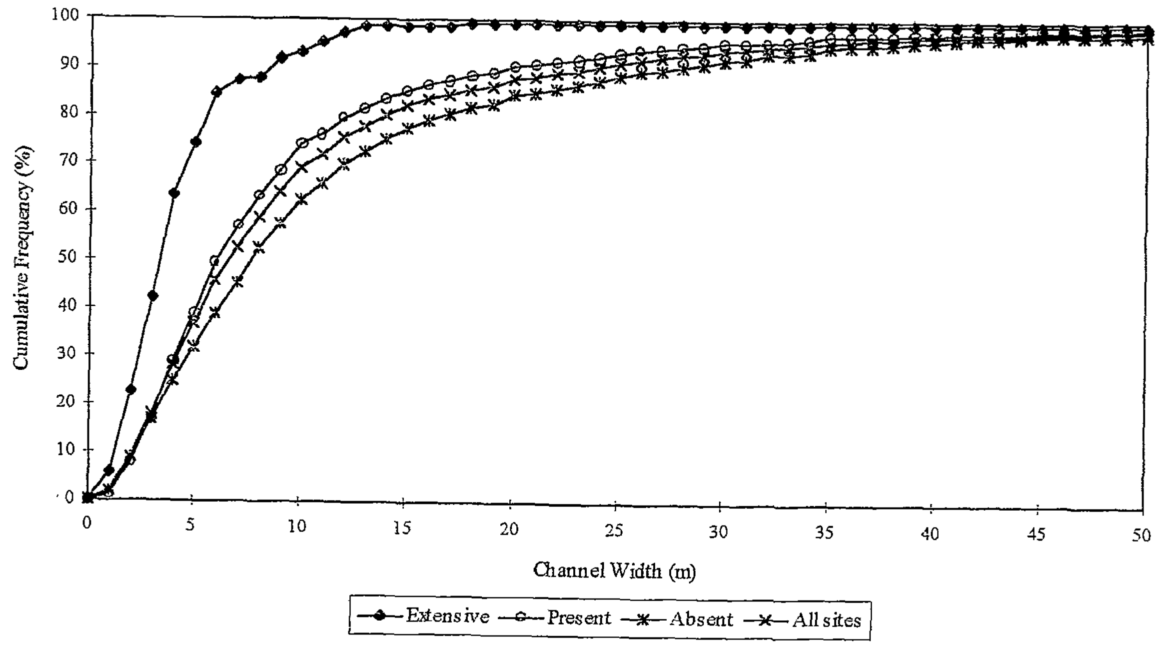


Figure 2.1 **Cumulative frequency of channel widths for all sites and with LWD *absent, present and extensive.***

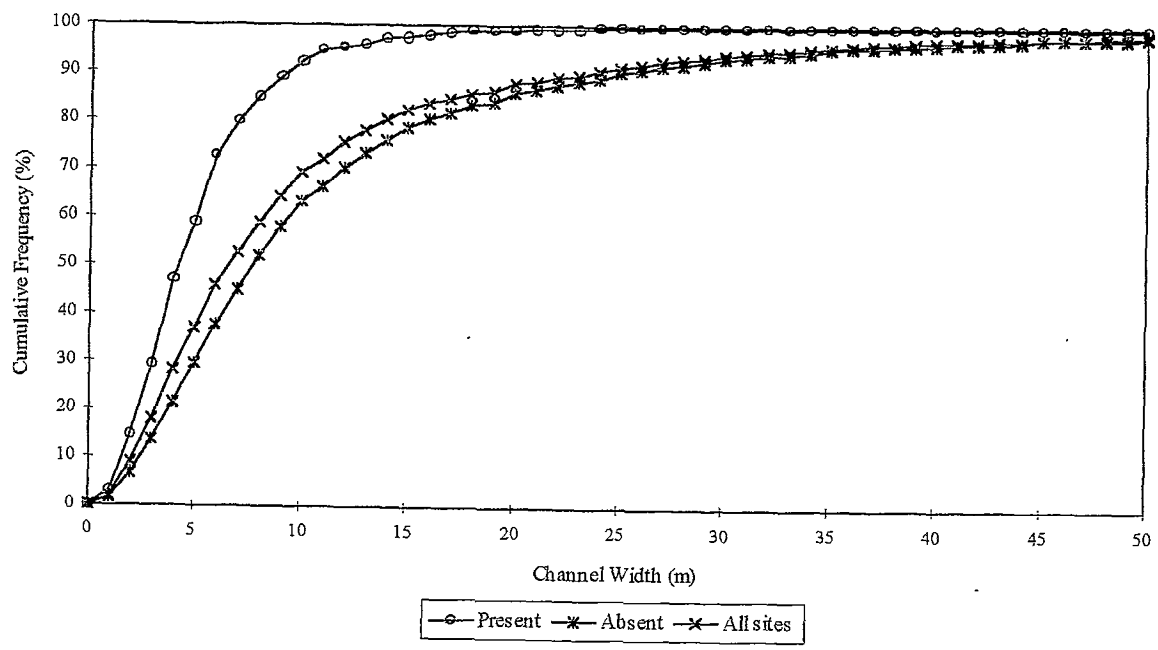
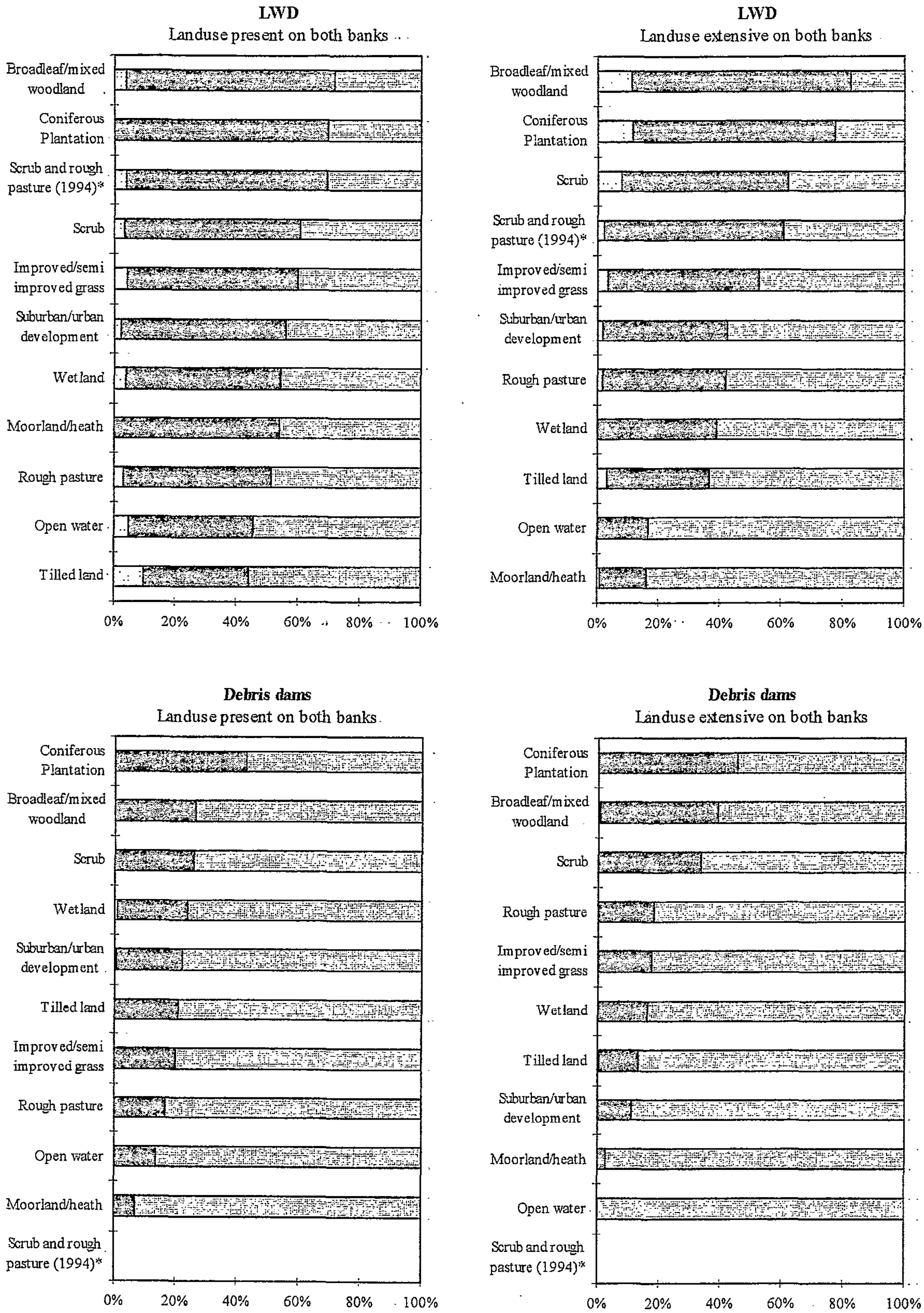


Figure 2.2 **Cumulative frequency of channel widths for all sites and with debris dams absent and present**



* Scrub and rough pasture were in the same category in 1994 (M Naura, *pers. comm.*). Debris dams were not recorded in 1994.

Figure 2.3 Occurrence of LWD and debris dams in association with riparian landuse.

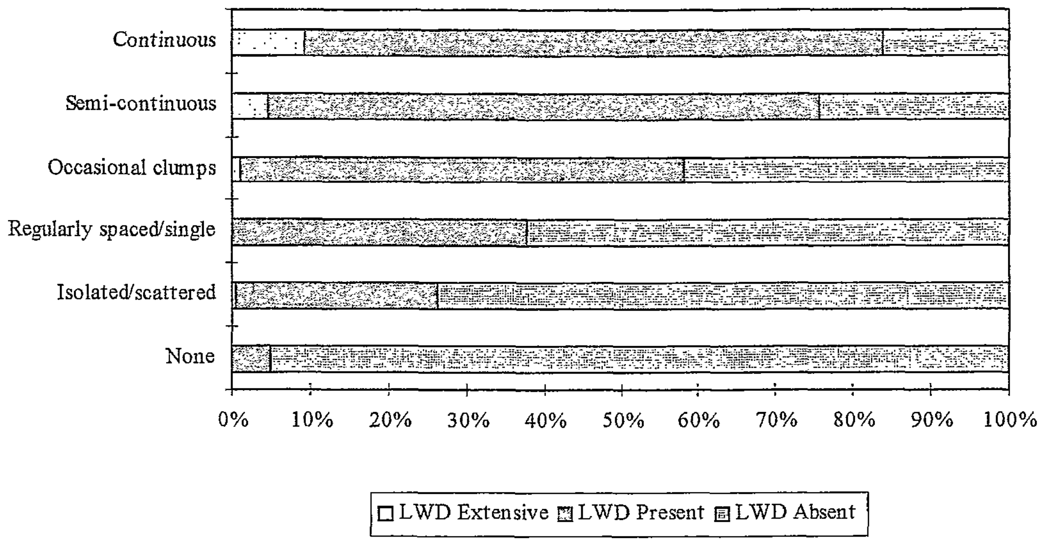


Figure 2.4 Occurrence of LWD in association with differing densities of riparian trees.

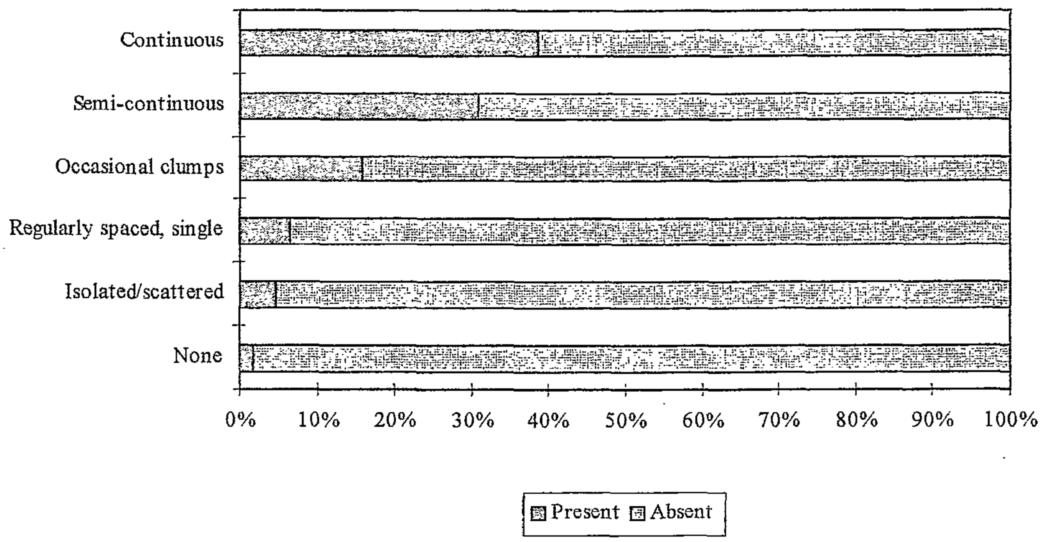


Figure 2.5 Occurrence of debris dams in association with differing densities of riparian trees.

2.3 Summary

- The abundance of LWD displays regional patterns related to regional variations in tree density. The distribution of LWD within regions also varies between upland and lowland sites, again as a result of differences in tree density, with lowland sites generally having a greater occurrence of LWD.
- LWD abundance is also related to stream type and the degree of anthropogenic stream alteration. Raven *et al.* (1998) presented data for four stream types, three of which had a

greater abundance of LWD on semi-natural sites and one, steep streams, displayed the opposite pattern of lower abundance on semi-natural sites. Small, lowland, riffle dominated streams had the highest occurrence of LWD with 78.4% of sites having LWD.

- LWD and debris dams occur most frequently on small streams as a result of increasing mobility and possibly more deliberate debris removal with increasing stream size. The average stream size with debris dams present (5.3m) is also smaller than the average stream size with LWD present (9.6m) indicating that, although LWD is present on moderate sized streams it only forms into stable accumulations on smaller streams.
- Since the 95 percentile of stream widths with debris dams present is 11.9m and the mean stream width with debris dams absent is 11.8m, a stream width of 10m appears to be a reasonable maximum width for defining British headwater streams for the purposes of this report.
- Riparian land use has a strong associaton with the presence and extent of LWD and debris dams. A greater proportion of sites with coniferous plantation, broadleaf/mixed woodland or scrub present or extensive contain LWD and debris dams than sites bordered by other land use types.
- The association between riparian land use and LWD is probably largely a reflection of riparian tree density, since riparian trees provide a source of LWD to the river. A strong association was observed between riparian tree density and the presence of LWD and debris dams. This suggests that a local input of LWD is necessary to maintain high LWD levels in the river systems.

3. HYDRAULIC, GEOMORPHOLOGICAL AND ECOLOGICAL IMPACTS OF LWD

3.1 Introduction

The primary influence of LWD on river channel processes is on hydraulics. LWD dams form major roughness elements, altering the spatial distribution, variability, range and average values of flow depths and velocities, and so increasing the hydraulic diversity within the channel. The increase in hydraulic diversity provides suitable conditions for a wider range of aquatic fauna over a wider range of discharges than a more uniform channel. The increased roughness due to LWD, however, is assumed to significantly increase the local flood hazard as a result of the increased depth associated with longer flow retention times.

The hydraulic effects of LWD dams lead to changes in the erosion, transport, sorting and deposition of sediment. These changes results in increases in the diversity of substrate sediment size, in higher sediment retention within the river channel system, and in an increase in the frequency of riffles and of pools. Such changes represent major alterations in the geomorphology of channels as a result of the presence of LWD dams. The combined effects of LWD dams on flow hydraulics, sediment transfer and channel morphology lead to an increase in physical habitat diversity and refuge habitats and an increase in the retentiveness of the river system for organic matter that can act as a food source for aquatic biota.

In addition to the potential increase in localised flood hazard as a result of the presence of LWD dams, another important management aspect of LWD dams is their stability. If dams are highly unstable, they may break during flood events and the wood pieces that are released may cause obstructions at sensitive sites such as weirs and bridges, where flooding may be particularly undesirable.

This section illustrates the extent of all of the above effects using examples from British headwater rivers in the Forest of Dean and the New Forest. LWD within these rivers remains relatively unmanaged and so the research results provide baseline information on the potential functioning of LWD within British headwater rivers in general. The hydraulic impacts of LWD dams are explored in 3.2. The ecological consequences of these hydraulic impacts are then modelled in 3.3 using the Physical Habitat Simulation model PHABSIM. The morphology of woodland streams containing LWD accumulations is described in 3.4. Finally, the consequences of the removal of LWD dams is assessed using a case study in 3.5.

3.2 The Hydraulic Effect of LWD Dams

3.2.1 Variations in the Hydraulic Effect of LWD with Changes in Discharge

On Blackpool Brook (Forest of Dean, Gloucestershire) three experimental reaches, each approximately 30m in length, were established to investigate the effect of LWD on channel hydraulics over a range of discharges. Reach one, contained no LWD in order to estimate natural variability in the hydraulic parameters being measured over the time scale of the study. Reach two incorporated the entire zone of influence of a single active LWD dam at the downstream end of the reach, including the upstream backwater zone and the downstream plunge pool. Reach three was more complex than reach two with two interacting, active LWD accumulations and a smaller accumulation of woody debris at the downstream end of the reach, held in place by a boulder. The most upstream accumulation, held in place by a living tree, caused flow avulsion at moderate and high flows and a well developed side channel was present. The next downstream LWD accumulation was stabilised by two fallen trees 6-7m long, aligned with the banks, which allowed a considerable amount of smaller organic debris to build up.

The three reaches had permanent cross sections established using wooden pegs. The cross sections were placed across every distinct habitat unit and across transition areas between units. Reach one had nine cross sections, reach two had ten cross sections and reach three had nine cross sections. For a range of discharges, depth and mean column velocity measurements were taken at 10 cm intervals across each cross section. The water surface level at each cross section was also measured relative to the other cross sections at three locations across the channel and averaged in order to calculate the water surface slope. During April 1997 the LWD was removed from reaches two and three. The reaches were allowed approximately 8 months to adjust and the measurements were repeated at a range of discharges. The summary results of these observations are as follows:

Depth
Reach mean depth, calculated by averaging all depth measurements, before and after LWD removal from reaches one, two and three are shown in figure 3.1. The removal of LWD from reaches two and three had the greatest effect upstream of the LWD accumulations as a result of the loss of the backwater effect. Reduction in the average depth downstream of the LWD accumulations also occurred as a result of morphological changes to the channel due to the infilling of plunge pools as a consequence of debris dam removal. The formation of plunge pools on Blackpool Brook is limited by the coarse, mainly cobble, substrate. It may, therefore, be expected that, on streams which develop larger plunge pools, such as those in the gravel-bed streams of the New Forest (see 3.4 and 3.5), the reduction of flow depths as a result of the removal of LWD dams may be more important.

Velocity
Reach mean velocity before and after LWD removal from reaches one, two and three are presented in figure 3.2. The data clearly show that mean velocity increases both with and without LWD as discharge increases and that LWD removal increases the mean velocity.

There was found to be no change in the relationship between velocity and discharge for reach one before and after LWD removal in the other two reaches, as would be expected for the control reach. However, for reaches two and three, there was a significant increase in reach mean velocity for any given discharge as a result of LWD removal.

Velocity distributions along cross sections below LWD accumulations in both reach two and reach three displayed higher variability than sections above the accumulations due to the manner in which the flow passes through LWD dams. When flowing through or over LWD dams the flow concentrates where there are gaps in the LWD matrix or at the lowest points of the accumulation resulting in threads of high velocity downstream. In the two reaches with LWD studied here these zones of elevated velocities were usually 30-40 cm wide. This type of velocity pattern creates good feeding habitat for salmonids as energy expenditure is reduced by holding in the low velocity areas, but there are adjacent areas of high velocity with high drift rates for feeding. These sites also have the advantage of the additional cover provided by LWD. Upstream of LWD accumulations the width and depth of the flow is increased by the backwater created by the LWD and velocities are significantly reduced, resulting in a more uniform distribution of velocity across the channel.

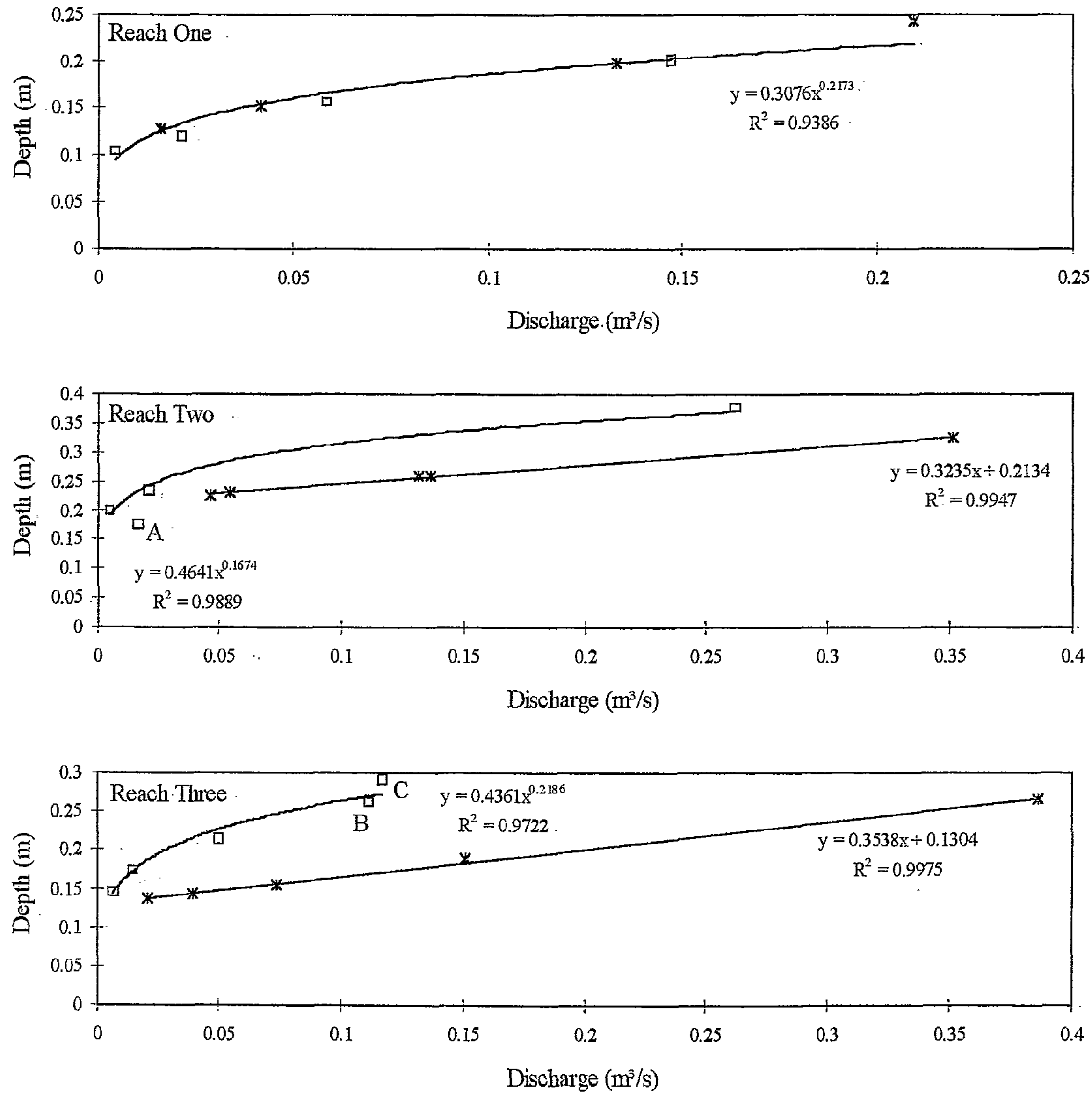


Figure 3.1 Reach mean depth for Blackpool Brook experimental reaches with and without LWD

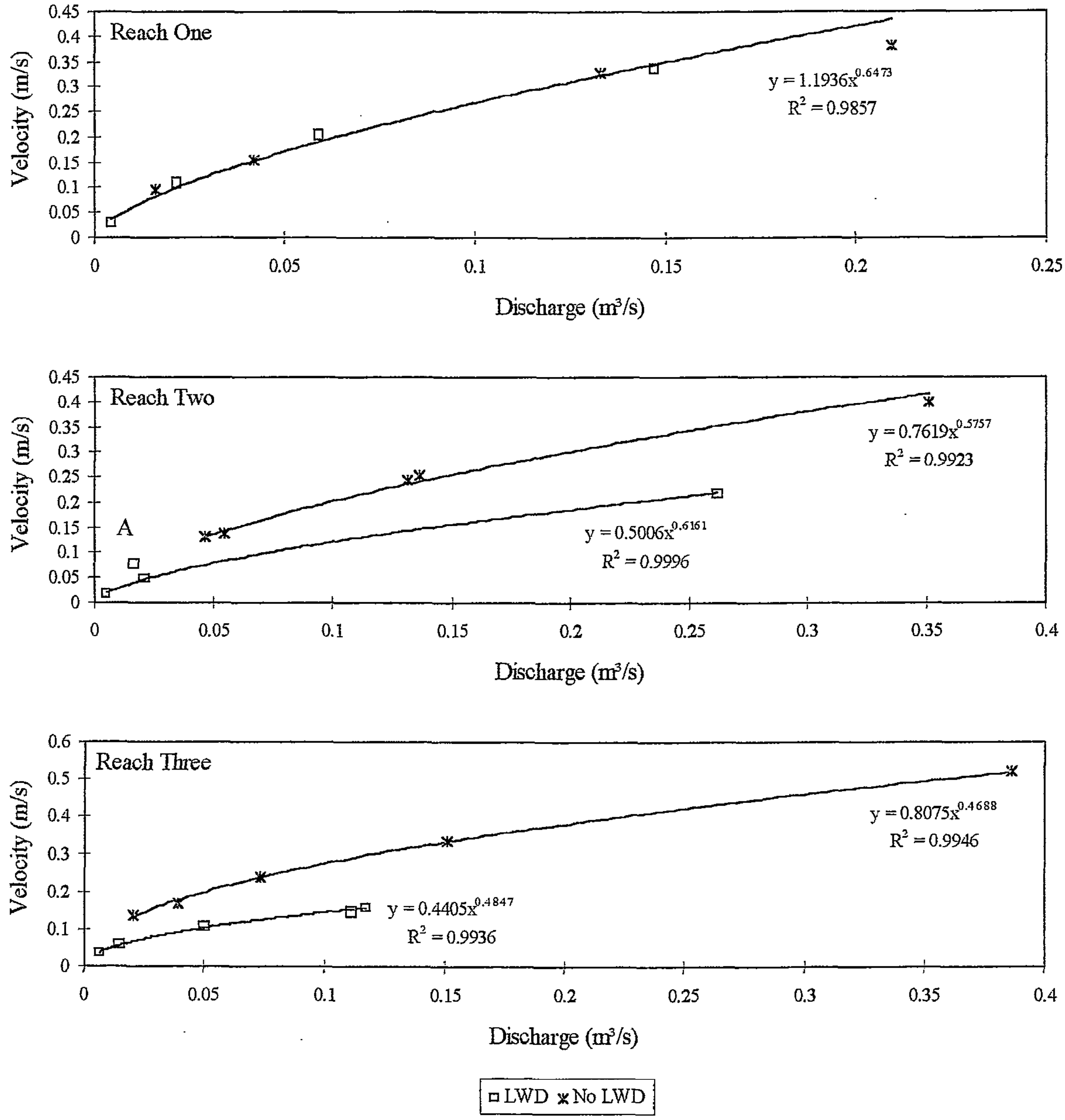


Figure 3.2 Reach mean velocity for Forest of Dean experimental reaches with and without LWD.

Channel roughness

The increased channel roughness due to LWD is a major reason for its removal from streams and it is, therefore, important to quantify the effect of LWD on channel roughness over a range of discharges.

Figure 3.3 shows that the increase of Manning's n due to the presence of LWD dams is greatest at low flow and decreases rapidly with a small increase in discharge, resulting in convergence of n with and without LWD as discharge increases. Complete convergence was not observed over the range of discharges sampled for this study. All flows, however, were within bankfull and further convergence would be expected as discharge approaches bankfull.

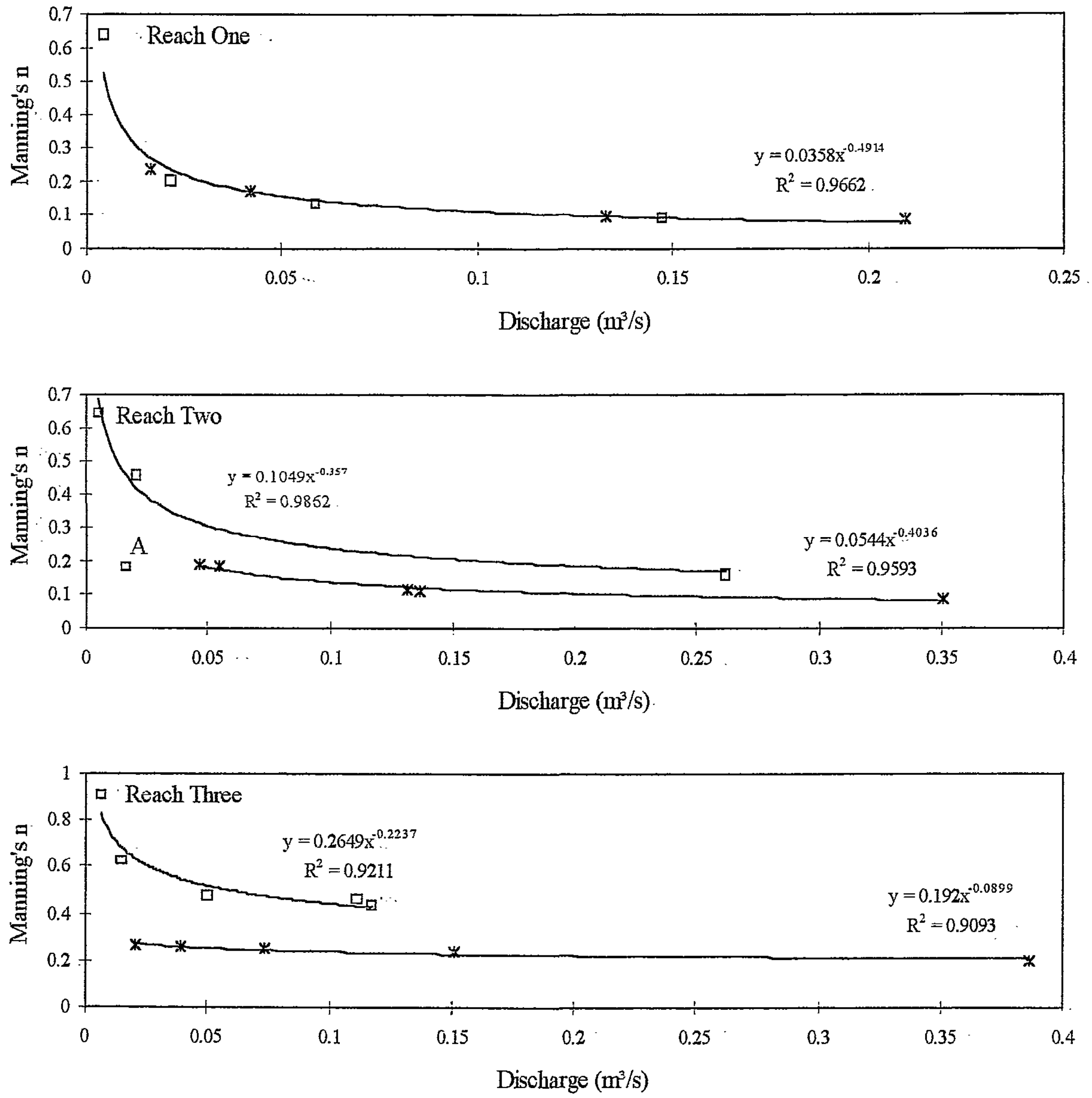


Figure 3.3 Manning's n against discharge for reaches one, two and three with and without LWD

3.2.2 Influence of LWD Accumulation Type on Reach Hydraulics

In order to investigate the influence of LWD accumulation type on hydraulics, tracer experiments were carried out on 25 reaches within a 4.5km section of the Highland Water, New Forest, Hampshire. The average bankfull channel width at the lower end of the section was 4.5m and was 2.5m at the upper end of the reach. Using dilution gauging, reach-integrated hydraulic parameters were estimated for each of the 25 reaches by recording the concentration of a tracer wave as it passed the upstream and downstream ends of the reach. Eight of the reaches contained active dams, two contained complete dams, six contained partial dams, and nine reaches without dams were monitored as control reaches. Although these four reach types were initially defined, because only two examples of reaches with complete dams were sampled, the observations from complete and active reaches were combined for the following analysis.

Depth

Over the 4.5km section of Highland Water where data were gathered, there was a significant reduction in channel size in an upstream direction. In order to correct for this variation in channel size, reach depth was divided by water surface width to produce a dimensionless measure of depth. The average dimensionless depths for active/complete, partial and control reaches are 0.178, 0.088 and 0.063, respectively. Using the Mann-Whitney U test to determine if these differences were statistically significant it was found that the depth of active/complete reaches was greater than either partial or control reaches ($p<0.01$). Although the average partial reach depth was greater than control reach depth, the difference was not statistically significant.

Velocity

Average velocities for the active/complete, partial and control reaches were $0.038m.s^{-1}$, $0.059m.s^{-1}$ and $0.084m.s^{-1}$, respectively. Using a Mann-Whitney U test the average velocity in active/complete reaches was found to be significantly lower than in control or partial reaches ($p<0.025$). Although higher, the average velocity of control reaches was not found to be statistically different from partial reaches.

Channel Roughness

The calculated values of Manning's n for the active/complete, partial and control reaches were calculated to be 0.963, 0.634 and 0.286, respectively. A Mann-Whitney U test demonstrated that n was significantly greater for active/complete and partial reaches than control reaches ($p<0.025$). The difference in n for active/complete reaches and partial reaches was not found to be statistically significant.

Discussion

The mean water depth within active/complete reaches was found to be greater than either partial or control reaches and the mean flow velocity was found to be lower. This is due to two effects of active LWD accumulations: the damming effect; and the creation of plunge pools. As these data were collected during a period of baseflow, the damming effect was small. However, the formation of plunge pools during high flows creates areas of deep flow downstream of the LWD accumulations, which are retained during lower flows. The range of reach mean depths was also greater for active/complete reaches than partial or control reaches as the magnitude of the effect of active LWD accumulations is, to a large extent, a function of its size and a wide range of LWD accumulation sizes occur on Highland Water. Although partial accumulations tend to create scour pools as a result of flow constriction, these are not as extensive as dammed and plunge pools and the difference in mean depth and velocity between partial reaches and control reaches was not statistically significant. As a result of these effects on the flow and channel morphology, LWD was found to increase Manning's n for both active/complete and partial reaches, despite partial and control reaches not having significantly different depths or velocities. Such a marked increase in Manning's n is consistent with the low flow observations in the Forest of Dean (3.2.1), and illustrates the considerable flow resistance of LWD accumulations during low flow conditions.

3.2.3 Effect of LWD on Stream Dead Zone Characteristics

The overall hydraulic effect of LWD dams can also be usefully summarised in terms of the dead zones that are created within the river channel. Dead zones are important for nutrient retention and for stream ecology. For example, these low velocity areas create refugia which are important for the survival of macroinvertebrates and fish during periods of high flow. Lancaster and Hildrew (1993) used the dispersive fraction, estimated from the ADZ model, to provide a reach-scale integrated measure of flow refugia. They stated that a low dispersive fraction is likely to be associated with stream reaches which have low refuge potential and with hydraulic characteristics that increase macroinvertebrate transport out of the reach. Therefore, the results presented here, which examine changes in dead zone properties due to LWD, can be viewed as an indication of the effect of LWD on refuge potential.

The Aggregated Dead Zone (ADZ) model (Beer and Young, 1983; Young and Wallis, 1986) uses a systems approach whereby all dead zones in a reach, at all scales, are aggregated as a single dead zone which accounts for all the dispersive properties of the reach. Once the Aggregated Dead Zone (ADZ) model is calibrated, the volume of the ADZ and the ratio of the ADZ volume to the volume of water in the reach, termed the dispersive fraction (D_F), can be calculated from the model parameters. D_F is a very useful model parameter as it provides an objective, scale independent, measure of dispersive properties. In order to calibrate the ADZ model the concentration of a slug-injected solute wave as it passes the upstream and downstream ends of the reach are needed.

Two experimental reaches were established on Blackpool Brook in the Forest of Dean to examine the relationship between LWD-created dead zone and discharge. One of the experimental reaches had no LWD and acted as a control. The reach was 16.6m long and the downstream end of the reach was located on a riffle crest. It included a full riffle-pool-riffle sequence. The LWD reach length was set at 18.2 m and contained a single, active, LWD accumulation. The downstream probe monitoring tracer concentration was located in a plunge pool and the upstream probe was subject to a variable backwater from the LWD accumulation. 16 tracer experiments were carried out at a range of flows for both the control and LWD reaches. Figure 3.4 shows the dispersive fractions of the LWD and control reaches plotted against discharge. The LWD reach displays a considerably higher D_F than the control reach, indicating its higher retentiveness and refuge potential.

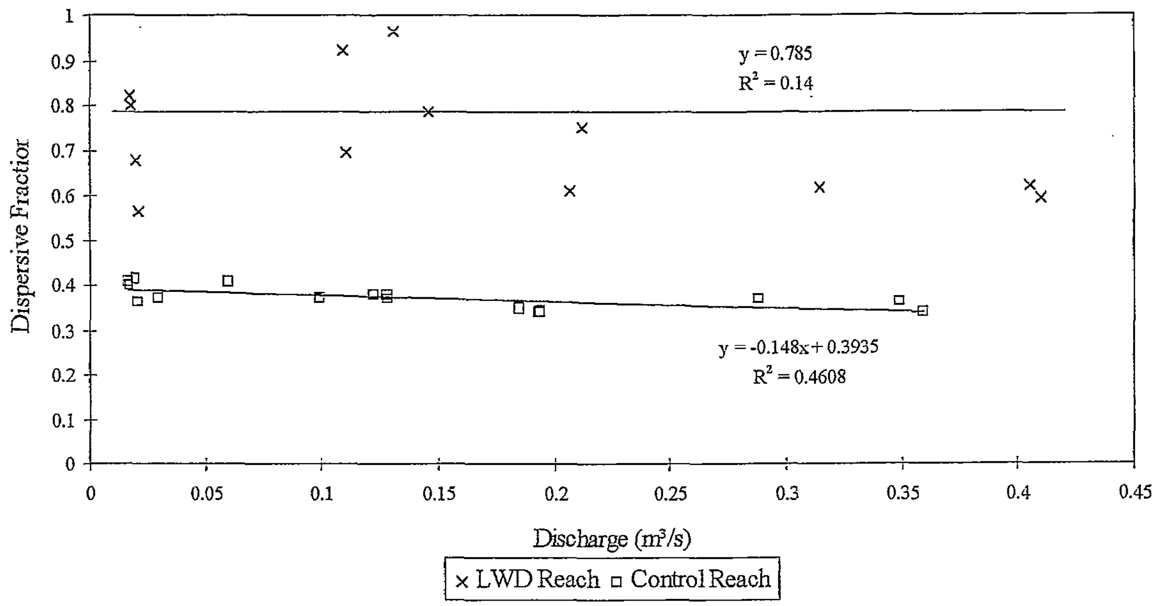


Figure 3.4 Variation in D_F with discharge for LWD and control reaches

3.3 Assessment of the Ecological Effects of Changed Hydraulic Conditions resulting from LWD Dam Removal

3.3.1 Methodology

Using the hydraulic data from reach three described in section 3.2.1 the Physical Habitat Simulation model (PHABSIM) was used to assess the changes in the quality and quantity of physical habitat in the reach as a result of LWD removal. This reach provides a good opportunity to test the effect of LWD on instream habitat as data of a suitable format for use with PHABSIM are available for the same reach with and without LWD. PHABSIM is the simulation component of the Instream Flow Incremental Methodology (IFIM), a broad conceptual framework for assessing instream habitat developed by the United States Fish and Wildlife Service (Bovee, 1982). PHABSIM itself is a collection of computer programs, the aim of which is to model instream physical habitat, based on measurements of hydraulic characteristics taken for a limited number of discharges, usually three, although up to five were used for this study. The PHABSIM model uses standard hydraulic modelling techniques with data from a range of flows to predict water surface levels (WSLs) and velocities for cells across selected stream cross sections at a series of user-specified discharges. Along with hydraulic data, information on other ecologically relevant parameters, usually cover and substrate, are collected for each cell. These hydraulic and channel attribute data are then combined with suitability curves which quantify the suitability of these conditions for a target species life stage to assess the quality and quantity of instream habitat for that species life stage over a range of discharges. The usable area (UA) is calculated as the total area of all cells that are usable to any degree. The weighted usable area (WUA) can be calculated using several algorithms but the one used for this study was the sum of the products of cell areas and their suitability values. The WUA, therefore, gives a combined index of habitat quality and quantity. Suitability curves for adult and juvenile brown trout were used for this study. However, as the aim of this study is not to provide an assessment of habitat for brown trout *per se* but to provide an assessment of habitat changes as a result of LWD removal, it was not important that the suitability curves used perfectly reflected the actual habitat use in the stream, simply that they provided an index of habitat quality and quantity.

3.3.2 Results

Figure 3.5 shows that the water surface area when a LWD accumulation is present, increases rapidly with discharge and is greater than when there is no LWD present in the stream. The rate of increase of water surface area both with and without LWD decreases with discharge. Figure 3.5 also shows the WUA calculated for juvenile brown trout. It can be seen that there is significantly greater WUA for juveniles when LWD is present in the reach. WUA with LWD also increases more rapidly with discharge than WUA without LWD at the highest modelled discharges. Figure 3.6 shows the percentage of the total water area that is usable (%UA) and the percentage of the total area that is WUA (%WUA) for juvenile brown trout before and after LWD removal. It can be seen that both with and without LWD removal a large proportion of the reach habitat is usable to some degree but the %WUA is higher with the LWD in place.

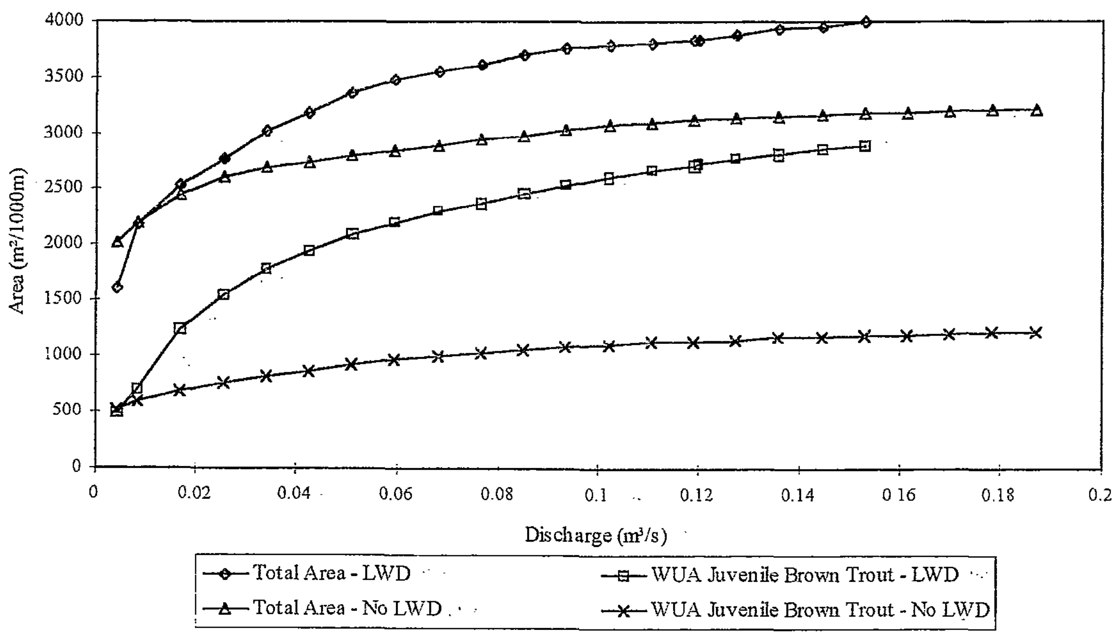


Figure 3.5 WUA and Total Area for Juvenile Trout.

To assess the quality of the available habitat, the effect of differences in UA with and without LWD and as discharge changes was removed by expressing WUA as a percentage of UA in figure 3.7. Figure 3.7 shows that, at low flows, usable habitat quality is similar with and without LWD. However, as discharge rises the quality of habitat without LWD remains constant but habitat quality with LWD, initially rises rapidly and then the rate of increase declines. At high discharges habitat quality with LWD is approximately double that without LWD. Thus, from figures 3.6 and 3.7 it can be seen that, in hydraulic terms, there is considerably greater habitat quantity and quality for juvenile brown trout when LWD is present.

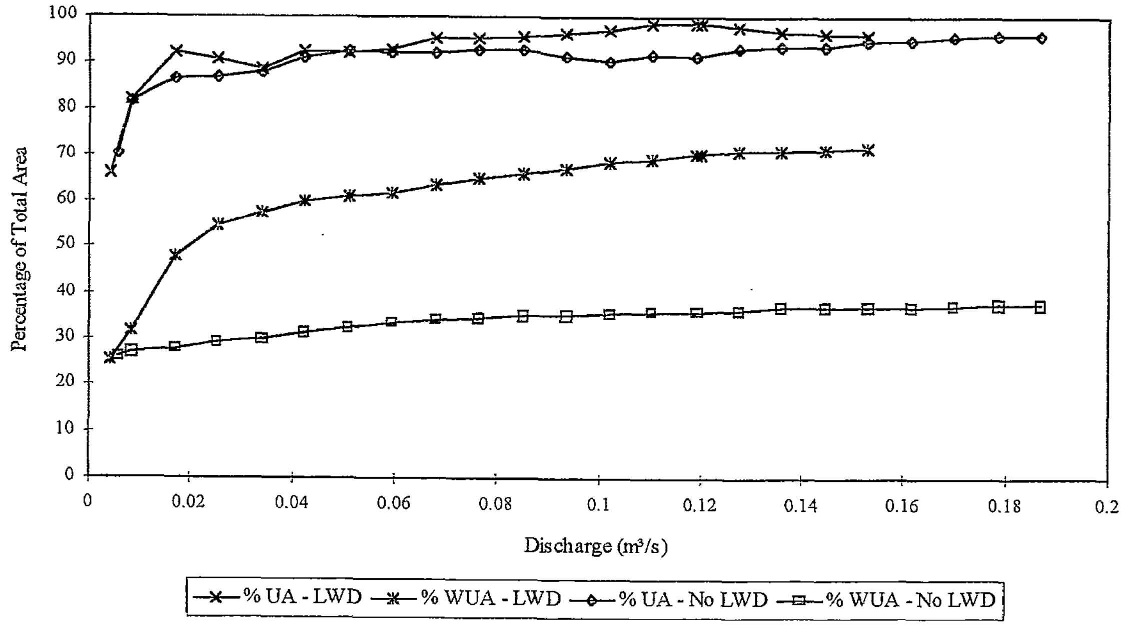


Figure 3.6 Percentage UA and WUA Pre and Post LWD Removal for Juvenile Brown Trout

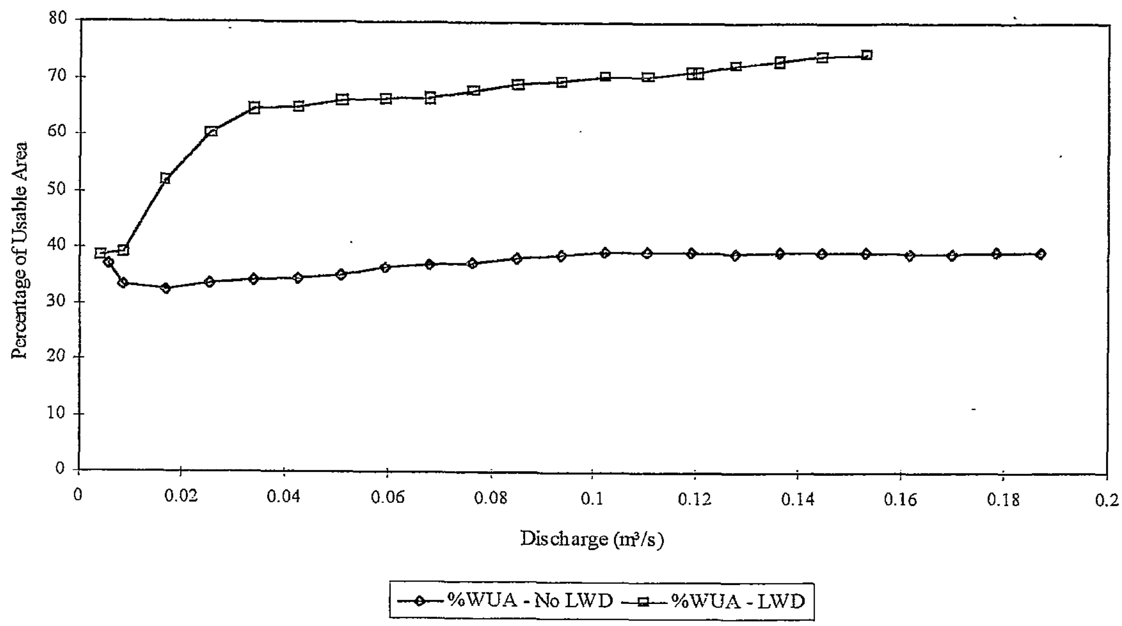


Figure 3.7 Percentage of UA represented by WUA

Figure 3.8 shows the WUA and total area for adult brown trout in the reach before and after LWD removal. As would be expected for a reach such as this, with relatively shallow water over most of its length, the WUA is lower than that for juvenile brown trout. As with juvenile habitat, WUA before LWD removal is considerably higher than the WUA after LWD removal and it increases with discharge, whereas without LWD WUA is relatively constant over most

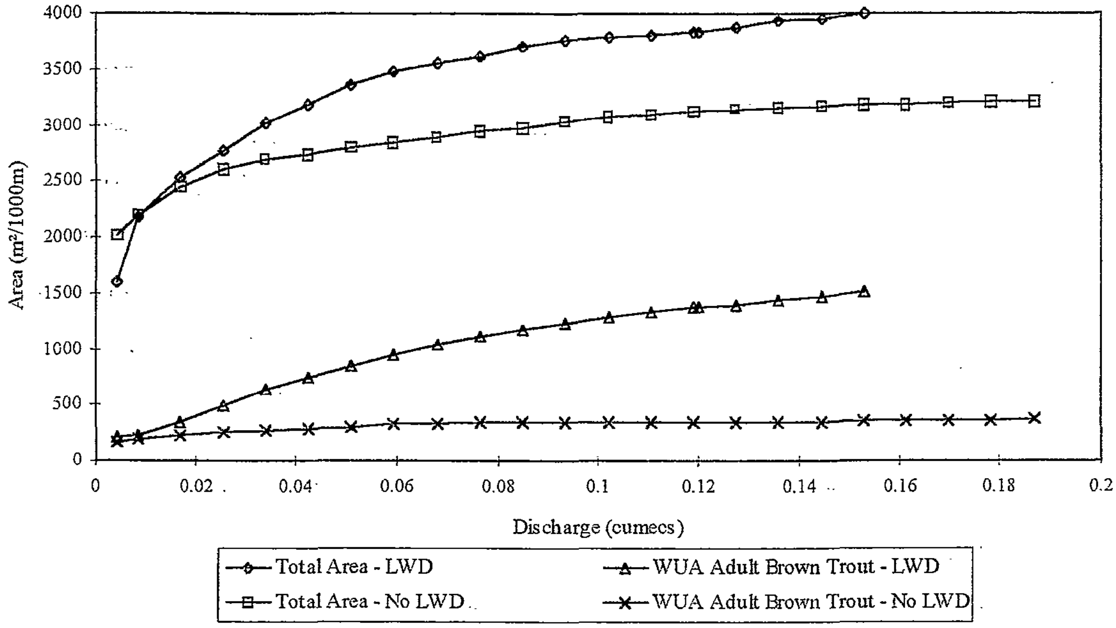


Figure 3.8 WUA and Total Area for Adult Trout.

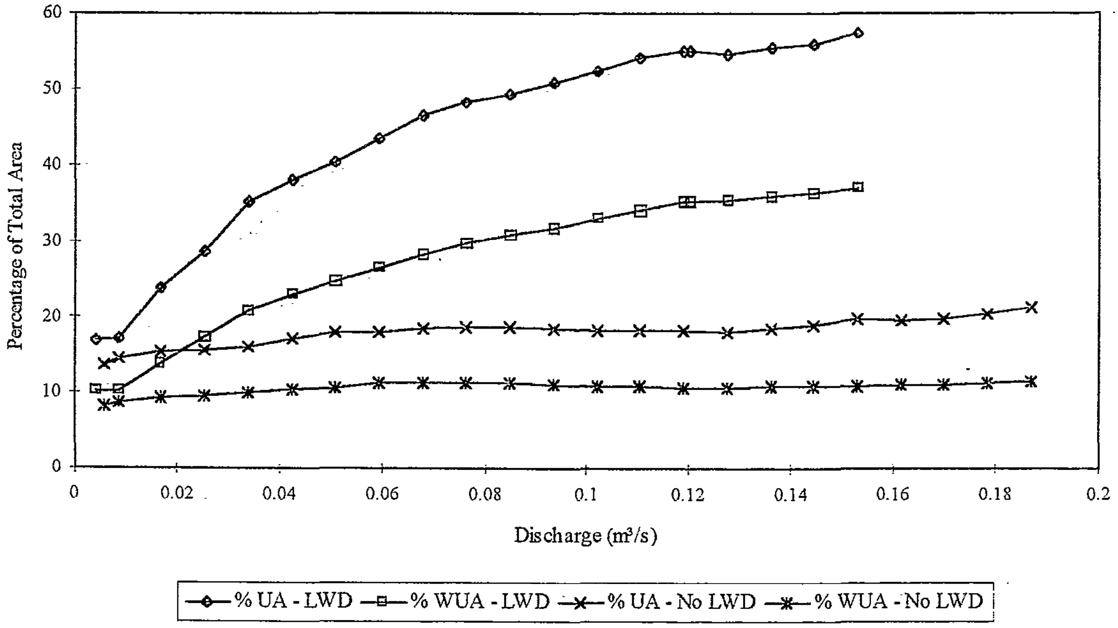


Figure 3.9 Percentage of UA Represented by WUA for Adult Brown Trout Before and After LWD Removal.

of the range of modelled flows. Figure 3.9 shows the %UA and %WUA for adult brown trout before and after LWD removal. The %UA and %WUA with LWD are significantly higher than without LWD. It can also be seen that %UA and %WUA increase with discharge when LWD is present, indicating that a greater proportion of the reach becomes usable with increasing discharge. The %UA and %WUA without LWD remains relatively constant with discharge.

It was demonstrated in section 3.2.1 that at low flows hydraulic conditions with and without LWD were similar. The various indices presented here also show that habitat quality and quantity are similar at low flow but diverge as discharge increases.

The output from PHABSIM, in terms of usable area and weighted usable area, shows that for both adult and juvenile trout there is more habitat of better quality when LWD dams are present. Much of the reach is unsuited to adult trout as the flow is too shallow, which is demonstrated by the much lower percentage of total water surface area that is UA and WUA for adults. The results also show that the removal of LWD has a greater effect on adult than on juvenile habitat. This is due to the fact that, although adults are more suited to the higher velocities, the reduced depths after LWD removal have a greater impact on adults

3.4 The Geomorphology of Woodland Streams

So far the discussion has concentrated on hydraulic effects of LWD accumulations and their ecological consequences. The hydraulic impacts of LWD accumulations also affect sediment scour, transport and deposition, and so affect the geomorphology of woodland headwater rivers. These geomorphological changes are ecologically important. This section explores the geomorphological impacts of LWD dams within relatively unmanaged headwater streams using information from the New Forest and Forest of Dean.

Pools and riffles are fundamental geomorphological elements of many types of river channel. They are a result of the erosion, transport and storage of bed sediment within the river channel. They are ecologically important, providing locations of differing flow depth, flow velocity and substrate, which contribute to the diversity of physical habitat within the river channel. It is widely accepted that naturally-occurring pools and riffles have an average spacing of 5-7 channel widths. However, smaller average spacings than 5-7 channel widths had been found in unmanaged channels as a result of the influence of LWD dams, indicating particularly high physical habitat diversity. This decreased spacing is observed in the Highland Water. For example, Figure 3.10 illustrates a ca. 5m width and 200m length channel section where there were 13 pools in 1992, giving an average spacing of ca. 3 channel widths. 48% of the reach length consisted of pools at low flow; and 11 of the 13 pools were located within one channel width of a LWD dam, indicating the close association between LWD accumulations and pools.

The increased frequency of pools and riffles in channels affected by LWD is a result of the hydraulic influence of the LWD accumulations. A number of different types of pool may be associated with LWD accumulations (Table 3.1). For example, upstream or dammed pools and downstream plunge pools occur widely in association with active dams. Pools of differing type tend to display differences in their relative depth and sediment calibre, providing a range of hydraulic, temperature and substrate conditions. Table 3.2 illustrates the close association between the spacing of pools and the frequency of LWD accumulations within different parts of the Highland Water. The total dam frequency and the frequency of active dams decreases with increasing channel width or stream order, whereas the frequency of complete dams remains relatively stable and the frequency of partial dams increases. The frequency of total and proximate pools also decreases with increasing stream order.

The association between LWD dams and pools is illustrated in Figure 3.11 using channel widths to standardise pool spacing in river channels of different size. The spacing between pools within individual 100m channel reaches of the Highland Water decreases with an increasing frequency of dams, although there appears to be a minimum pool spacing of two channel widths regardless of the number of LWD dams present. This suggests that in the Highland Water an average pool spacing of two channel widths (considerably less than the generally-accepted 5-7 channel widths) could be achieved if there was no management of LWD.

Upstream pools dammed behind active or complete debris dams can cause avulsion during high river flows (i.e. overflow of water from the river channel onto the floodplain). Figure 3.12 shows a section of a tributary to the Highland Water, illustrating that the most hydraulically active and stable LWD accumulations affect the structure and dynamics of the channel system through avulsion. Three types of channel can be identified: perennial, intermittent and ephemeral. Low flows are contained within a single perennially-flowing channel; seasonally higher flows extend into intermittently-flowing channels; and flood flows extend even more widely into ephemerally-flowing channels. If dams persist at a particular location, the above effects on the channel structure and dynamics can result in more permanent flow diversion and channel pattern change.

These impacts of LWD accumulations on both channel form and stream network structure and dynamics have both hydrological and ecological importance. The hydrological importance relates to water storage, flow pathways and storm hydrograph attenuation. The pools provide areas for surface water storage at low flows, sustaining surface water for longer periods during drought conditions. At high flows, the pools and backwaters behind LWD accumulations and water storage in ephemeral and intermittent channels result in increased flood peak travel times and attenuation of flood hydrograph shape. Further hydrological impacts of in-channel water storage behind LWD accumulations are improved hydrological connectivity between channel and floodplain and enhanced underflows within the channel bed at LWD dam locations. All of these hydrological effects have important consequences for stream ecology by greatly enhancing the hydraulic and physical habitat diversity within the channel and riparian zone and by affecting water quality.

A major management concern is the stability of LWD, since high LWD movement during floods could cause blockage and flooding around structures such as bridges and weirs. No studies of the dynamics of individual LWD pieces have been undertaken in either the New Forest or the Forest of Dean, but there have been a number of surveys of the locations of

LWD dams in the New Forest study area. These studies show that the debris dams are far more mobile than those reported in North American studies. For example, in a section of the Highland Water containing almost 300 debris dams, over 15 months there was some form of change (in dam type, dam removal or the creation of new dams) at over 60% of sites at which dams had been observed in the two debris dam surveys. Nevertheless, the degree of mobility of dams varied with dam type. For example, Table 3.3 presents information on the mobility of some of the above dams located along a 5km section of the Highland Water. The surveys showed that the most substantial, hydraulically and geomorphologically important active dams changed least between survey dates, with a total of 11% being removed and 7% being created. The main changes associated with active dams involved a change in dam type, typically to or from the less hydraulically active complete type. In contrast, partial dams underwent considerable change, with 44% of dams newly created and 31% of dams removed between surveys. Most of the change associated with partial dams was loss or creation, with only 13% partial dams changing to another dam type and only 9% of dams changing to the partial type from another type. The complete dams showed an intermediate level of stability between the partial and active categories.

Figure 3.10 gives further evidence of the permanence of active dams. It shows the changes in dam location and class over a 10 year period in a 200m length of the Highland Water. The map illustrates high mobility in the partial dams, but two of the large active dams recorded in 1982 remain in the same location after ten years. It seems that major active dams, particularly those where the key piece or pieces of LWD are particularly large, can persist for decades, acting as a retention structure for smaller pieces of debris, and so providing an important control on the rate of downstream transfer of woody debris as well as being the most important influence on the geomorphology of woodland headwater rivers.

There are important LWD management implications of these observations. Clearly, the most mobile structures are the partial dams. Although active and complete dams may change in type as wood pieces join or leave the structures, they tend to remain in position providing an important buffer to the downstream movement of wood, including that generated by the failure of partial dams. Thus removal of the active and complete dams is more likely to increase than to decrease the mobility of the pieces of wood that remain.

Table 3.1 Classes of pool identified during surveys of New Forest streams (from Gurnell and Linstead, 1998)

Pool Type	Definition
Free Pools	Pools unrelated to obstruction by LWD accumulations. (Pools located more than one channel width from LWD accumulations)
Proximate Pools	Pools located close to LWD accumulations. (At least a part of the pool is located within one channel width of a LWD dam)
Types of Proximate Pool:	
Upstream Pools	Proximate-backwater pools dammed upstream of LWD accumulations
Pools at LWD Accumulations	Proximate pools created by: (i) underscour beneath a LWD accumulation; (ii) lateral scour as a result of flow deflection and funnelling by partial LWD accumulations
Downstream Pools	Proximate pools created by: (i) flow plunging over the LWD accumulation; (ii) lateral flow eddies downstream of the LWD accumulation

Table 3.2 Debris dam and pool frequency in relatively unmanaged sections of the Highland Water, New Forest [1]

Stream Order	1	2	3	4
Dam frequency / 100m				
Total dams	9.0	4.2	3.2	3.6
Partial dams	1.5	1.8	1.8	2.3
Complete dams	1.3	1.1	0.8	1.0
Active dams	6.2	1.3	0.6	0.2
Complete+Active dams	7.5	2.4	1.4	1.2
Pool frequency / 100m [2]				
Total pools	-	8.7	6.5	5.6
Free Pools	-	3.0	4.1	2.8
Proximate Pools	10.0	5.7	2.5	2.8
Upstream pools	3.5	1.1	0.7	0.7
Pools at dams	1.2	2.6	0.4	0.9
Downstream Pools	5.3	2.0	1.3	1.2

1 data are derived from surveys at different dates to represent situations where there was negligible management of LWD for at least 5 years prior to the survey.

2 data derived from geomorphological maps where only pools > 2m maximum length were analysed

Table 3.3 Changes in the frequency and location of debris dams in 100m sections of a 5km length of the Highland Water, September/October 1982 to January 1984 (from Piégay and Gurnell, 1997)

Type of change observed in 100m sections	Number of dams of each type (% of 1982 totals given in parentheses)			
	Partial	Complete	Active	Total
1982 Total	90	40	28	158
Dam Additions, 1982-4				
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, 1982-4				
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)

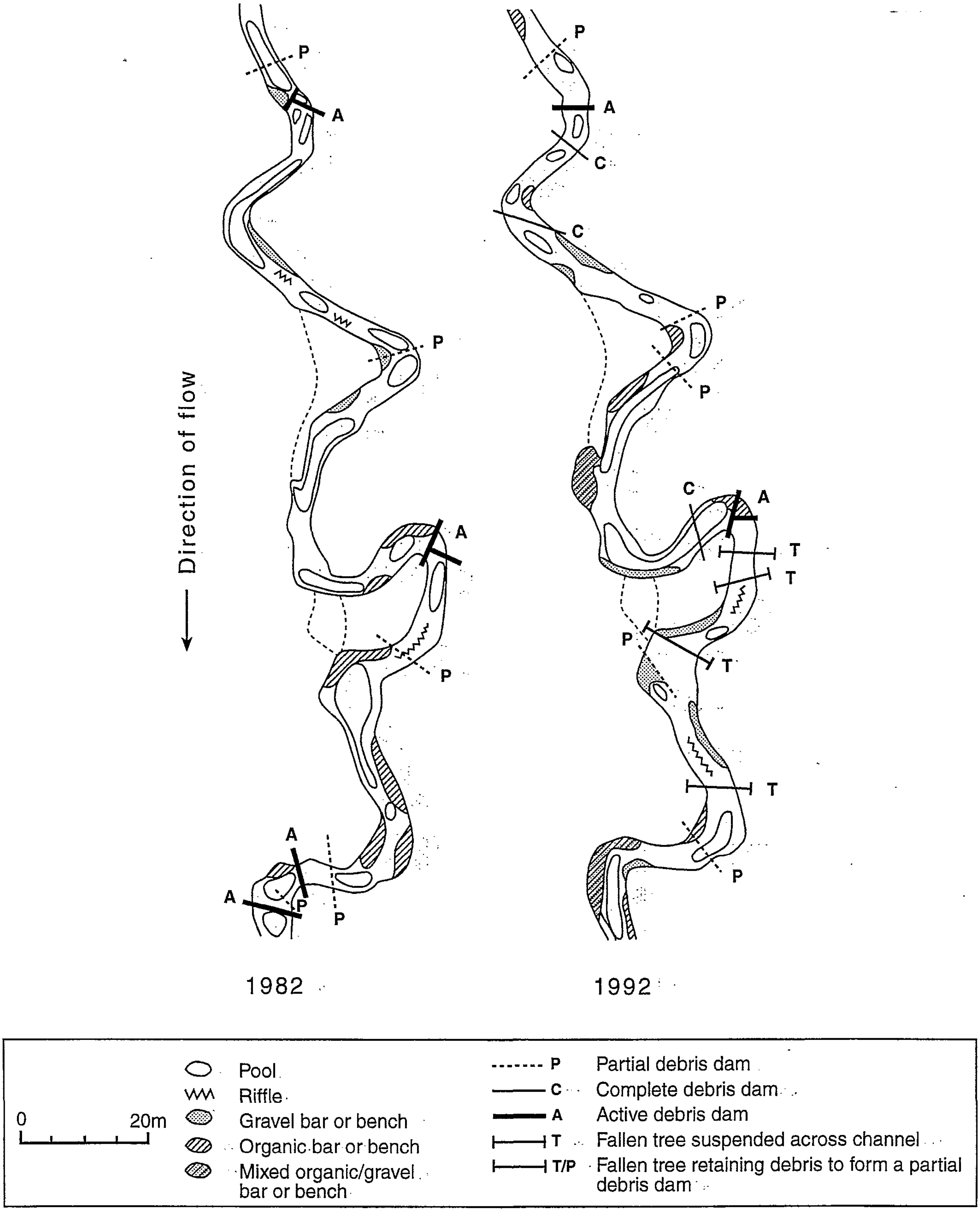


Figure 3.10 Geomorphological maps of a reach of the Highland Water, 1982 and 1992. (surveys by C.T. Hill)

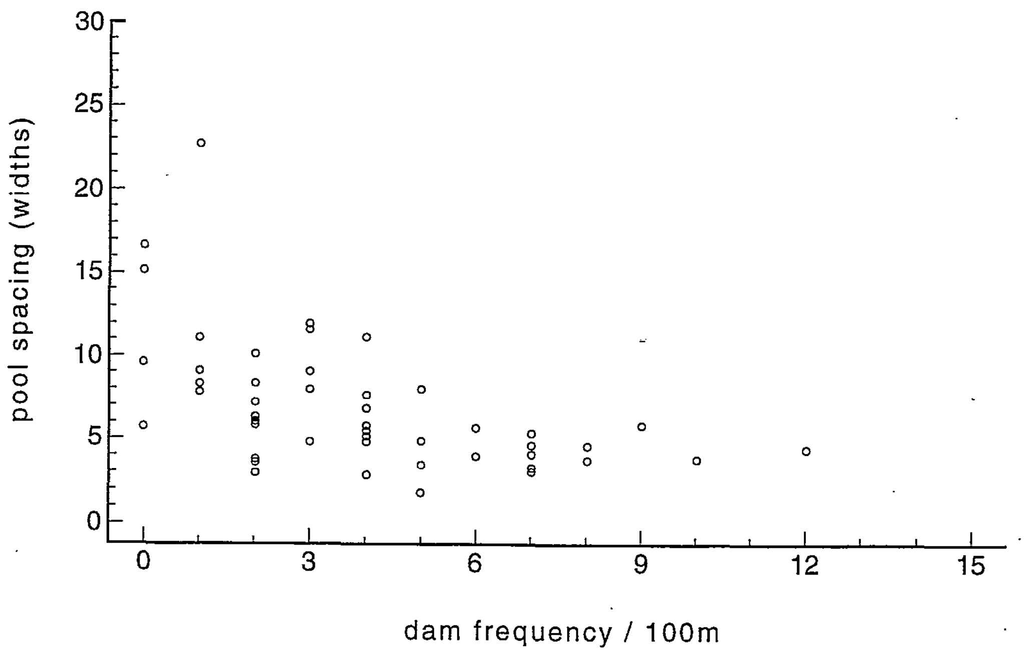


Figure 3.11 The relationship between pool spacing (in channel widths) and debris dam frequency in 100m reaches of the Highland Water, 1996.

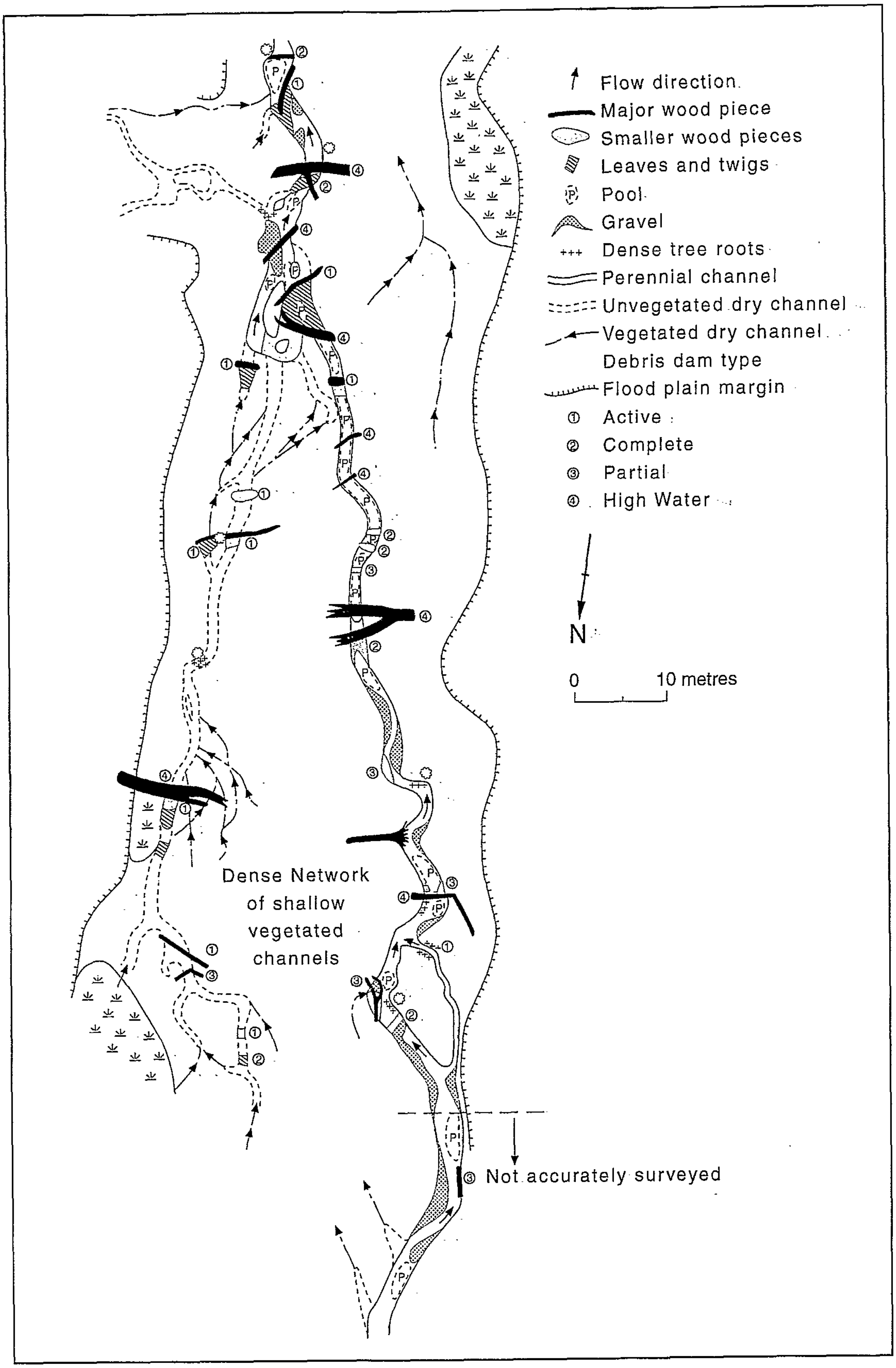


Figure 3.12 Flow avulsion associated with active and complete LWD accumulations feeds intermittently and ephemerally flowing channels on a tributary to the Highland Water (from Gurnell and Linstead, 1998)

3.5 A Case Study illustrating the Impact of LWD Clearance on LWD and Pool Dynamics

This section describes a case study, which illustrates the enormous importance of LWD dams for stabilising headwater river systems, and for maintaining the high diversity of physical habitat which is so important for the ecology of these river systems.

Although river channels and LWD are lightly managed in the New Forest in comparison with most British rivers, occasional LWD dam clearance has occurred and channels have been straightened to aid forest plantation drainage. A 600m stretch of the Highland Water was channelised into a straight uniform channel in the 1960s in association with tree planting, and a major clearance of LWD dams was undertaken over a 5 km length of channel in 1989. The impact of both of these management events provides important insights into the effects of LWD management.

Figures 3.13 and 3.14 illustrate the recovery of LWD accumulations after clearance. The section of the river that was straightened in the 1960s spans 100m reaches 15 to 22 in Figures 3.13 and 3.14. Debris clearance occurred in reaches 1-50 but not downstream.

Figure 3.13 illustrates the change in total dam frequency in 52 100m reaches of the Highland Water at a series of survey dates in comparison with 1982. The vertical bars represent the survey date dam frequency in each 100m reach subtracted from the 1982 dam frequency. Thus, positive values indicate less dams and negative values more dams than were observed in 1982. The 1984 survey shows small positive and negative changes typical of a period of natural adjustment, when debris was not being managed. The large positive values for January 1990 in reaches 1-14 and 23-50 illustrate the impact of dam clearance in 1989, whereas the absence of bars in reaches 15-22 reflects the fact that there were very few dams in this channelised section before or after clearance. By July 1990, two lengths of the channel show negative values (an increase in dam frequency in comparison with 1982): the channelised section, indicating that it is accumulating debris; and the most downstream reaches, indicating that debris mobilised by dam removal upstream is becoming trapped by the section that was not cleared. There was a major wind storm immediately after the January 1990 survey, which introduced LWD into the channel. Significant tree fall also occurred during the storm, but the trees mainly bridged the channel and the majority were subsequently cut up and removed. By November 1990, the new dams in the channelised section and in the downstream reaches had disappeared, leaving an overall reduction in the number of dams in comparison with 1982. Thereafter the number of dams gradually recovered until by 1996/7 the overall total of dams was greater than in 1982 and there was no clear downstream pattern in retention of more or less dams.

Figure 3.14 shows the response of the three types of dam to clearance. Partial dams follow a very similar pattern of recovery to that for total dams, the only major difference being the larger number of partial dams present throughout the river length in 1996/7 in comparison with 1982. By 1996/7, complete dams appear to have recovered to approximately their pre-clearance frequency, but the number of active dams is still relatively low.

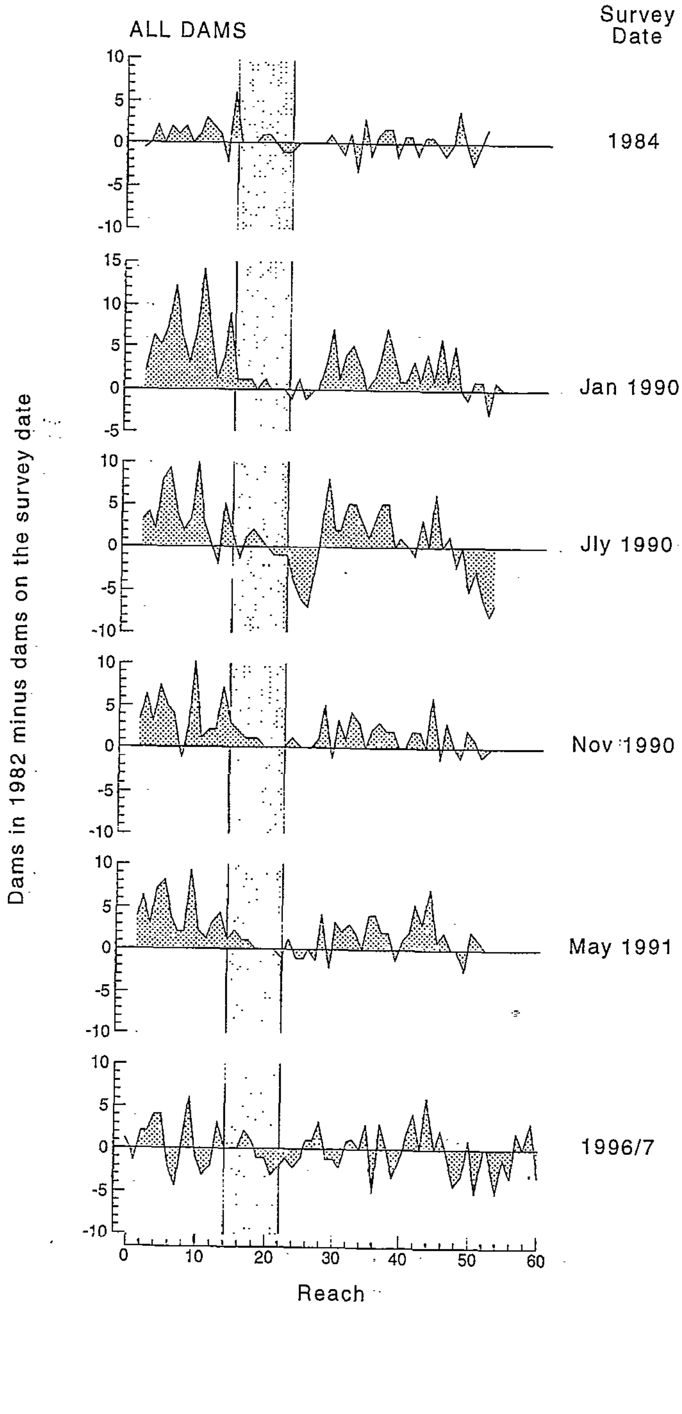


Figure 3.13 Total dams in 100m reaches of the Highland Water in 1982 minus total dams in the same reaches in 1984, January 1990, July 1990, November 1990, May 1991 and 1996/7. The reaches numbers increase in a downstream direction, stippling marks the section channelised in the 1960s. (from Gurnell and Sweet, 1998).

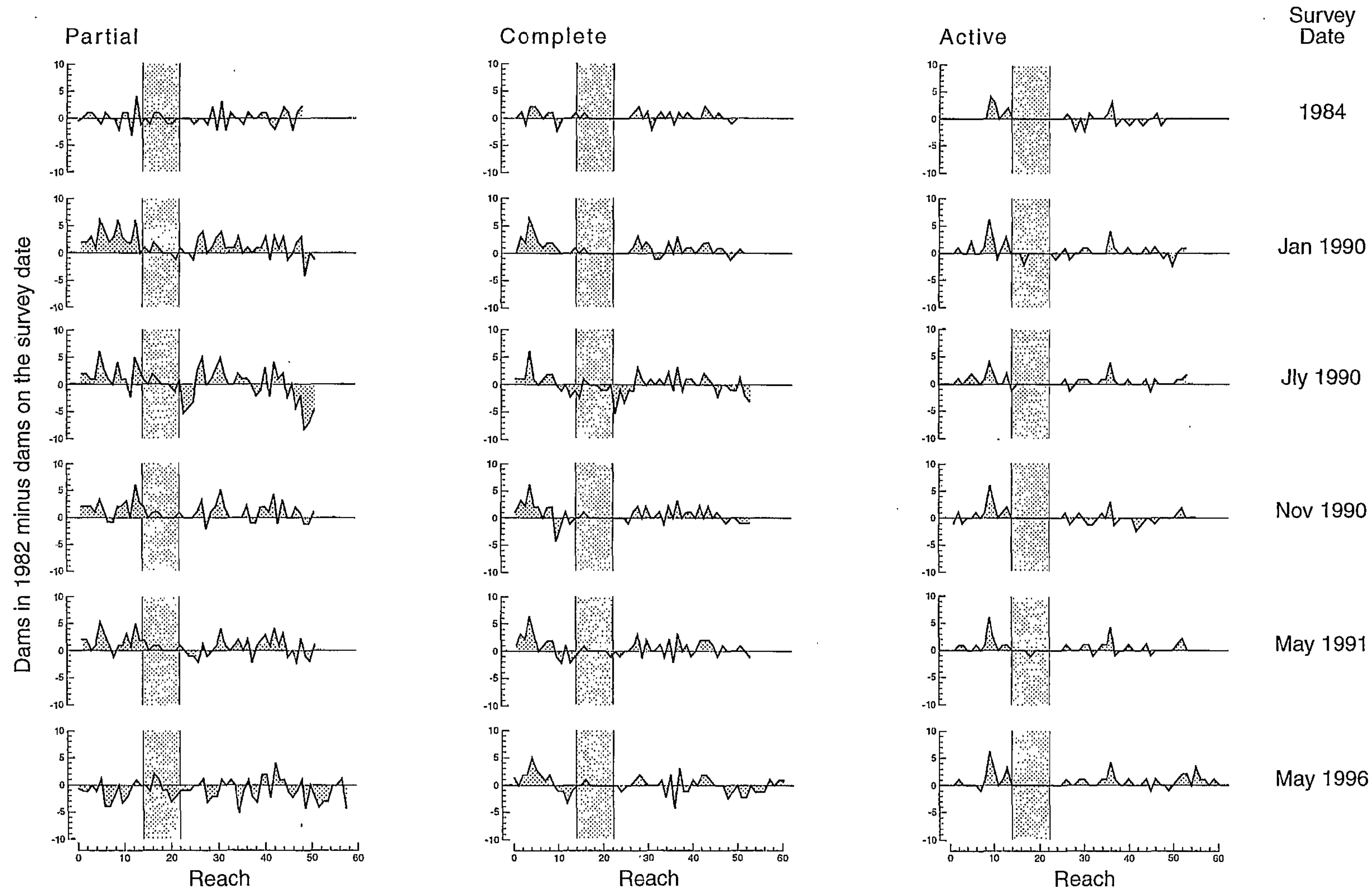


Figure 3.14 The frequency of A - partial dams; B - complete dams; C - active dams in 100m reaches of the Highland Water in 1982 minus frequency of partial, complete and active dams, respectively, in the same reaches in 1984, January 1990, July 1990, November 1990, May 1991 and 1996/7. The reaches numbers increase in a downstream direction, stippling marks the section channelised in the 1960s. (from Gurnell and Sweet, 1998).

The important implications of these observations are:

- Although the total number of dams in 1996/7, 8 years after LWD clearance, is greater than that in 1982, the hydraulically-important active dams have not re-established to pre-clearance levels. Complete and active dams are important controls on LWD movement, and are also highly significant for the retention of smaller organic matter and mineral sediment.
- The clusters of dams that appeared in the straightened section and the downstream reaches in the July 1990 survey and then disappeared by the November 1990 survey were mainly unstable partial dams. In the absence of major active dams, LWD pieces associated with these partial dams was very mobile and had probably been transported well downstream by the November 1990 survey.

Downstream plunge pools, upstream dammed pools, lateral pools and accumulations of mineral sediment are characteristic geomorphological features associated with LWD accumulations. The removal of LWD dams releases stored sediment and also removes a major control on the channel long profile. It was clear in the field during 1996/7 surveys, that up to 0.3m of bed incision and considerable bank erosion had occurred recently in the channelised section of the Highland Water despite the fact that the channelisation was over 30 years old. It was also clear from deposited plumes of fresh bed sediment, particularly at the upstream end of many pools, that river bed sediment was very mobile, particularly downstream of the channelised section.

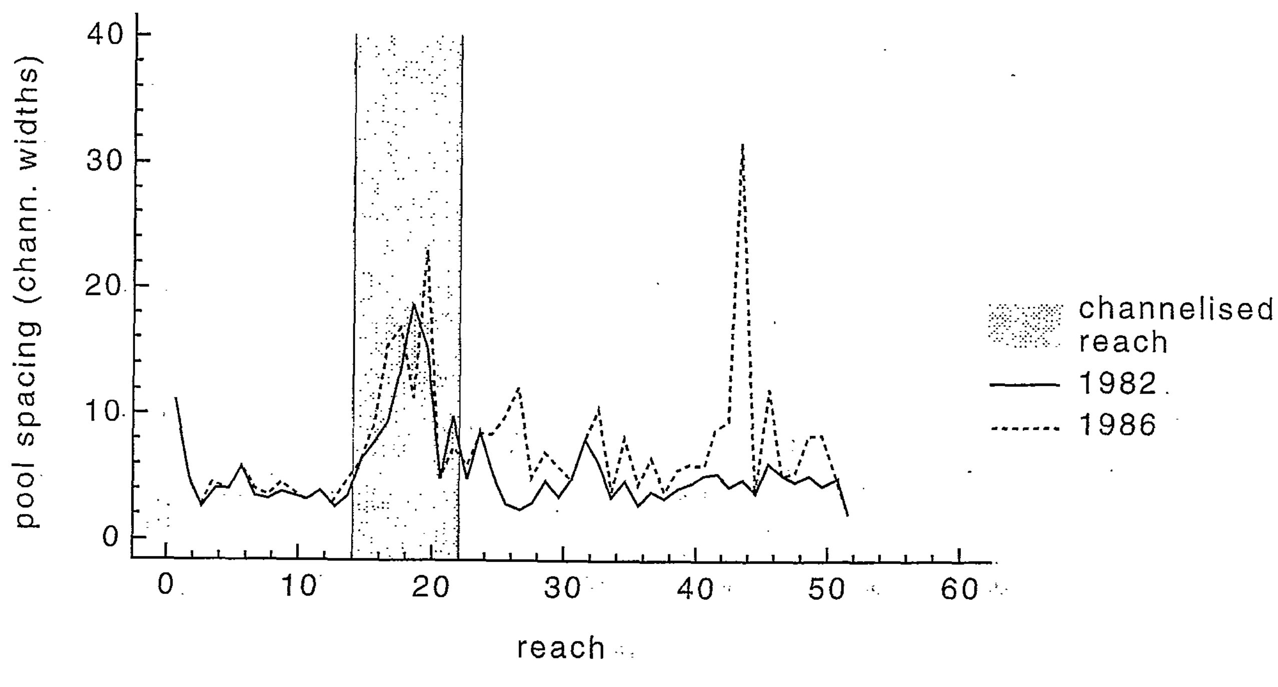
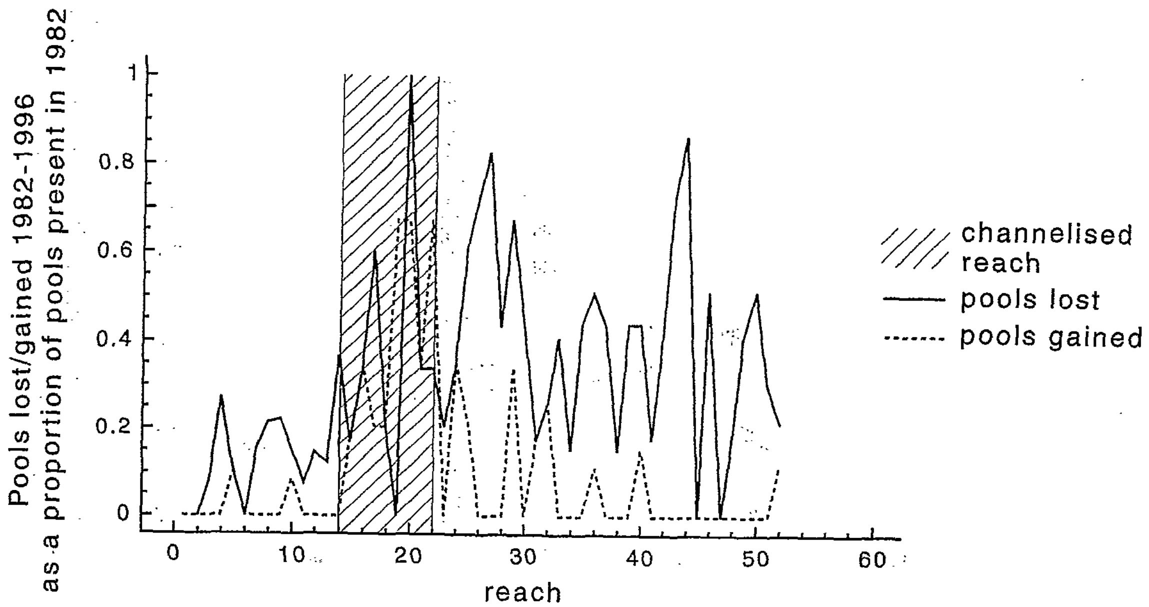


Figure 3.15 Pool spacing in 100m reaches of the Highland Water in 1982 compared with 1996/7, expressed in channel widths. The reach numbers increase in a downstream direction, stippling marks the section channelised in the 1960s. (from Gurnell and Sweet, 1998).

Geomorphological maps of the channel in 1982 and 1996/7 were used to assess geomorphological change as a result of dam clearance and subsequent recovery. Comparisons of mapped pools were made between 1982 and 1996/7 to record their number and also any changes in pool size. Figure 3.15 shows the spacing between pools within 100m reaches of the Highland Water in 1982 and 1996/7. Figure 3.16 shows changes in pool size between 1982 and 1996/7.

In 1982, before LWD clearance, all 100m reaches apart from those that had been channelised, had a virtually identical average pool spacing of approximately 4 channel widths. By 1996/7, pool spacing downstream of the channelised section had increased in comparison with 1982. There were also major changes in the size of pools throughout the river between 1982 and 1996/7. With the exception of the channelised section, all reaches had experienced a reduction in pool size, although reaches immediately downstream of the channelised section suffered the greatest reduction in pool size and loss of pools. The channelised section included the only reaches to undergo any significant increase in the size of pre-existing pools or to gain new pools between 1982 and 1996.

- The reduction in the number and size of pools in all but the channelised section was very marked. Field evidence of sediment mobilisation in these reaches was also clear. These changes seem to be associated with the release of stored sediment as a result of LWD dam removal.
- The particularly large changes in reaches immediately downstream of the channelised section suggest that erosion, caused by an increase in the channel slope, as a result of channel straightening, and a lack of LWD dams to dissipate flow energy and to trap moving sediment, has further increased the sedimentation of pools immediately downstream. Here almost half of 1982 pools have disappeared completely, one third have decreased in area, and one quarter have experienced more than a 50% reduction in area.
- The increase in the number of pools and the enlargement in pools in the channelised section can be seen in the field to result from bed scour during channel incision.
- In summary, LWD removal appears to be associated with pool sedimentation causing both the loss of pools and a reduction in the size of remaining pools. High rates of erosion associated with channel incision in the straightened section have increased the rate of pool sedimentation in the reaches immediately downstream. This important change has occurred recently despite the fact that the channelisation is quite old. This indicates the importance of active LWD dams as controls of the long profile of the river. Indeed, three large active dams, which have established downstream of the channelised section have each trapped a significant depth of sediment over an upstream channel length of at least 50m, illustrating the importance of LWD accumulations in controlling the downstream movement of bed material and channel incision.



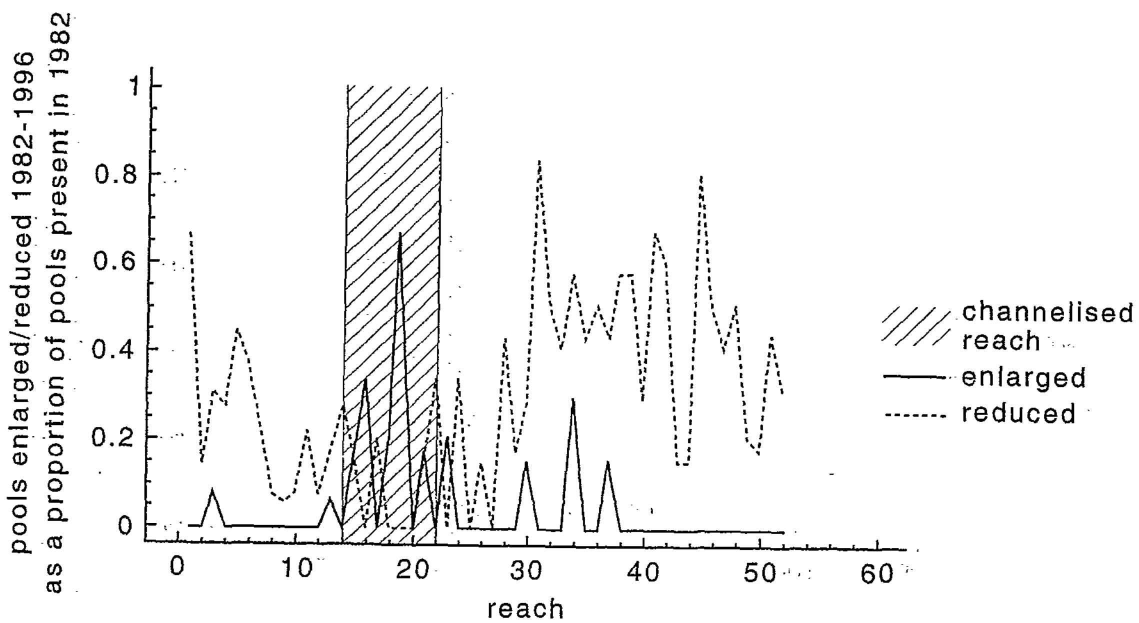


Figure 3.16 Pools lost or gained (upper graph) and enlarged or reduced in area by > 25% (lower graph) between 1982 and 1996, expressed as a proportion of 1982 pools in 100m reaches of the Highland Water. The reach numbers increase in a downstream direction. (from Gurnell and Sweet, 1998).

3.6 Summary

3.6.1 Hydraulic impacts of LWD accumulations:

- The presence of LWD increases reach average water depth and flow resistance and decreases velocity.
- Within reaches affected by LWD, water depth and velocity are more diverse than when LWD is removed.
- Although Manning's n increases in the presence of LWD accumulations, the difference in n before and after LWD removal converges with increasing discharge so that the contrast was estimated to be small at bankfull stage for the reaches studied.
- The effect of LWD on depth and velocity was found to be small at low flows and to increase with increasing discharge although the rate of increase declined at higher discharges.

3.6.2 Ecological implications of the hydraulic effects of LWD accumulations:

- The application of PHABSIM to a 30m reach before and after LWD removal demonstrated that the removal of LWD reduces both habitat quantity and habitat quality for juvenile and adult brown trout.
- Proportionately greater adult habitat was lost or reduced in quality when LWD was removed suggesting that adults may be more sensitive to the removal of LWD than juveniles. This is due to the fact that the stream is small (*ca* 3m wide, 0.22m deep with LWD) and, based on the suitability curves used, depth appeared to be the limiting factor for adults which were, therefore, affected to a greater degree by the reduced depths after LWD removal.

3.6.3 Geomorphological characteristics of relatively unmanaged British woodland headwater streams:

- The hydraulic impacts of LWD accumulations affect the scour, transport and deposition of sediment and so affect the geomorphology of woodland headwater rivers.
- Pools and riffles are fundamental geomorphological elements of many types of river channel, which result from the erosion, transport and storage of bed sediment within the river channel. They are ecologically important, providing locations of differing flow depth, flow velocity and substrate, which contribute to the diversity of physical habitat within the river channel..
- It is widely accepted that naturally-occurring pools and riffles have an average spacing of 5-7 channel widths. However, pools have been found to be more closely spaced in headwater channels containing LWD dams. In the Highland Water a pool spacing of ca. 4 channel widths is common and a spacing of 2 channel widths might be achieved if there were no management of LWD.

- A number of different types of pool have been found in association with LWD dams. Pools of differing type tend to display differences in their relative depth and sediment calibre, providing a range of hydraulic, temperature and substrate conditions for aquatic biota.
- Active dams are particularly important for the formation of large, deep pools.
- Active and complete dams also form sites for flow avulsion (i.e. overflow of water from the river channel onto the floodplain) which feed perennial, intermittent and ephemeral river channels. Low flows are contained in the perennial channels, seasonally higher flows extend into the intermittent channels and flood flows extend into the ephemeral channels. If major LWD dams persist at a particular location, avulsion can result in more permanent flow diversion and channel pattern change.
- The impacts of LWD accumulations on channel form and on stream network structure and dynamics have both hydrological and ecological importance. The hydrological importance relates to water storage, flow pathways and storm hydrograph attenuation. The pools provide areas for surface water storage at low flows, sustaining surface water for long periods during drought conditions. At high flows, the pools and backwaters behind LWD accumulations and water storage in ephemeral and intermittent channels result in increased flood peak travel times and attenuation of flood hydrograph shape. Additional hydrological impacts of in-channel water storage behind LWD accumulations include improved hydrological connectivity between channel and floodplain and enhanced underflows within the channel bed at LWD dam locations. All of these hydrological effects are important for stream ecology.
- A major management concern is the stability of LWD within headwater rivers. LWD dams in the Highland Water have been found to be quite unstable even during periods of no management disturbance. Nevertheless, the most mobile LWD structures are the partial dams, whereas active and complete dams are far more stable. Active and complete dams may change in type, particularly from active to complete and *vice versa* as wood pieces join or leave the structures, but they tend to persist in the same position providing an important buffer to the downstream movement of wood pieces. As a result, management of LWD which involves removal of the active and complete dams is more likely to increase than to decrease the mobility of the pieces of wood that remain.

3.6.4 Geomorphological implications of LWD clearance

- Although LWD dams may re-establish quite rapidly after clearance, the development of the most important, active dams takes a long time. In the LWD clearance case study described, active dams had not re-established to pre-clearance levels after eight years.
- Clearance of LWD increases the mobility of LWD pieces because of the slow re-establishment of major complete and active dams which are capable of trapping and stabilising LWD pieces.
- Complete and active dams are important controls on LWD movement, and are also highly significant for the retention of smaller, organic matter and mineral sediment.
- The presence of LWD accumulations is strongly associated with an increased frequency of pools, an increase in pool size and the presence of a diverse range of pool types. The removal of LWD dams is associated with sediment mobilisation and the complete or partial sedimentation of pools.

- Recovery of pools from sedimentation after LWD clearance takes a long time. In the case study discussed, the total number of LWD dams had recovered 8 years after LWD clearance, but the number of active dams remained lower than before clearance, and the number and size of pools remained well below pre-clearance levels.

4. SUMMARY AND RECOMMENDATIONS FOR MANAGEMENT

4.1 The Role of LWD in Headwater River Systems

The role of LWD within headwater river systems in relation to both physical habitat and the retention characteristics of stream channels are well described in the following quotations from Gregory et al. (1991) based upon research in the Pacific Northwest of the United States:

'Productivity of riverine fish communities is determined by both habitat and food resources .... Geomorphic processes within the valley floor and modification of those processes by riparian plant communities create the habitat for fish communities. Channel morphology is strongly influenced by streambank stabilisation by riparian vegetation and large woody debris. Complex lateral habitats, such as backwaters, eddies and side channels, are created by the interaction of streamflow and lateral roughness elements that include living vegetation and large woody debris. These areas provide refuge during floods and serve as rearing areas for juvenile fish.'
Gregory et al, (1991, p548)

'Geomorphic and hydraulic processes, riparian vegetation, and aquatic biota are linked functionally through processes of retention. Organic material and inorganic sediment must be retained within a stream to serve as either nutritional resources or habitats for most aquatic organisms. Boulders, logs and branches trap material in transport, and low velocity zones are depositional areas where particles drop out of suspension. These features of channel complexity also slow the transport of water and dissolved solutes, increasing the potential for biological uptake or physical adsorption of dissolved materials.'
Gregory et al, (1991, p547)

This research report has shown that although accumulations of wood in British rivers may have different characteristics to those in the USA, particularly those in old-growth forest catchments, LWD nevertheless plays a similar functional role in Britain.

4.2 Observations on the Role of LWD in British Headwater Rivers

This report has presented research observations from several British sites where large wood remains relatively unmanaged. The main conclusions regarding the role of LWD in British headwater rivers, based upon these observations, are as follows:

4.2.1 Hydraulic impact:

- LWD accumulations cause an increase in the flow resistance of river channels. At low flows this increase in flow resistance may be considerable, but the contrast in Mannings n between channels with and without LWD accumulations converges with increasing discharge.

- The increased flow resistance induced by LWD accumulations leads to an increase in reach mean flow depth and velocity and also an increase in the variability or diversity of flow depth and velocity within the reach.
- Reaches containing LWD accumulations are more retentive than debris-free reaches, exhibiting a higher dispersive fraction.

4.2.2 Geomorphological impact:

- The hydraulic changes induced by LWD accumulations result in changes in the morphology of the channel.
- LWD accumulations in headwater streams are associated with a range of types of pool which play an important role in retention of water, sediment, solutes and organic matter. Upstream (dammed) and downstream (plunge) pools are particularly common. Pools may occur as frequently as every 2 channel widths where LWD accumulations are unmanaged.
- Although not specifically researched for this report, dammed pools appear to be particularly important sites for organic and mineral sediment retention, so attenuating its transfer downstream. Where plentiful sediment is available, dammed pools may become filled with sediment creating a physical step in the bed profile.
- Dammed pools behind major, hydraulically-active dams also serve as locations of flow avulsion during high flows. Ephemerally- and intermittently-flowing channels may establish linked to the location of major active dams. If the dams persist for long enough, this process may lead to a change in the position of the main, perennially-flowing channel.

4.2.3 Physical habitat:

- LWD accumulations contain important and complex suites of hydraulic and physical conditions which promote high within-dam habitat diversity. They also induce increases in the variety and complexity of habitat in the surrounding river channel and floodplain.
- The increased diversity in flow depths and velocities within reaches containing LWD accumulations lead to an increase in hydraulic habitat diversity.
- The morphological changes induced by the hydraulic effects of LWD accumulations provide high physical habitat diversity in the form of pools of different size, riffles, and marginal benches within the channel, and the development of perennial, intermittent and ephemeral channels across the adjacent floodplain surface. The plunge and dammed pools associated with many LWD accumulations also form important refuges for aquatic fauna during low flows.
- The application of the physical habitat simulation model PHABSIM has demonstrated that the removal of LWD dams reduces both the habitat quantity and quality for juvenile and adult brown trout. Proportionately greater adult habitat was lost or reduced in quality.

4.2.4 Stability:

- LWD accumulations have been shown to be less stable in British headwater rivers than has been observed in North American studies. Active dams form the most stable dam type, persisting for many years at the same location, and trapping and storing mobile debris pieces. The overall stability of LWD within headwater river channels appears to be closely linked to the presence of active dams. Active dams take the longest time to re-establish after disturbance.

- Although active dams have a major hydraulic effect, they rarely cause a rigid barrier within the river. Even if the dam is braced by an entire tree which is essentially immobile, smaller wood pieces within the structure will shift, mainly as a result of flotation, with variations in river flow. This means that although the LWD structure settles to pond back water at low flows, water (and fish) can readily pass through it at higher flows.

4.3 Recommendations for LWD Management

The research results summarised above suggest that LWD accumulations have enormous importance for the structure and diversity of physical habitat, water quality and temperature, and substrate conditions within British headwater rivers. Active dams are particularly important in this regard, and also in stabilising and trapping LWD and sediment movement within headwater river systems. Removal of major, active LWD dams destabilises the LWD that remains and results in the mobilisation of sediment, the incision of the channel bed and a reduction in habitat diversity. These effects not only reflect a reduction in physical habitat diversity at the sites of LWD dam removal but also have consequences for downstream channels which will receive larger inputs of LWD and sediment.

LWD accumulations also have benefits in relation to the control of runoff at the catchment scale. Reaches containing LWD accumulations have a higher flow resistance than LWD-free reaches, although the values of Manning's n converge with increasing discharge. The hydraulic effect of LWD accumulations causes geomorphological adjustments, which result in increased within-channel and floodplain water storage. Although these effects may be relatively small when only a single LWD accumulation is considered, their aggregate effect may be very significant. LWD accumulations in headwater streams provide a potentially significant contribution to flood attenuation at the catchment scale because they help to desynchronise headwater and downstream-generated flood peaks by attenuating upstream-generated floods and increasing flow travel times from the headwaters. Similar desynchronisation of floods draining from different headwater catchments would result from contrasting land uses and thus differing amounts of LWD. Such flood attenuation advantages are at best free and at worst inexpensive if the management guidelines suggested below are implemented.

The adverse on-site and downstream effects of LWD removal give support to the view of Benke et al. (1985) that 'Although there are certain situations that may require wood removal to eliminate stream blockage, the wisest management practice is no management'.

Our management recommendations, which are specifically for British headwater streams develop from North American recommendations summarised in Gurnell et al. (1995) but are tailored on the basis of our research results for the British environment:

1. First it is important to define a 'headwater river' for the purposes of the applying the management guidelines. In the present context, a headwater river is a river where LWD can accumulate into dams across the entire channel. Thus the size of a headwater river in relation to LWD is one where the channel is narrower than the length of the larger pieces of wood

delivered to it. On the basis of typical key wood piece lengths observed in active dams and evidence from the analysis of RHS data (see section 2), **10m seems to be a suitable upper limit of headwater river widths in British river systems.**

2. In these headwater rivers, indiscriminate removal of LWD should be avoided. This is particularly important for wooded and tree-lined sections, where LWD accumulations are a natural feature of the channel. Figure 4.1 lists a gradient of riparian land use from natural woodland to heavily urban and gives preferred in-channel and riparian zone management strategies, emphasising the importance of LWD minimising management within natural and semi-natural woodland sections.

3. Some removal of LWD may be necessary under certain circumstances as indicated in Figure 4.1 by the arrow of increasing economic cost of flooding. Figure 4.1 considers reaches and their riparian land use in isolation, but there are additional advantages of considering reaches within their catchment context. For example, an increase in in-channel water storage, flow avulsion, overflow channels and flooding associated with LWD dams in areas of low economic cost and high environmental benefit, such as in semi-natural woodland areas, would have a beneficial flood-attenuation impact for downstream higher-risk areas. The following circumstances can be viewed in a site and catchment context:

(i) Where flooding and LWD blockage of man-made structures forms a major management problem in headwater streams, complete removal of LWD may be necessary. However, this should only be undertaken along a restricted length of the upstream river channel. Such focused removal of LWD is highly cost-effective and maximises management benefits, since upstream retention of active dams will reduce the delivery of LWD to the site from which it has been removed. It also has a relatively small geomorphological and ecological impact because LWD accumulations, particularly large active dams, are retained elsewhere. Active dams are particularly important for river morphology and ecology and play an important role in attenuating the delivery of wood to downstream cleared reaches.

(ii) If flooding is a less severe and localised problem, selective removal of debris within affected reaches is preferable to complete removal since the major environmental benefits of LWD dams are retained when the most stable pieces of wood are not disturbed (see point 4. below)

(iii) Inputs of large quantities of small wood pieces, particularly small branches, twigs and leaves from riparian management and forestry operations can cause excessive sealing of active dams, making them too effective a barrier to fish movement. Such wood input should be avoided. If small wood pieces from the above activities become a problem, selective removal (see point 4. below) rather than complete removal is recommended. If the riparian forest is not being managed, it is extremely unlikely that any LWD accumulations will present a problem for fish movement and so debris removal is unnecessary.

4. When debris removal is necessary, selective rather than complete removal is preferable. Again, risks and benefits must be assessed in relation to the type of riparian land use associated with the headwater reach and also in association with the potential risks and benefits for downstream reaches. The following guidelines are relevant where excessive amounts of small wood pieces have entered the channel or where there is a requirement to

increase the conveyance of a reach but where complete clearance of debris is unnecessary. Remove debris that is :

(i) not anchored or buried in the stream bed or bank at one or both ends or along the upstream face; or is

(ii) not longer than the channel width; unless it is

(iii) LWD (i.e. pieces longer than 1m and wider than 10 cm) which are braced by boulders, bedrock outcrops, riparian trees, or by pieces of large wood that do not fall into categories (i) or (ii).

5. LWD accumulations are a natural component of headwater streams bordered by riparian woodland. The addition of LWD will improve physical habitat in woodland streams where LWD has previously been cleared or where, as a result of the age structure of the riparian trees, the LWD supply to the river channel is low. It will also help to counteract channel incision and the downstream delivery of high, pulsed sediment loads. The introduced wood pieces should be capable of forming the key pieces in stable debris accumulations, so they should be at least as long as the channel width with a diameter of at least 0.1 m or 0.05 channel width, whichever is larger.

In order to further increase the potential for wood to form stable structures, the spacing of the introduced pieces should reflect expected natural spacings of LWD accumulations. Based upon our field observations, a spacing of approximately 7-10 channel widths is appropriate. Wood pieces should be introduced into stable positions such as upstream of channel constrictions or braced on the downstream side by boulders, bedrock outcrops, or riparian trees. Where necessary, wood pieces can be secured to prevent downstream movement, but wherever possible, it is preferable to leave the introduced wood loose to adjust its position, move locally and settle unconstrained into the channel.

6. Riparian woodland is the natural source of LWD. Tree clearance and heavy pruning close to the river channel disrupt the supply of wood to the river. Therefore, riparian tree management should be kept to a minimum within a buffer strip along the river margin, particularly in reaches bordered by natural or semi-natural woodland. Ideally this buffer strip should be 20m wide and should consist of trees of mixed age and size. A 20m buffer strip is ideal because it approximates the height of mature native tree species and thus it ensures that wood delivery to the river, for example by wind throw of entire trees, simulates the rate that might be expected from a more extensive tree cover. Where this approach is adopted to accompany forestry operations, some initial active management of trees, including tree planting, within the buffer zone will accelerate the development of a strip of mixed age and possibly mixed species woodland, which will provide a good LWD supply to the river.

Points 2. to 6. build from simple, easily applicable recommendations about LWD removal, through more far-reaching guidelines on emplacement of debris and the development of a self-sustaining system of natural debris supply. Whilst a more sophisticated approach to removal than complete clearance (points 2. to 4.) is easily supported on both cost-benefit and environmental grounds, a more holistic management of the riparian-river channel system through the development of riparian woodland buffer zones has cost implications which need to be set against the enormous environmental benefits for the river corridor. Figure 4.1

attempts to summarise some of these management suggestions and to emphasise that the environmental gains resulting from sensitive LWD management achieve a maximum in headwater streams with natural or semi-natural riparian woodland. LWD has environmental benefits wherever it occurs but as riparian land use becomes more intensive, the economic consequences of flooding become more severe and LWD dams become more difficult to sustain because of low wood input rates and a reduction in wood piece sizes.

Figure 4.1 Management suggestions for LWD in British headwater rivers

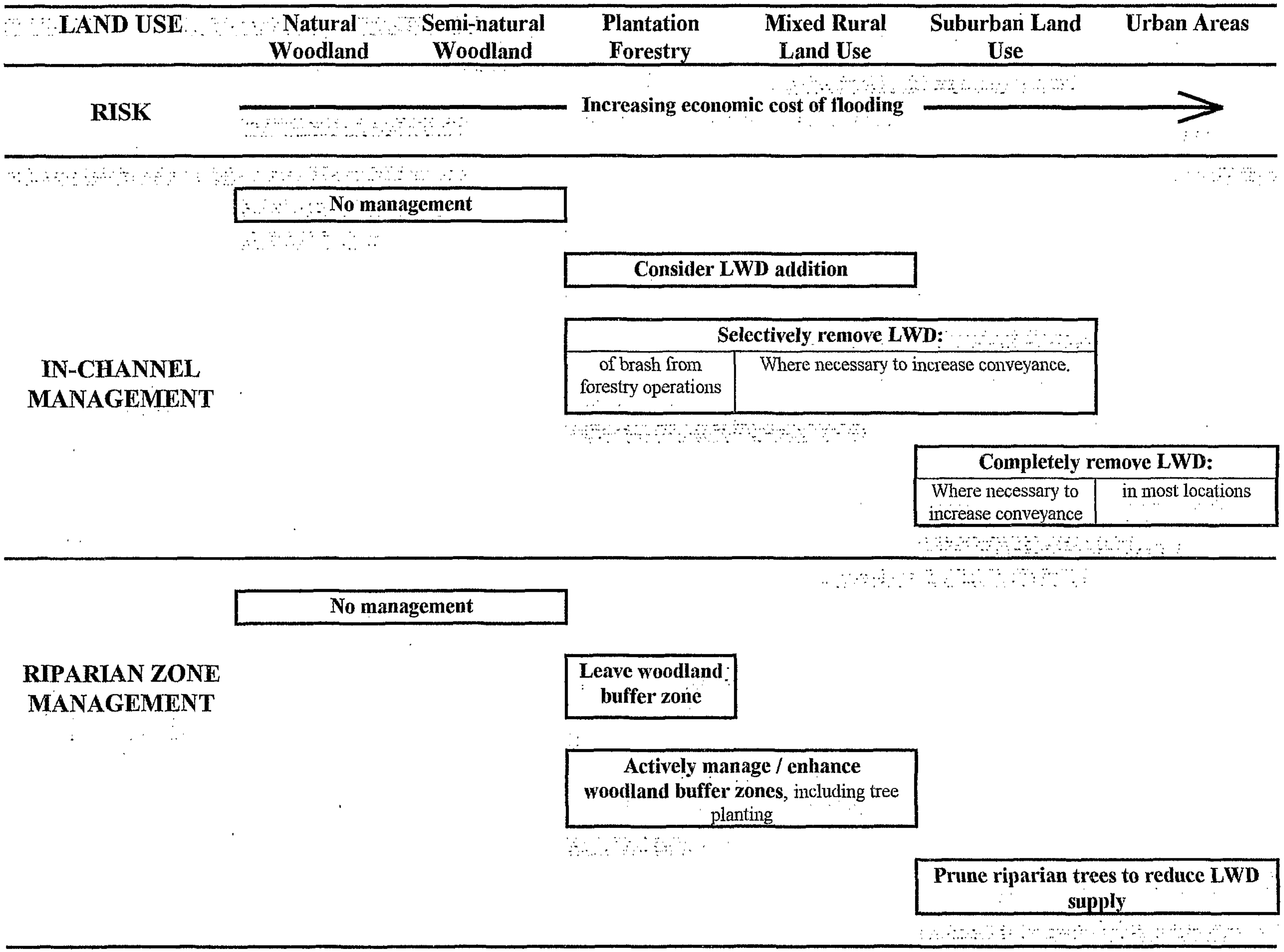
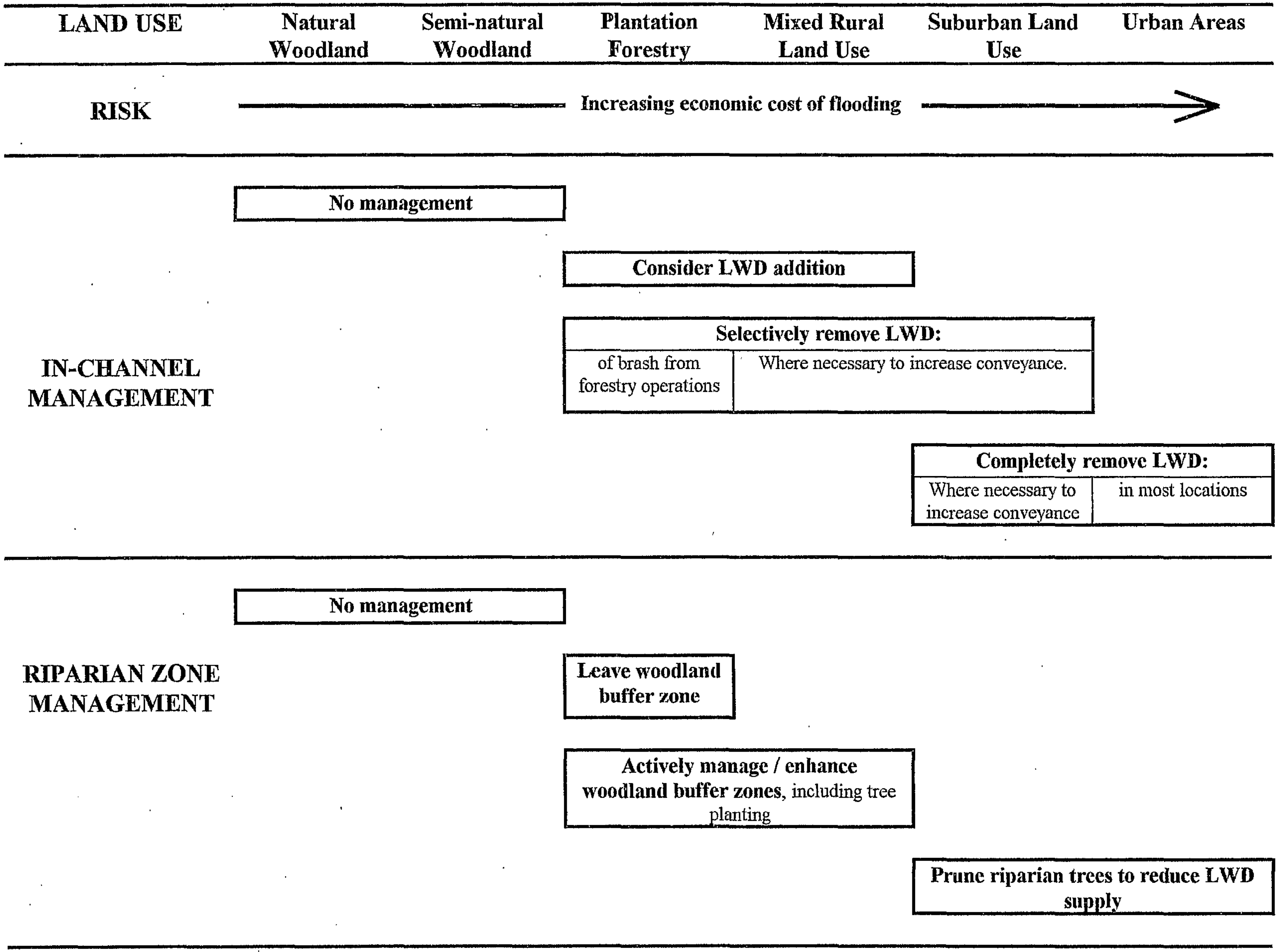


Figure 4.1 Management suggestions for LWD in British headwater rivers



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