UNIVERSITY OF SOUTHAMPTON

The effect of woody vegetation on the geomorphology of a lowland floodplain: a study of a basin in southern England

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Dark brown is the river,
Golden is the sand.
It flows along forever,
With trees on either hand.

Robert Louis Stevenson, Where go the Boats?

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ABSTRACT

FACULTY OF SCIENCE
GEOGRAPHY

Doctor of Philosophy

THE EFFECT OF VEGETATION ON THE GEOMORPHOLOGY OF LOWLAND FLOODPLAINS: A STUDY OF A BASIN IN SOUTHERN ENGLAND

by Richard Jeffries

Floodplains result from fluvial processes, and fluvial processes can be modified by vegetation. This thesis aims to investigate how forest vegetation influences floodplain formation.

The floodplain is an area of land around a river created by fluvial erosion and deposition, and is a characteristic feature of lowland environments. Although the climatic climax vegetation community in temperate regions is deciduous woodland, most floodplains have been cleared for agricultural, industrial or urban uses. In the absence of woody vegetation, these cleared floodplains primarily result from the balance between two processes: lateral and vertical accretion and erosion (Wolman and Leopold, 1957), both of which are driven by fluvial hydraulics. However, trees and large woody debris (LWD) can significantly modify these hydraulic structures, changing floodplain processes and thereby determining floodplain evolution.

Previously published research has not explicitly investigated lateral and vertical accretion on lowland wooded floodplains. This thesis describes how these lacunae were addressed with three field campaigns undertaken along the Highland Water, a small lowland stream that is surrounded by one of the largest areas of uncleared woodland in England.

Firstly, a catchment-scale survey identified the geomorphology of this lowland forested floodplain. Visual observations were made of floodplain features and channel characteristics; and the width of the channel, the area most recently flooded, and the maximum extent of the floodplain were measured. This survey provides the first inventory of geomorphological features found on a wooded lowland floodplain. The channel and floodplain were split into reaches that were observed to be geomorphologically homogenous. The outcomes from this survey were that management and in-channel accumulations of woody debris appeared to be primarily responsible for changes in floodplain formation.

A second survey, similar to the first but more focused upon lateral channel change, provided evidence to suggest that lateral accretion was frequently determined by vegetation. Rates of channel change were found to be extremely low, except in the vicinity of in-channel accumulations of debris, which caused change at the reach scale (10^1-10^2 m). In contrast with cleared floodplains, lateral river accretion was not focused at meander apices, but instead within zones of discrete floodplain activity directly caused by in-channel blockages of woody debris. This debris also caused significant areas of overbank flow to occur.

Thirdly, reach-scale experiments into floodplain sedimentation determined that vertical accretion did occur, but the pattern and amount of sediment deposited was a direct result of floodplain vegetation, particularly trees and LWD. These experiments demonstrated that the amount deposited was spatially variable, and over a distance of less than 1 m ranged from 0 to 26 kg m^{-2} for a single flood event. These quantities were several times the maximum recorded by other researchers working on cleared lowland floodplains. The zones of greatest deposition appeared to be associated with fine-scale turbulent eddies that formed in the wake of trees during floodplain inundation.

These controls of vegetation upon fluvial and floodplain processes also have implications for long-term landscape development and may explain the palaeoenvironmental history of many lowland floodplains. The findings from this thesis could also be used to design and implement sustainable forest floodplain management practices.

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This research relied on fieldwork, and therefore on fieldworkers. Marie always said yes when I asked for her help. She always got muddy and cold, and was permanently cheerful. She makes the best cakes in the universe. This combination of qualities is rare and welcome: three cheers to the fieldwork star! My deep thanks to the other fieldworkers: Sally, who was better at geodimetering than most people are at breathing, and who helped proof read several things; Matt; Sarah, who picked up plenty of sediment traps with more interest than most physical geographers; Gary made me laugh quite frequently, except at 115 mph; Doug was eaten by midges; Nick 'wet-leg' Odoni provided endless enthusiasm; Mark let me nick the current meter on more than one occasion; Nick H geodimetered and dug with gusto. ES provided useful equipment and advice, including the loan of their new laptop to take to a conference. Thanks to you all.

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Finally, the people who got me interested in looking at the world in the first place, and who probably don't know it, are Steve Law the late Keith Yates.

Chapter 1
Orientation

1.1 Introduction

Scientific knowledge of rivers and their environs is deepening through better understanding of fundamental physical principles, and is broadening by considering how variables interact over greater temporal and spatial scales. Although it is increasingly clear that vegetation can significantly control morphological processes, an enormous amount remains to be understood about this interaction.

Forest floodplains are, perhaps, sites of the most complex and dynamic interaction between fluvial and ecological processes, but because the manner of their formation is not fully comprehended, and the compounding effects of vegetation are still less clear, understanding them is difficult. This is natural for a variety of reasons. Factors driving fluvial change are highly variable in space and time and result in a wide range of river forms. Floodplains, areas 'of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding,' (OED) embody a fluvial history across a broader spatial and temporal scale, and are additionally complex. They are often inextricably linked to the socio-economic status of many areas and are extensively modified for industrial, urban or agricultural use: 'Floodplains cover some 10 % of the land in England and Wales, and nearly 6 million people live there.' (Environment Agency website). Therefore, few natural floodplains covered by trees currently exist in the UK.

The most widely-recognised model perceives that floodplains are formed either from lateral reworking or from vertical accretion (see Wolman and Leopold, 1957). However, while it is clear that these processes do occur in many systems, they cannot explain the high morphological diversity found on many forest floodplains (Piégay et al., 1998 and Brown, 1998). Piégay et al., 1998 state:

"Si le rôle des processus hydrauliques et morphologiques en lit mineur est bien connu sur les rivières à méandres, l'influence du lit majeur et notamment de sa couverture végétale a plus rarement été abordé" p. 189.

Which can be translated as:

"Although hydraulic and geomorphological processes are well understood in the river channel, the influence of the floodplain and, in particular, its cover of vegetation, has been neglected."

1.2 Aims and objectives

This thesis aims to explain the morphological diversity of a lowland forest floodplain and to investigate how this is affected by vegetation. There are three objectives:

1. Investigate the contemporary conceptual model of floodplain formation and critically assess how well it explains the formation of forest floodplains (literature review and identification of research gap, chapter 2); quantify and define the geomorphology of a forest floodplain (baseline survey, chapter 3). Identify study sites and research agenda.
2. Research the required components; investigate processes of forest floodplain formation and test hypotheses (field-based investigation, chapters 3 and 4).
3. Objective 3 – Redefine the conceptual model and assess its relevance for floodplain research; synthesis of conclusions from earlier chapters and discussion of their wider implications (chapter 5).

1.3 Thesis strategy

Early on in the research a relative lack of information about lowland forest floodplains was apparent. Although published literature suggests that the formation of 'cleared' floodplains may largely be explained by processes of lateral or vertical accretion (chapter 2), there was no clear expression of what processes create forested floodplains, nor what geomorphology they resulted in. Thus, the first step was to address this lack with a baseline survey (chapter 3) of one of the largest areas of primeval floodplain woodland in England, which occurred around the Highland Water.

The channel processes of the Highland Water have been intensively studied (Gregory et al., 1985; Gregory et al., 1994a) but, prior to this study, no research had been directed at understanding the geomorphology of its floodplains. Nevertheless, implied within Gregory's work is that woody debris in the channel plays an important role in influencing floodplain processes, and field visits confirmed this. Also, previous undergraduate work on the effect of debris dams on local fluvial geomorphology concluded that '[debris] dams affect channel form through their morphology acting on energy dispersion at a local scale,' and that 'in the long term, dams clearly influence channel location... . Evolution of the floodplain may therefore rely heavily on dam formation' (Jeffries, 1998, p. 67-68). The baseline survey concluded that new types of lateral and vertical accretion were responsible for floodplain formation, and the rest of the thesis explicitly aimed to investigate each process.

A second survey was undertaken to assess lateral accretion (chapter 3), which highlighted that in-channel accumulations of woody debris were the most important factors to influence lateral accretion. Overbank flow only occurred around large dams that blocked the main channel, and the largest example was chosen as an experimental site to investigate processes of overbank accretion (chapter 4). These experiments demonstrated that overbank sediment deposition did occur, but again was strongly influenced by vegetation, particularly dead wood and trees on the floodplain surface. Hence, living and dead vegetation controlled both lateral and vertical accretion of a lowland forested floodplain. Finally, chapter 5 discusses the implications of these findings, and suggests how management practices can be implemented to increase the value of forest floodplains.

Chapter 2
Floodplains and vegetation

2.1 Introduction

The interaction of floodplains and vegetation, which is central to this thesis, can be investigated either from a geomorphological or an ecological perspective, and these are presented in turn. The first part of this chapter reviews geomorphic research focused on how vegetation interacts with the floodplains of lowland meandering rivers. The second part discusses floodplain concepts that originate from ecology. Finally, a short section describing floodplain management and restoration precedes a summary.

2.2 Geomorphic floodplain research

A floodplain is 'an area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding' (OED, 2001). They are complex landscape units (Fig. 2.1) that are extensively used for agricultural, industrial or urban development. Hence, natural or undisturbed floodplains - including those that are forested - are rare in developed countries (Penning-Rowsell and Tunstall, 1996; Ward et al., 2001). Many have been modified beyond recorded history, and their natural origin and geomorphological role is often poorly understood both by river managers and the public (Adams and Perrow, 1999; Ward et al., 2001). Despite extensive use, few studies have investigated the human impact on floodplains (Penning-Rowsell and Tunstall, 1996). While few lowland floodplains in heavily developed countries currently support natural forest, palaeoenvironmental reconstructions suggest that most were densely forested during the Holocene (Brown, 1996). Thus, most European and American floodplains are so heavily influenced by humans that much floodplain research has in fact been focused on modified systems. The scientific understanding of forest floodplains is therefore lacking: 'established research... concepts may fail to fully recognize the crucial roles of habitat heterogeneity and fluvial dynamics owing to the lack of fundamental knowledge of the structural and functional features of morphologically intact river corridors.' Ward et al. (2001); p. 311.

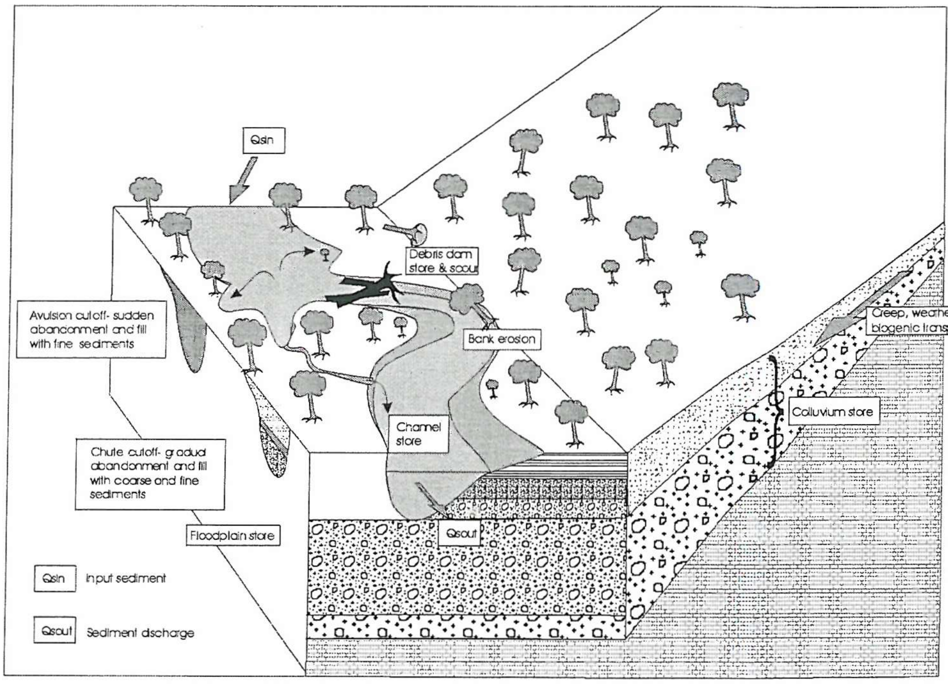


Figure 2.1 A floodplain of a meandering river and some associated landform units (Modified from Brown, 1996)

Non-forested floodplains are generally considered a result of the interaction of two or three processes (e.g. Wolman and Leopold, 1957; Brierly and Hickin, 1992; Magilligan, 1992; Zwolìnski, 1992; Gomez et al., 1998; Siggers et al., 1999). These are (i) **lateral** accretion of relatively coarse grained deposits from river meandering or braiding; (ii) **overbank** (vertical) accretion of usually fine grained sediments and (iii) **other** processes, an eclectic category that by default includes all processes linked to vegetation (Table 2.1). Lateral and vertical accretion are driven by hydraulic features that are understood reasonably well, but 'other' types of accretion have been relatively neglected.

Table 2.1 'Other' types of floodplain erosion and accretion

Process & type of river	Example(s)	Reference
Floodplain dissection and renewal in large, high-energy piedmont rivers leading to the formation of fluvial islands	Fiume Tagliamento, Italy; Squamish R., B.C.; Plum Creek, Colorado; Snake R., Idaho	Gurnell et al., 2001; Brizga and Finlayson, *1990*; Osterkamp, 1998
Areal erosion of small vegetated islands in active zones of floodplains	Fiume Tagliamento, Italy	Gurnell et al., 2001
Island growth promoted by stabilization from vegetation	Fiume Tagliamento, Italy; Queets R., Washington	Gurnell et al., 2001; Fetherston et al., 1995
Longitudinal zones of high and low floodplain activity controlled by vegetation	Ozark plateaux rivers, Missouri and Arkansas	McKenney et al., 1995
Debris flows in small, steep (30-40°) rivers	Many channels in the Queen Charlotte Is, B.C.; Saru River, Hokkaido; Blue R., Cascade Mts., Oregon	Hogan, 1987; Nakamura et al., 2000
Mass wasting in steep (30-40°) rivers	Saru R., Hokkaido; Blue R., Cascade Mts., Oregon	Nakamura et al., 2000
Catastrophic flood surges after debris-dam breakup in steep (30-40°) rivers	Saru R., Hokkaido; Blue R., Cascade Mts., Oregon	Nakamura et al., 2000
Flash flooding (1) leading to floodplain stripping, followed by braiding, aggradation and recovery in sandy rivers	Gila R. Arizona; Plum Creek, Louviers, Colorado	Burkham, 1972; Friedman et al., 1996
Flash flooding (2) via artificial dam breakup	Drainage channel for reservoir no. 3 for Centralia, Washington.	Costa and O'Connor, 1995
Anthropogenic modification such as channelisation and floodplain disconnection followed by recovery and the definition of a new floodplain	Many streams in W. Tennessee	Hupp, 1992
Formation of organic deposits in rivers with high productivity	Amazon	Mertes, 1987

Table 2.2 The amount of floodplain storage expressed as a percentage of sediment input (modified from Marron, 1992)

River	Drainage basin area (mile $^{-2}$)	% budget stored in floodplain	Source
Yuba River, California	3500	10	Gilbert (1917)
American River, California	5000	12	Gilbert (1917)
Whitewood Creek,	260	13	Marron (1992)
Feather River, California	5000	14	Gilbert (1917)
Van Duzen River, California	580	17	Kelsey (1980)
Coon Creek, Wisconsin	360	18	Trimble (1983)
Lone tree Creek, California	1.74	19	Lehre (1982)
Bear River, California	<200	24	Gilbert (1917)
American River, California	<200	27	Gilbert (1917)
Western Run, Madison Co.	160	29	Costa (1975)
Feather River, California	5000	29	Gilbert (1917)
Belle Fourche River, SD.	19000	29	Marron (1992)
Bear river, California	1300	31	Gilbert (1917)
Swale, Yorkshire	1856 (est.)	31	Walling (1999)
Ure, Yorkshire	338 (est.)	34	Walling (1999)
Ouse, Yorkshire	3315	40	Walling (1999)
Wharfe, Yorkshire	818	49	Walling (1999)
Nidd, Yorkshire	1273 (est.)	50	Walling (1999)
Yuba River, California	3500	52	Adler (1980)
Yuba River, California	3500	53	Gilbert (1917)
Bear river, California	1300	55	James (1985)
Coon Creek, Wisconsin	<70	87	Trimble (1983)

2.2.1 The formation of 'cleared' floodplains

Sediment sources and processes of entrainment

Within a drainage basin, sediment weathered from bedrock (or relict sediment), is transferred to and stored in the channel and floodplain for a variable length of time before being moved out of the system. Floodplains store significant amounts of the annual sediment yield (Table 2.2). For example, Trimble (1983) found that for Coon Creek, USA, between 1938 and 1975, around 40 % of sediment was deposited in the valley floors. Lehre (1982), working in canyons dominated by mass movements and with very steep (35-80^{o}) valley sides and minimal observable floodplain, still found that 22.3% of sediment was deposited as bed and bank material. The influence of forest vegetation on this storage has not been quantified. Vegetation usually increases floodplain roughness and therefore will tend to trap sediment; hence, forest floodplains may store more sediment than their 'cleared' counterparts. At the basin scale, therefore, the floodplain is a temporary *store* of sediment. Yet, at the scale of floodplain processes, it is also a *source* from which particles are eroded.

Particle entrainment whether in the river or on a floodplain depends on two main factors: the ability of the water to entrain and transport debris; and the resistance of the sediment to erosion. The ability of water to entrain sediment depends on several factors, the principal one being shear stress. Following Knighton (1984), this is defined as:

$$\tau = \mu\,(\mathrm{d}v/\mathrm{d}y) \qquad (1)$$

where τ is shear stress, μ is viscosity and $\mathrm{d}v/\mathrm{d}y$ is the rate of change of velocity with depth. This occurs in laminar flow, but beyond a certain velocity threshold turbulent eddies are created, which move parcels of water rapidly through the water column. In such cases the shear stress is expressed by:

$$\tau = (\mu + \eta)\,(\mathrm{d}v / \mathrm{d}y) \qquad (2)$$

where η is the eddy viscosity.

The forces acting on a given grain of sediment are comprised of driving and resisting forces. Driving forces include those applied by the action of the water and the weight of the particle in the downstream direction. Resisting forces include the normal weight of the particle, holding it in place, as well as protection by or electrostatic attraction from the surrounding particles:

$$\tau_{cr} = \eta\, g\, (\rho_s - \rho)\, (\pi / 6)\, D \tan \phi \qquad (3)$$

where τ_{cr} is the critical shear stress required for initiation of movement; η is a grain packing constant; g is the gravity constant; ρ_s is sediment density; ρ is water density; D is the grain diameter; and ϕ is the friction angle of the particles (Knighton, 1984).

The shear strength Sr, (or resistance to erosion) of a sedimentary unit can be described as:

$$Sr = c' + (\sigma - \mu) \tan \phi' \tag{4}$$

where c' is the effective cohesion; σ is the normal stress; μ is the pore pressure; and ϕ' is the effective friction angle (Simon et al., 1999). If, however, the soil is not saturated then the *apparent* cohesion c_a, of the soil, diverges from the effective cohesion:

$$c_a = c' + \Psi \tan \phi^b \tag{5}$$

where Ψ is the matric suction and ϕ^b is the angle describing the increase in shear strength with increasing matric suction. The matric suction itself is defined as:

$$\Psi = (\mu_a - \mu_w) \tag{6}$$

where μ_a is the pore air pressure and μ_w is the pore water pressure. Drier soils, which have negative pore water pressures (or positive matric suction) then have greater shearing resistance than wetter soils (Simon et al., 1999), because (Fredlund et al., 1978):

$$Sr = c' + (\sigma - \mu_a) \tan \phi' + (\mu_a - \mu_w) \tan \phi^b \tag{7}$$

In theory, therefore, the balance between the driving forces (shear exerted by the water) and the resistance posed by the shear strength of the substrate should control the onset of erosion. In practice this relationship is complexified by factors such as vegetation, which modify local shear stress and substrate shear strength.

Vegetation increases soil strength by the presence of roots; and stems, leaves and other organic material increase the surface roughness (Tabacchi et al., 2000). Vegetation patterns can thus influence driving and resisting forces and the observed patterns of erosion (e.g. McKenney et al., 1995). The strength of sediments can be theoretically increased by the reduction in pore water pressure that results from the take-up of water by vegetation and subsequent transpiration to the atmosphere (Tabacchi et al., 2000). However, two factors usually militate against this. Firstly, vegetative roughness significantly reduces wind speed across the floodplain, reducing the potential for turbulent diffusion processes to remove water vapour. Shading also reduces the solar energy available to heat the surface and to evaporate water; and thus forest floors are generally more damp than those areas without forests, which reduces the sediment shear strength according to the equations described above (Simon et al., 1999). These factors also affect the evaporation and transpiration component of floodplain hydrology.

However, the indirect effect that vegetation has on pore water pressure is likely to be subsumed by the direct impacts that organic material (both living and dead) can have on entrainment processes. The general effects of any living vegetation or organic debris are to increase surface roughness (Fischer-Antze et al., 2001; Tabacchi et al., 2000), restrict flow pathways (Piégay, 1997; Piégay et al., 1998) and increase the shear strength of the floodplain surface through dense root networks (cf. Zimmerman et al., 1967; Abernethy and Rutherfurd, 1998; 2000; 2001). Also, vegetation often promotes sites of sediment accretion leading to island development (e.g. Gurnell et al., 2001; McKenney et al., 1995; Osterkamp, 1998). Conversely, scour channels form across the floodplain surface when overbank flow pathways become channelled between trees and other vegetation (Hickin, 1984; Piégay et al., 1998), thereby creating a source of sediment from the floodplain surface.

More specifically, debris dams can block the channel and create localised overbank flow (Brown, 1998), thus increasing water and fine sediment transfer to the floodplain, although no previous research has investigated this. Dams may also lead to alluvial cutoffs and avulsions, inherent in which is surface scour. Biotic processes can also contribute directly to sediment production from, for example, windthrown trees or animal activity.

The lateral migration of the river through the floodplain provides a source of sediment from the eroding riverbank. Bank material is entrained by (i) direct action of the water, along the same principles as outlined above; (ii) through subaerial weathering processes such as frost action; and (iii) through failure of large blocks of the river bank (Knighton, 1984; Simon et al., 1999). The principles involved in the first of these have already been covered and the second is important for bank preparation processes (Lawler, 1992). Both can also be modified by vegetation strengthening riverbanks (e.g. Abernethy and Rutherfurd, 1998).

Modification of secondary in-channel flows by biota, particularly by debris, is severe (e.g. Gregory et al., 1985; Gippel, 1995; Newell, pers. comm., 2001) but associated changes in hydraulic processes are poorly understood. Although bank erosion commonly occurs around debris dams (e.g. Gregory, 1992), its contribution to the fluvial sediment load has not been quantified.

The mechanics of bank failure are covered succinctly in Simon et al. (1999), but in essence rely on the relationship between the driving forces (gravity, critical friction angle of the soil, pore water pressure) and the resisting forces (cohesion and shearing strength) of the river bank. A number of factors complicate this relationship. The bank may be composed of units of different strengths, or it may be vegetated, the effect of which will vary according to the type of vegetation. The same modification of sediment shear strength by pore water pressures applies as described above (equations 1-7).

The final area of sediment mobilisation is that from biogenic activity. Burrowing animals (Black and Montgomery, 1991) can provide a significant source of sediment for rapid entrainment because it has usually been dug out in the form of relatively small aggregates. Bovine animals, however, can be a more significant source of sediment by reducing vegetation (and the protection it provides) and trampling river banks, pushing sediment into the river (Trimble and Mendel, 1999).

Sediment pathways

The two broad routes of sediment are: movement down hillslopes (mass movement; soil creep, mixing and biogenic processes); and movement through the floodplain and channel (debris flows; ephemeral channel scour and wash load; biogenic transport; bank erosion and lateral migration; alluvial cutoffs, avulsion and infill; overbank flooding and flooding around debris dams; and suspended load transport and bedload transport in the main channel).

A detailed investigation of hillslope processes is beyond the scope of this study, but it is recognised that they can in some locations be a principal source of sediment to the floodplain (e.g. Nakamura et al., 2000). In drainage basins with steep gradients, mass wasting processes occur and have a major impact on stream channel morphology by scouring and depositing large deposits of sediment in the channel (Hogan, 1986; 1987; Hogan et al., 1995; 1998; Lehre, 1982; Nakamura et al., 2000). However, in lowland drainage basins with a more subdued landscape morphology, such mass wasting processes are less dominant. Instead chronic input will occur via slow hillslope movement. More rapid transport from shallow hillslopes will occur from ephemeral channel networks, particularly at the base of the slope where throughflow causes saturation of the soil surface and overland flow occurs. Finally, where an active meander cuts into the valley wall it will be directly tapping a source of colluvium.

The processes of sediment transport across floodplains are similar in basic principles to those operating in confined river channels and fall into three basic categories: bedload transport (the proportion of sediment moved by traction and saltation along a flat inundated surface); suspended sediment transport along flowlines; and dissolved load, which will not be considered further because it tends to comprise a very small proportion (< 1%) of the total transport (Walling and Webb, 1987). Overbank deposits are usually fine-grained but may include medium to coarse particles up to 2mm (Allen, 1970). However, whether sediment is supported depends on the upward-acting forces, which is a spatially heterogeneous variable (James, 1985). 'Bedload,' may therefore be carried in suspension, and likewise suspended load may be saltated or rolled along the surface.

The hydraulics of 'cleared' floodplains

The intricate hydraulic structures that exist between the channel and the floodplain (Fig. 2.2) have proven a challenge to quantify (Knight, 1989; Knight and Shiono, 1996; Nicholas and McLelland, 1999); but the interaction between riparian vegetation and hydraulics is probably more complex and has received less investigation (Tabacchi et al., 2000). The interaction of floodplain flow with vegetation has been simulated (e.g. Darby, 1999), but the detailed hydraulic characteristics of secondary flows on the floodplain remain poorly understood. No published research documents were found that explicitly quantified the affects of vegetation on the hydraulics of secondary currents in river meanders.

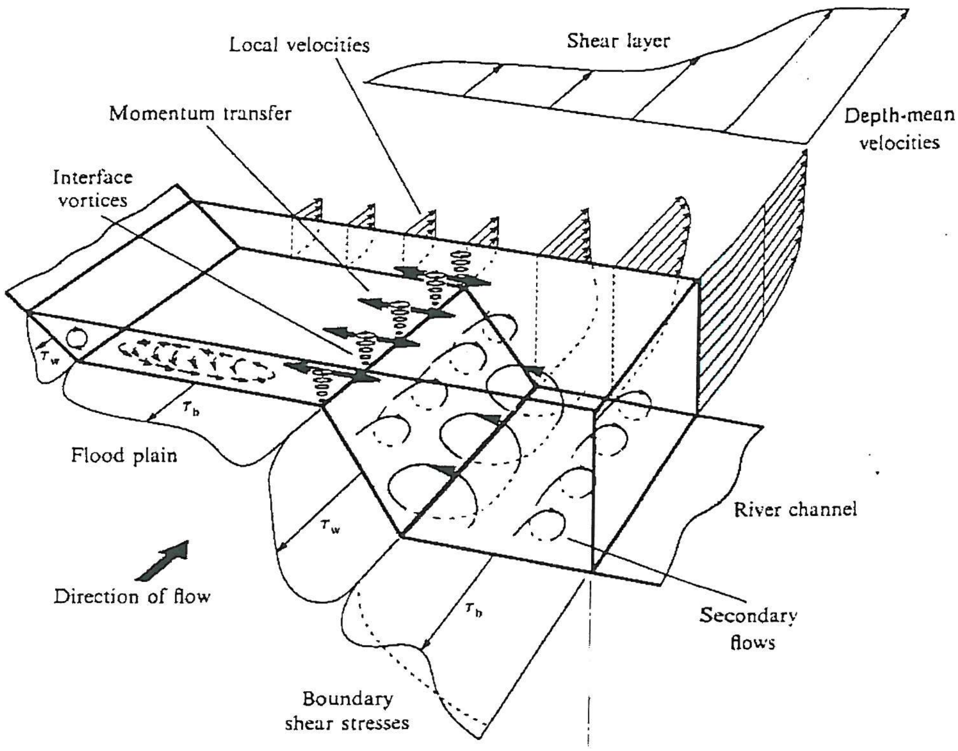


Figure 2.2 The interaction of in-channel and floodplain flow (Knight, 1989)

First, in-channel hydraulics will be considered, because these exert a direct influence on overbank flow structures and vectors. The question is, therefore, what is the interaction between the flow structures that originate from the main channel, and flow across the floodplain surface? This subsection investigates this area, but the full scope of in-channel hydraulics is too wide a subject area to be considered in detail in this review, and only the principles most applicable to (i) lateral accretion and (ii) the interaction of in-channel flow with overbank flow, will be considered.

As water moves through a meander bend it is subjected to centrifugal forces that direct the flow radially outwards against the outer bank (Allen, 1970; Bathurst et al., 1977; Thorne et al., 1985), against which water accumulates, and a superelevated water surface profile develops across the bend (Fig. 2.3). This transverse water surface slope creates a cross-stream pressure gradient force, which exceeds the outward centrifugal force near the bed (where flow velocity is low) and which is less than the centrifugal force near the surface, where downstream flow velocities are greatest. This therefore sets up a transverse flow circulation, as shown in Figure 2.3.

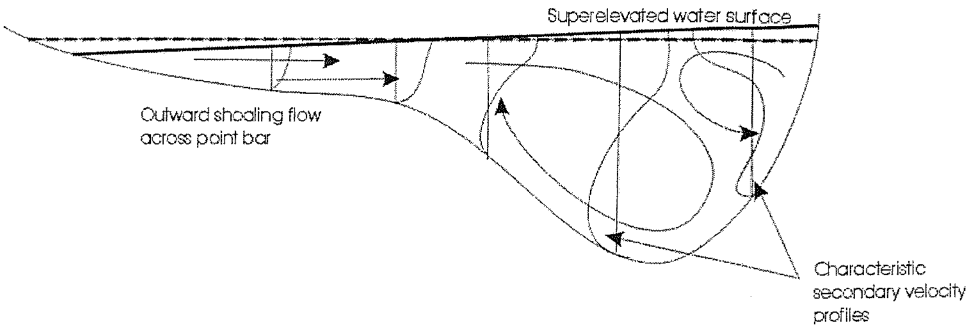


Figure 2.3 Secondary flow in a river bend apex (after Markham and Thorne, 1992)

Whereas gravity drags the largest particles of sediment to the bottom of the pool, this transverse circulation brings smaller particles up from the bed toward the top of the bar. It is for this reason that point bars tend to have coarse material at their bases with finer particles being carried toward the top of the bar. Direct measurements of flows in meander bends (Bathurst et al., 1977; Dietrich and Smith, 1983; Thorne et al., 1985) have demonstrated that this model is in essence true, but misses some of the finer detail of secondary flow. A second circulation cell is often found in the upper half of the channel on the outside of the meander bend and these appear to be most evident where the outer bank is steep (Thorne et al., 1985; Bathurst et al., 1977). This alters the velocity profiles and, therefore, the shear stress distributions. Dietrich and Smith (1983) observed that water shoals as it passes across the top of the point bar, and this accumulation at the inner bank decreases the pressure gradient force, leading to a dominance of centrifugal force across the point bar. This leads to net outward flow over the point bar. For a meandering channel with a flat bed they also propose a model of point bar evolution: "in a flat-bottomed channel the downstream decrease of the high boundary shear stress near the inside bank must cause the sediment transport rate to diminish, and net deposition must occur at the downstream end of the bend. Sediment deposition by this process contributes to emergence of the point bar. As the flow shoals, an outward component of boundary shear stress and thus sediment transport develop. An equilibrium point bar depth is established when the decreasing sediment transport along the inside bank is exactly balanced by topographically induced outward sediment transport." Dietrich and Smith, 1983. The flow along a meandering river channel therefore results in the existence of a flow field that perpetuates the existence of the meanders. It is considered that meander development could follow on from alternate bar development (Keller, 1971), but the geomorphic mechanism forming such regular bars is uncertain.

Nelson and Smith (1989; cited in Whiting and Dietrich, 1993), demonstrated that where there is an in-channel obstruction, a downstream variation in shear stress is set up that redistributes energy by increasing the shear stress and, therefore, the erosion immediately downstream or cross stream of the object. The material eroded from this area of high energy is then deposited as a new bedform where the water velocity and shear stress decrease, and this sets up another shear stress variation, and so the first perpetuates its form downstream. Hence a meandering course is assumed; and this may originate from or be modified by in-channel accumulations of woody debris. Alternating pool-riffle bed forms are often associated with meandering rivers, (Clifford and Richards, 1992), and these sequences appear to have a relatively stable relationship with channel width: spacing is usually five to ten times channel width, and is often around seven. This relationship has also been shown to vary according to the presence or absence of large woody debris dams (Gregory et al., 1995). However, the author has found no published research into the impact of in-channel debris upon processes of lateral accretion.

Overbank flows first occur where the banks are lowest (Lewin, 1978); or where the local water surface is elevated or ponded (e.g. in the vicinity of in-channel obstructions, such as bridges or dams). Floodplain flow can be investigated in a variety of manners, ranging from descriptive observations to more complex models designed to simulate instantaneous or flood flows. Sellin (1964) first described how the vortices that exist in the shear layer between the deeper, faster main channel and the slower, shallower floodplain cause lateral transfer of momentum. The processes operating inside these features are still not yet fully understood, which makes understanding the interaction between in-channel and overbank flow structures difficult (Knight and Shiono, 1996, and references therein). Nicholas and McLelland (1999) have investigated this shear zone, but a clearly defined model of turbulence within the direct zone of interaction is still not available.

Approaches to the numerical simulation of fluid flow in natural channels are based on the use of a set of equations describing the conservation of mass and momentum of water. These are coupled with empirical 'laws' which in turn describe the flow resistance and turbulence. The main problem with these approaches lies in the fact that they are specifically designed to simulate flow structures in confined channels, and they account for neither for the non-linear or non-monotonic rate of change that occurs as flow goes overbank, nor for the complex turbulent hydraulic structures thereby generated.

Flow modelling across floodplains requires understanding of the relationship between flow vectors and the depth of inundation. The ratio of channel water height to floodplain water height (X) can be defined as

$$X=((H-h)/H) \qquad (8)$$

where H is bankfull channel depth (m), which is a fixed value; and h is floodplain water depth (m) (Knight and Shiono, 1996). Initial state is therefore 1, when the floodplain inundation height is zero. As waters rise the ratio will decrease while a vertical free shear layer develops along the bank top. This layer temporarily breaks down to form turbulent eddies, which transfer energy and matter to the floodplain. The passage of these high energy pockets of water onto the floodplain causes an increase in shear stress on the surface, and this is greatest when X is between 0.9 and 0.5 (Knight and Shiono, 1996).

Floodplain models were reviewed by Knight and Shiono (1996), who classified them into one, two and three dimensional analyses. The simplest type of model is the one dimensional or cross-sectionally averaged model. There are a number of approaches to solving this model, but these have tended to be devised for prediction of stage discharge curves, are well documented elsewhere (Knight and Shiono, 1996) and so will not be considered in detail. In essence, however, this approach involves the use of empirically derived flow resistance equations (such as those derived by Manning or Darcy-Weisbach) to estimate flow across a given cross section. There are problems with this method (it was derived to describe fluid flow in pipes, and it does not account for form roughness) but it may nonetheless be as useful as a means of predicting flow over floodplains as it is in confined river channels because the models used are fairly simple.

Three dimensional analyses of floodplain hydraulics use the mass-momentum equations to simulate flows in vertical and both horizontal dimensions. This allows a full representation of in channel flow processes, though it may not allow for the complex turbulence that develops between the main channel and the floodplain when the floodplain inundated to between 5 and 50% of channel depth. Knight and Shiono (1996) note that there are problems associated with modelling this zone due to the complexity of the processes that occur there. There is no published research on using 3-D modelling to investigate the influence of vegetation on floodplain hydraulics.

There have, therefore, been a number of different approaches to understanding floodplain hydraulics using floodplain modelling. It is clearly necessary to consider the hydraulics of flow before accurate estimations of shear stress can be related to sediment transport. Despite a lack of a full understanding of floodplain hydraulics, there are nevertheless a number of models that attempt with varying degrees of success to relate the hydraulic interaction between the channel and the floodplain to sediment transport over short and long term scales.

Lateral accretion

The helical flow structures described above cause erosion occurs on the outside of meander bends and deposition on the inside (Allen, 1970; Figs. 2.3 and 2.4). The floodplain is therefore reworked, with old flood deposits being 'destroyed,' so that new deposits - usually in the form of a point bar - occur on the inside of the meander bend. Successive bars lead to a ridge and hollow topography (scroll bars and swales) (Allen, 1965; 1970; McKenney et al., 1995). The rate of meander migration can be used to determine a time within which the entire floodplain will be reworked.

The sedimentary structures within and on point bar deposits in gravel bed rivers are well-documented (Allen, 1965; 1970; Markham and Thorne, 1992; Brown, 1996). The channel hydraulics described above drive the helical flow pathways that occur in river meanders (Bathurst et al., 1977; Dietrich and Smith, 1983; Thorne et al., 1985).

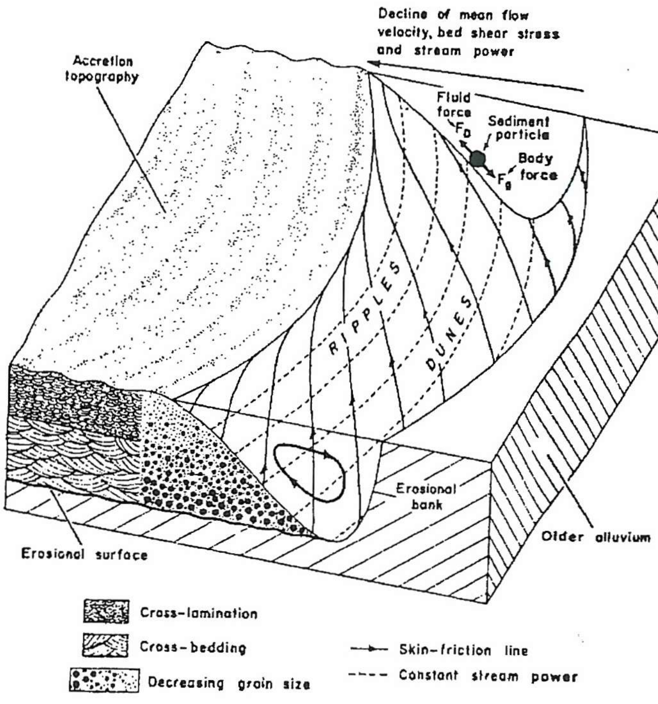


Figure 2.4 Point bar deposition in a river meander (Allen, 1970)

Rates of lateral migration are sometimes difficult to estimate because they are often low (Wolman and Leopold, 1957; Macklin, 1985). Keller et al. (1995) note that in small, low gradient, meandering streams, migration can be less than one channel width across the floodplain during the last several hundred to 1000 years. A theoretical optimum time scale to observe meander migration rates will vary according to the river, but can be more than 200 years, which is too long for contemporary observations and too short for palaeogeomorphological reconstruction (Macklin, 1985). This is particularly true in low-gradient rivers which historical records suggest are relatively stable (Macklin, 1985). Proxy techniques, such as dating the minimum ages of trees (thereby a minimum age of the floodplain on which they stand) have been used by Nanson (1980), but again these only work where rates of migration are fairly high, and may be masked if complex floodplain flows result in a patchy mosaic of vegetation.

The rates of lateral migration can be extremely variable even within the same river: Kolb (1963, cited in Hooke, 1979) noted that the rate of the migration of the Mississippi varied from 0.61 to 305 m/yr. Rates between rivers effectively vary from nil in some to kilometers or more a year (Wolman and Leopold, 1957). As Hooke (1979) p. 60. concluded for the River Severn: "... the amount of erosion... is controlled by a complex combination of conditions and... no single model of control emerges". Bank migration rates therefore provide a variable source of information about the longevity of floodplains.

Coarse sediments are usually reworked in the channel, although overbank transport of gravel was recorded in a high-energy piedmont river by Piégay et al. (1998). The rate of channel evolution will control turnover of sediment but can be highly variable even within reaches of the same river (McKenney et al., 1995), a pattern that is made more complex by the effect of vegetation on river bank processes (Gregory, 1992; Hupp and Osterkamp, 1996). Downstream sediment transmission is also regulated by debris dams (Mosley, 1981; Fetherston et al., 1995); and log steps in streams in Oregon store the equivalent of 123 % of the annual sediment discharge (Marston, 1982).

The ability of shallow floodplain flow to entrain and transport coarse fractions of sediment is limited when compared to the deeper and often faster flow in the channel. Nevertheless, bedload transport across the floodplain has been documented (Asselman and Middelkoop, 1995; Brown, 1983; Gomez et al., 1998). Brierly and Hickin (1992) observed that floodplain development on the Squamish river, British Columbia, involved stripping of relatively coarse surface sediments by overbank flow. Brown (1983) noted that overbank flow deposits may vary from fine sediment to large boulders during catastrophic events (cf. The Lynmouth Flood in August

1952 – Dobbie and Wolf, 1953; Delderfield, 1954). Gomez et al. (1998) noted that current velocities on the Waipaoa river, New Zealand, were in fact too high to permit settling of suspended sediment and bedload transport occurred instead.

Therefore, overbank flow contains a mixture of particle sizes usually up to sand or fine gravel, with rarer overbank movement of pebbles, cobbles and even boulders. There have been few studies into coarse sediment transport over forested floodplains, although Piégay et al. (1998) observed advancing gravel layers in the floodplain forest of the Ain River, France.

Vertical accretion

The models of James (1985) and Pizzuto (1987) predict two types of suspended sediment transport over non forested floodplains: (i) movement via turbulent eddies, which can be modelled as a diffusion process (James, 1985) or (ii) advection, where floodplain flow has a component perpendicular to the main channel. Although molecular diffusion of suspended sediment occurs between laminar flow layers, the majority of particles are moved by turbulent eddies that form at the interface between the main channel and floodplain surface (James, 1987; and see Fig. 2.2).

James (1985) modelled overbank flow numerically by defining equations for diffusion and advection. He assumed that velocity gradually decreases away from the fastest flow zone (usually the main channel). The sharpest velocity gradient occurs roughly parallel to the top of the banks, and this results in the development of a free shear layer (Allen 1970; Nicholas and McLelland 1999). Within this, internal fluid shearing promotes the formation of turbulent eddies that detach themselves and diffuse away towards calmer areas. The model also assumes that suspended sediment transport is highest in the main channel, and that the eddies tend to provide a net loss of sediment from the channel. Each eddy contains a limited amount of kinetic energy and, when this is depleted, the turbulent upwellings then descend below the critical threshold needed to act against gravitational pull on suspended sediment. Settling and deposition therefore occur.

In the James (1985) model, most sediment is therefore deposited on the floodplain near the top of the bank (in the zone of turbulent eddy shedding from the main channel; cf. Knight and Shiono, 1996), and deposition exponentially decreases toward distal areas. His model included an empirically derived component (ε_z), which varies the rate of lateral diffusion. Diffusivity beyond the zone of interaction (assumed to be the area of interaction of turbulence on the floodplain) is considered as an empirically calibrated function of flow width and water depth. Diffusivity within the interaction zone is assumed to be a similarly derived function of varying water velocities from both the channel and the floodplain.

According to the James model, turbulent diffusion alone occurs when the channel is parallel to the direction of floodplain flow. This ensures no lateral convection of water masses, turbulence or suspended sediment. If, however, the channel is aligned at 90° to the floodplain, more deposition occurs on the lee or downstream side of the channel than on the stoss or upstream side and this results in asymmetrical deposition.

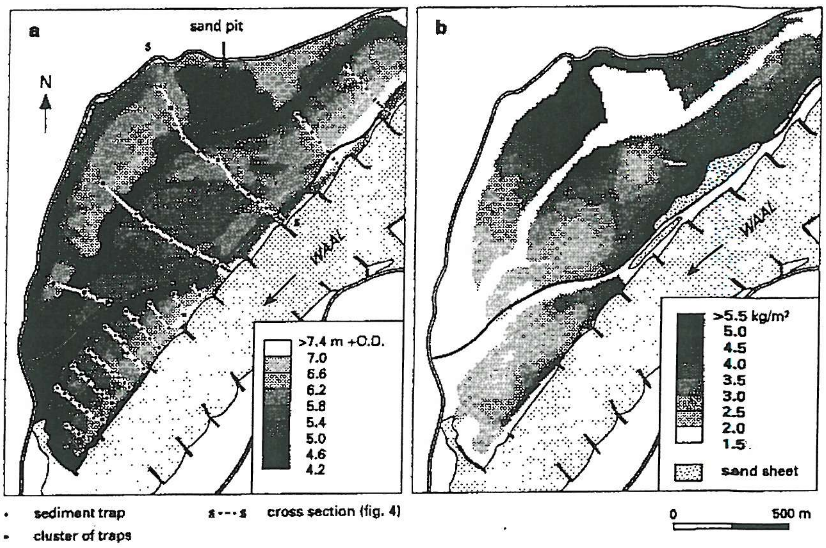


Figure 2.5 The relationship between (a) floodplain elevation and (b) sediment accumulation the River Waal, Netherlands (Middelkoop and Asselman, 1998).

Pizzuto (1987) included terms for bedload transport but noted that spatial variation in turbulent diffusion is difficult to define and quantify (this is what James (1985) undertook empirically using ε_z) so he considered it as a constant. He included specific terms for the availability of sediment supply, transport and erosion. It is more difficult to quantify erosion than deposition because sediment entrainment depends on hydraulics, type of sediment on the floodplain (described above) and on the amount of sediment in suspension (competence of the instantaneous water body for transport). Pizzuto therefore followed work initiated by Cheng (1984), which assumes that transport rates are determined by the capacity of the flow and by the rate of deposition. This empirical approach therefore relies on correct models of the rates of transport and deposition, which are in turn dependent on correct estimation of settling velocities. Pizzuto empirically calibrated and tested the model with data from Brandywine Creek, Pennsylvania (the site where Wolman and Leopold devised their model in 1957), finding that the overall profile of the floodplain was reproduced quite well, though without detailed topographic variation.

Although the concept of lateral diffusion is supported by observations from laboratory flumes (James, 1985), field studies of the amount of overbank deposition highlight real-world complexity. Upon both vegetated and 'cleared' floodplains, surface morphology can significantly control flow pathways (Bates et al., 1998), and vegetation increases channel (Darby et al., 1997; Darby 1999) and floodplain roughness (Fischer-Antze et al., 2001). Middelkoop and Asselman (1998) describe how some sites on the River Meuse conform to the James (1985) and Pizzuto (1987) models, but others have highly variable patterns of overbank deposition controlled by topography (Fig. 2.5). These patterns of deposition are controlled less by distance from the channel and more by floodplain topography (Middelkoop and Asselman, 1998; Siggers et al., 1999; Walling, 1999). The process of lateral diffusion can also be modified by processes that significantly alter floodplain topography, such as when abandoned channels fill with sediments carried by overbank flow. The type and setting of abandonment can determine the type of infill. A suddenly-abandoned length of channel will tend to fill with fine suspended sediment (e.g. Brierly and Hickin, 1992; Erskine et al., 1992). Cutoffs that gradually occur disconnect the old channel more slowly so that a plug of coarse bedload is deposited at its upstream end; and fine sediment is deposited in the low-energy area downstream (see Nicholas and McLelland, 1999). Middelkoop and Asselman (1998) found that floodplain channels filled with sediment during low flow and scoured during higher flow.

While these models give values of overbank deposition per event, the average rate of accretion can be determined either by using sediment traps or by estimating the loss downstream. The comparison of short and long-term estimates provided in Table 2.3 highlights a possible decrease in overall sedimentation rates over the past 100 years (estimates from Pb-210 dating tend to exceed those from Cs-137). Also, estimates of long term rates are much lower than those derived for individual floods. As Gomez et al. (1998) noted, the average rates over decades, centuries or millenia of floodplain accretion are very low (between 0.2 and 10mm per year). In reality, periods of rapid aggradation build up the floodplain during a short space of time.

Lateral or vertical accretion?

On 'cleared' floodplains, lateral accretion is often considered to be more dominant than vertical accretion. Wolman and Leopold (1957) originally investigated the relative dominance between these two processes. Their hypothesis assumed that 'each time the stream overflows a given level it deposits a specific thickness of material,' (p.100) and, by combining this increase with computed flood frequencies, they calculated the hypothetical time taken to reach a given elevation (Fig. 2.6). The fairly active floodplain they tested this hypothesis on – Brandywine Creek, Pennsylvania – had been radiocarbon dated to be a minimum of 1450 years old, and the accretion curve for this floodplain (Fig. 2.6) demonstrated that, if the hypothesis held true, the floodplain should be four feet higher. For this channel, it is clear that vertical accretion is not always the dominant control on floodplain elevation. Wolman and Leopold concluded that lateral accretion must dominate.

Table 2.3 Some vertical accretion rates derived from Cs-137 (30 year), Pb-210 (100 year) and field study based approaches. Adapted from Walling (1999). 1 – Walling and He (1999); 2 – Walling (1999); 3 – Siggers et al. (1999); 4 – Macklin (1985); 5 – Middelkoop and Asselman (1998); 6 – Walling and Bradley (1987); 7 – Gomez et al. (1997).

Rate of overbank sediment accretion				River and location	Source
Per flood	Per year	Last 33 yrs	Last 100 yrs		
kg cm^{-2}	mm a^{-1}	g cm^{-2} a^{-1}			
		0.95	1.04	Ouse, York	1, 2
		0.21	0.46	Vyrnwy, Llanymynech	1, 2
		1.22	1.42	Severn, Atcham	1, 2
		0.15	0.28	Wye, Preston on Wye	1, 2
		0.86	0.95	Severn, Tewkesbury	1, 2
		0.46	0.66	Warwickshire Avon, Langley Burrell	1, 2
		0.88	1.01	Usk, Usk	1, 2
		0.39	0.33	Bristol Avon, Langley Burrell	1, 2
		0.51	0.64	Thames, Dorchester,	1, 2
		0.7	0.93	Torridge, Great Torrington	1, 2
		0.6	0.65	Taw, Barnstaple	1, 2
		0.56	0.43	Tone, Bradford on Tone	1, 2
		0.45	0.42	Exe, Stoke Canon	1, 2
		0.35	0.32	Culm, Silverton	1, 2
		0.51	0.4	Axe, Colyton	1, 2
		0.04	0.04	Dorset Stour, Spetisbury	1, 2
		0.11	0.14	Rother, Fittleworth	1, 2
		0.39	0.48	Arun, Billingshurst	1, 2
		0.51	0.71	Adur, Partridge Green	1, 2
		0.15	0.23	Medway, Penshurst	1, 2
		0.51	0.45	Start, Slapton	1, 2
		0.206		Ouse, Wharfdale	1, 2
		0.28	0.33	Severn	1, 2
		0.4 (est.)		Culm, Devon	3
	8.8			Axe, 1670-1710	4
	4.6			Axe, 1711-1857	4
	16			Axe, 1858-1863	4
	2.4			Axe, 1864-1982	4
1.2-4				Waal, Netherlands	5
1.0-2				Meuse, Netherlands	5
0.104				Culm, Rewe	6
0.051				Culm, Silverton	6
0.079				Culm, Rewe	6
0.008				Culm, Silverton	6
0.043				Culm, Champerhaies	6
0.102				Culm, Silverton	6
0.227				Culm, Rewe	6
0.038				Culm, Rewe	6
0.185				Mississippi	7
0.11-0.3				Waipaoa, New Zealand	7

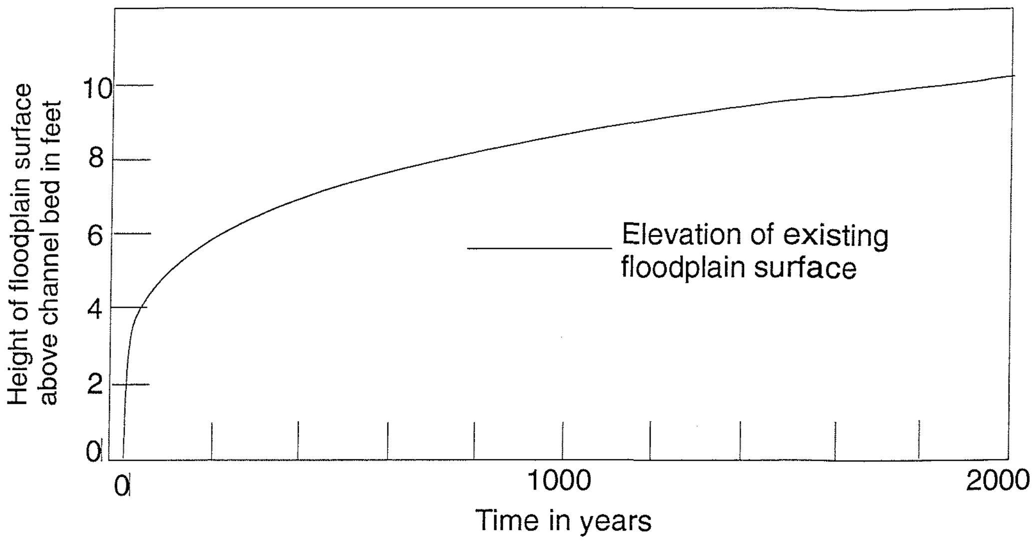


Figure 2.6 The hypothetical increases in the elevation by overbank deposition of Brandywine Creek, Pennsylvania, USA (Wolman and Leopold, 1957)

However, other studies, based in the UK, undermine this hypothesis: Brown et al. (1994) found that, during the Holocene, both the Soar and the Nene, Leicestershire, have undergone vertical accretion with little lateral movement. An increase in channel capacity (from increased overbank accretion, channelisation or incision) can significantly reduce the frequency of overbank flow (Bates et al., 1998). If overbank flows are infrequent and shallow, the reduction will reduce the likelihood of inundation. Conversely, where overbank flow is relatively frequent and deep, then the volume of water required to inundate the 'extra' area of channel is comparatively small, and both floodplain inundation and hydraulics are likely to be unaffected.

The extra discharge required to inundate the floodplain to a given level as aggradation occurs may be compensated for by other changes: the *number* of channels can reduce; the cross sectional *area* of the channels can reduce; or there can be a compensating *increase* in discharge as a result of landuse or climate change. This is known as the Stable Bed Aggrading Banks (SBAB) model (Brown et al., 1994). The extra depth required may occur more locally where flow is unequally partitioned between more than one channel, which results in elevated flood water levels in one channel at the expense of the others (Harwood and Brown, 1993; Piégay et al., 1998).

A reduction in discharge (and in the frequency of overbank events) as the floodplain aggrades can be offset by an increase in sediment discharge. Magilligan (1992) documented a variable sediment supply that resulted in 3m of vertical accretion in 160 years. Erskine et al. (1992) found that cut-off alluviation was related to phases of high and low flood activity from climatic forcing. Therefore, external controls on flow and sediment sources can have a large impact on the rate of vertical accretion. The rate, amount and location of vertical accretion is therefore controlled by a number of variables and these can be divided according to whether they are an external influence (exogenic) or controlled by the river system (endogenic) (Table 2.4). However, little importance has been attributed to the impact of vegetation on floodplain aggradation, but the compensatory changes noted by Brown et al. (1994) were biotically influenced, and what Wolman and Leopold (1957) did not address was the influence of vegetation on floodplain aggradation.

Sinks

The main outputs from the basin are dissolved load, suspended load and bedload discharge from the river channel. The solute fraction is usually insignificant (Walling and Webb, 1987). While floodplain sediments can be consolidated and incorporated into the sedimentary record, this occurs within geological timescales, and is not considered here. However, floodplains are important semi-permanent stores of sediment over contemporary and management timescales ($10^0 - 10^2$yr).

Table 2.4 *Endogenic and exogenic controls over floodplain sedimentation.* Notes: (1) this is a local effect within the river channel; (2) this is a local effect of and across the floodplain surface only.

Variable		Likely effect on	
Exogenic		Vertical accretion	Lateral accretion
Sediment supply	decrease, all size fractions	↓	↑
	coarsening	↓	↑
	fining	↑	↓
	increase, all size fractions	↑	↓
Flood frequency	(1) reduction in flooding and discharge	↓	↓
	(2) increase in flooding and discharge	?	↑
Tectonic change	Incision from base level increase	↓	↓
	Stream incompetence from base level decrease	↑?	↑?
Endogenic			
Disturbed channels	See sediment supply changes	↓	↑
In-channel flow pathways	Local overbank flow from debris dams	↑ (1)	↓
Floodplain topography	Flat - promotes deposition near channel Topographically diverse - promotes variable deposition. Management works may prevent floodwater from reentering the channel	Variable (2)	Little or no direct impact
Floodplain roughness	Rougher floodplain surface	↑ (2)	No direct impact
	Smoother floodplain surface	↓ (2)	

Floodplain geomorphology

The processes described above result in a variety of floodplain features, and these have been classified (i) according to their origin (Allen, 1965; 1970; Brown, 1996), (ii) their sedimentology (Brown, 1996), and (iii) their location (Zwolìnski, 1992). Many of these are characteristic of 'cleared' meandering river systems, and features found on forested types of floodplain tend not to be included (Table 2.5).

Lateral river migration generates point bars that, over time, leave a series of ridges and swales across the floodplain surface (Allen, 1970). Scroll bars are a similar feature to swales and are also formed by lateral migration, but are the remnants of abandoned levees (Brown, 1996). Oxbow lakes result from meander cutoffs and leave a topographic low permanently inundated by the water table. These and other low, wet areas may also be known as sloughs or backwater areas. Levees are formed where flow enters the floodplain and deposits sediment (see above). During bankfull flow, levees can be breached, leading to crevasse cuts with a sand splay behind each (Zwolìnski, 1992). This list (scrolls, swales, levees, splays, sloughs and so on) is typical of features found on non-forested floodplains.

However, there are a number of less well-documented features that are characteristic of forested floodplains (Table 2.5). These include occasionally inundated ephemeral channels; debris jams in the base of trees (e.g. Piégay et al., 1998; Hickin, 1984); extensive (peaty) organic deposits and small debris jams.

The most widely-accepted conceptual model of floodplain process and evolution was proposed by Wolman and Leopold in 1957, and is discussed in detail below. Other classifications also exist, such as those of sedimentary structures (Allen, 1965, 1970; Lewin and Hughes, 1980; Brown, 1996; Zwolìnski, 1992), and of patterns of floodplain inundation (McKee et al., 1967 (quoted in Zwolìnski, 1992); Allen, 1970; Gupta and Fox, 1974 (quoted in Zwolinski, 1992); Ray, 1976 (quoted in Zwolinski, 1992); Lewin et al., 1979; Lewin and Hughes, 1980; Hughes, 1980; Zwolinski, 1992; Howard, 1996)). Geostatistical analyses of the spatial change in floodplain structures (e.g. Bates et al., 1998; Middelkoop and Asselman, 1998) demonstrate a greater variability of floodplain features perpendicular to the channel than parallel to it, which suggests that processes are centred around the main channel.

Table 2.5 Floodplain geomorphological features

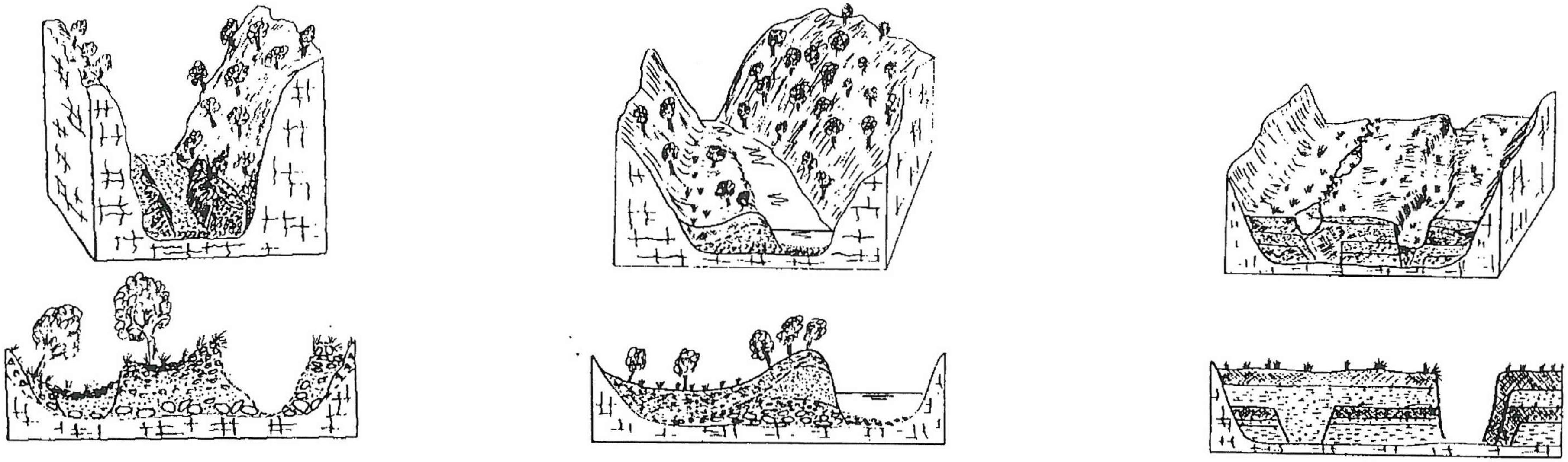
Feature	Location	Sedimentology	Form	Origin	Purpose/ function	Vegetation cover	Activity /age
Point bar	Transitional from channel	Bedded, sorted from coarse to fine	Bar form	Fluvial activity	Maintenance of 3-D flow	Little or none	Modern (in phase)
Scroll bar	Floodplain parallel to the channel	Similar to point bar overlain by levee sediments	Relict bar or ridge	Previous point bar activity	Channelise surface flows	Drier species; probably fairly dense	Probably modern, but could be older
Oxbow lake	Distal channel	Fine (varved) with organics	Elongate depression	Former channel - since avulsed or cutoff	Loci for quiet flow; trap sediment and organics. May reactivate	Wetland vegetation	Meso - will infill given > centuries
Other backwater area	Backwater - distal from channel	Fine - layer of overbank sediment	A 'fill the gap' feature between others?	? Planing off during ob flow; otherwise fill	Fines trapping; vegetation establishment	Organically productive rushes and wetland spp.	Fairly old?
Levées	Next to channel	Layered sand	Elongate ridge next to channel	Incompetence of overbank flow	Locus for OB flow deposition; reduce return flow	Resistant, dry liking but wet tolerant spp.	Modern (in phase)
Crevasse cuts	On levée	Coarse - active face	Oval / fan formation	Overbank flow cutting into levée	Energy expenditure; locus for water to enter floodplain	Little or none (depends on age)	Modern (in phase)
Palaeochanne ls	Floodplain (no particular location)	Coarse base, filled with fines	Topographic low sinuous areas: may be subsurface	Abandoned channel	Former channel: may channel flows; may be resistant	Dense / high nutrients	Former system state
Mid / side channel bars	In channel	Coarse or fine depending on location	Diverse see Petts and Foster (1985)	Submerged fluvial activity	Energy dissipation or sediment depostion	None or aquatic macrophytes	Modern
Chute bar	Side of main channel	Coarse surficial sediments from floodplain and bank	Fan	Accelerated flow re-entering channel and losing competence	Where overbank flow re-enters the channel	Some bank vegetation - depends on age	Modern
Ephemeral channels	On the floodplain between	Scour feature: base is made from floodplain	Channel: elongate	Scour Depositon around it	Channelise flow; convey material	? Depends on age, activity,	Modern, though may be a result

between trees	topographic highs	sediment	floodplain depression			time of year	of old scroll bars
Debris jams	Base of trees	Non or some coarse sediment	Elongate protective aprons	Floodwater-rafted debris	Protects areas behind them; stores OD	It is vegetation	Modern (requires high flooding)
Vegetation - established sheltered area	Behind trees or other vegetation	Mixture: should trap all size fractions though more fines (stops fast flow)	Depends on layout of vegetation	Dependent on vegetation type and structure	Depositional area	Resistant, wet-tolerant species	Modern
Topographically sheltered area	Distal to channel?	Fine sediment trapping, though all sizes caught	Topographic low	Low energy area / accretion around it?	Traps fines	Dense / wetland spp.	Could be very old (e.g outwash plain)
Extensive organic deposits	Distal to channel	Fine / low deposition / sheltered	Topographic low; high water table	Major organic production	Organic production and fines trapping	Dense, high turnover	Old? Probably not active
Surface debris dam	On floodplain across ephemeral channels	Trap fine sediment (or whatever is passing)	Finite area elongate OD structure	Water rafted debris	Protects areas behind; dissipates energy; slows water	? None	Modern
Anastomosed islands	Between channels; comprise floodplain	Graded: may be relict features topped by fines	Islands	Floodplain dissection Resistant areas from vegetation Relict braid	Depositional area / divide flow	Varied (can be related to tree throw)	Ancient?
Vegetation mosaic	According to previous activity	Depends on activity	Patchy mosaic depending on sediment type and disturbance	Link of vegetation and geomorphic action	Primary production and affect other processes	Whatever makes the mosaic!	Modern although it could be a previous system
Tree throw pits	Depends on wind pressure and health of tree	Unsorted: depends on location	Hole: discrete and messy	Unhealthy tree / storm / environmental conditions	Dissipation of energy by fallen tree translated by root network	None / tree	Modern

2.2.2 Floodplain classification

Few authors have attempted to categorize floodplains, probably because they are dynamic sites within an enormous range of physiographies and management systems. However, from a geomorphic perspective, the identification of common patterns within the full spectrum would be an important achievement, and some attempts in this direction have been made. The classification used below (Fig. 2.7) is based on the genetic floodplain, which was defined by Nanson and Croke (1992) as a 'largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow regime.' A tripartite division of fluvial energy (high, medium, low) provides the first division, and cohesive and non-cohesive sedimentology a further two subdivisions. This modified floodplain is included in Fig. 2.7 within two classes: industrial-urban and agricultural-silvicultural (Fig. 2.7c), both of which tend to be disconnected from the river channel.

Ecology provides an alternative perspective to classify and understand floodplains, usually with a focus on the ecological impact of geomorphological variables (e.g. Hughes et al., 2001; Ward et al., 2001). These authors suggest that a much greater potamologic understanding can be achived if frameworks used in established ecological techniques (e.g. landscape ecology) are used to structure research and management agendas (Ward et al., 2001). These ecological viewpoints are discussed in section 2.3.

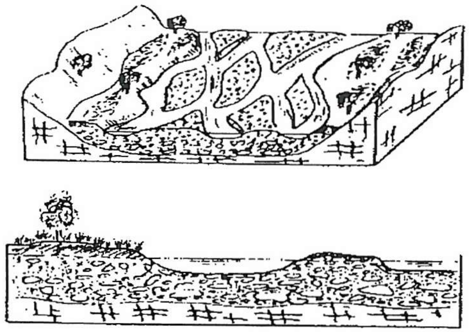


Confined coarse-textured floodplain
stream power = >1000Wm^{-2}

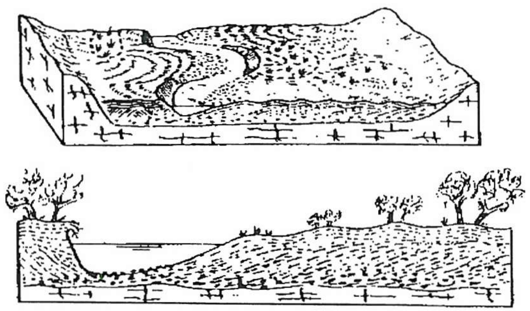
Confined vertical accretion sandy floodplain.
Stream power =300 - 1000Wm^{-2}

Cut and fill floodplain
Stream power = ~300Wm^{-2}

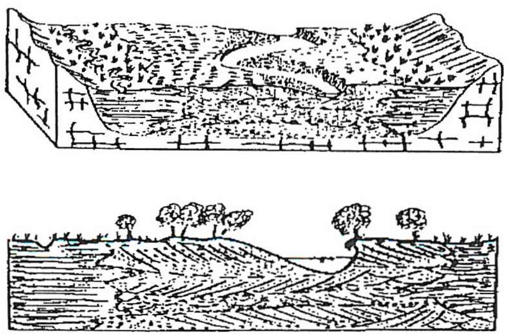
Figure 2.7a High energy, non – cohesive floodplains (Nanson and Croke, 1992)



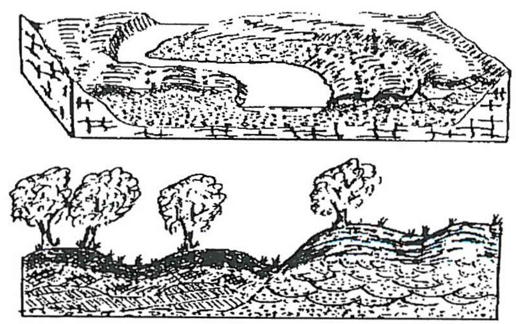
Braided river floodplain
Stream power = 50-300Wm^{-2}



Lateral migration scrolled floodplain
Stream power = 10-60Wm^{-2}

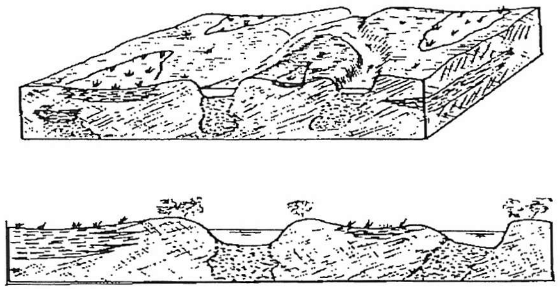


Lateral migration/ backswamp floodplain
Stream power = 10-<<60Wm^{-2}

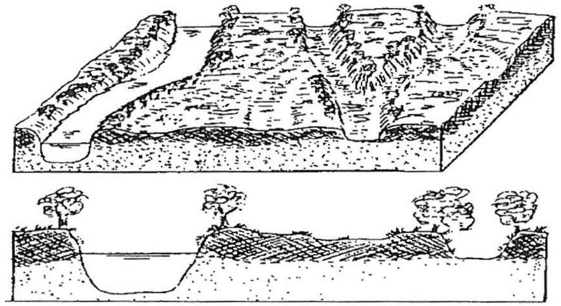


Lateral migration, counterpoint floodplain
Stream power = 10-<<60Wm^{-2}

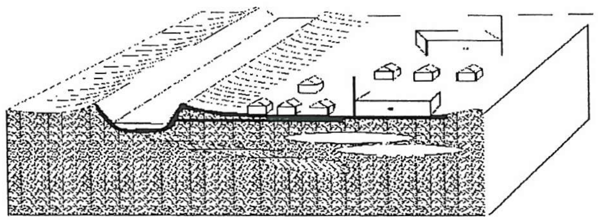
Figure 2.7b Medium energy, non-cohesive floodplains (Nanson and Croke, 1992)



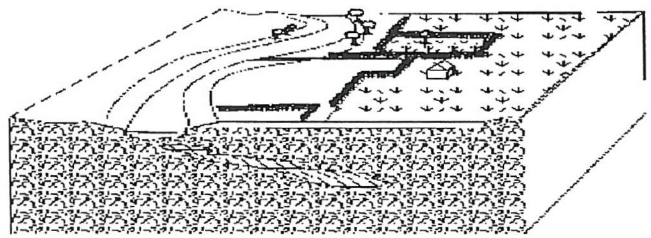
Anastomosing river, organic rich floodplain
Stream power = $<10wm^{-2}$



Anastomosing river, inorganic floodplain
Stream power = $<10wm^{-2}$



Modified river, disconnected
industrial and urban floodplain
Stream power = $<10wm^{-2}$



Modified river, disconnected
agricultural floodplain
Stream power = $<10wm^{-2}$

Figure. 2.7c Low-energy, cohesive and disconnected floodplains (modified from Nanson and Croke, 1992)

2.2.3 Hydrology

The pathways of water through a floodplain have been conceptualized by Burt (1997) and Mertes (1997), and are summarised in Figure 2.8. At the basin scale the floodplain acts as the buffer between hillslope processes and the fluvial processes (Burt and Haycock, 1996; Burt, 1997; Gurnell, 1997). Floodplain hydrology is, therefore, a function of the connectivity between hillslopes, groundwater and hydrogeomorphological processes.

Along with overbank flooding and groundwater, hillslopes are one of the major sources of water to the floodplain. Precipitation on surrounding hillslopes works its way to the channel or groundwater either via saturated (groundwater) flow or unsaturated (percolation) flow and this movement varies according to regolith, surface drift and vegetation cover (Gurnell, 1997). Hillslope hydrology also determines convergence of flow pathways, such as saturated areas at the base of slopes, which can determine where ephemeral tributaries occur and, hence, how different water bodies mix (Mertes, 1997).

Sub-reach (10^{-1}-10^{2}m) floodplain hydrology is a function of:

(i) the local hydraulic conductivity of the alluvial architecture (Gurnell, 1997; Richards et al., 1996; Wondzell and Swanson, 1999),

(ii) the effects of vegetation (Tabacchi et al., 2000):

(a) biotic runoff control (hydraulic impact of biota both upon the passage of water across the floodplain and channel), about which relatively little is known;

(b) physiological impacts of biota (takeup for metabolic functions and loss to atmosphere; Franz and Bazzaz (1977));

(c) water quality change via biotic processes.

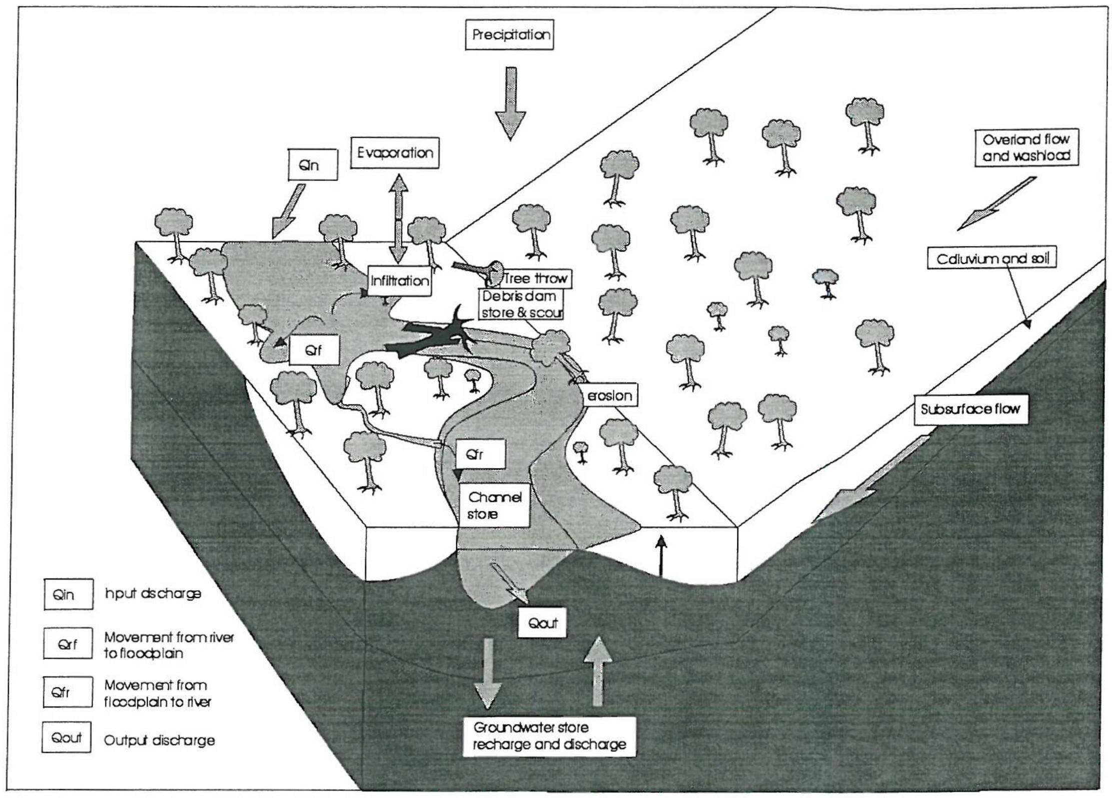


Figure 2.8 Reach scale hydrological pathways through a floodplain (modified from Mertes, 1997)

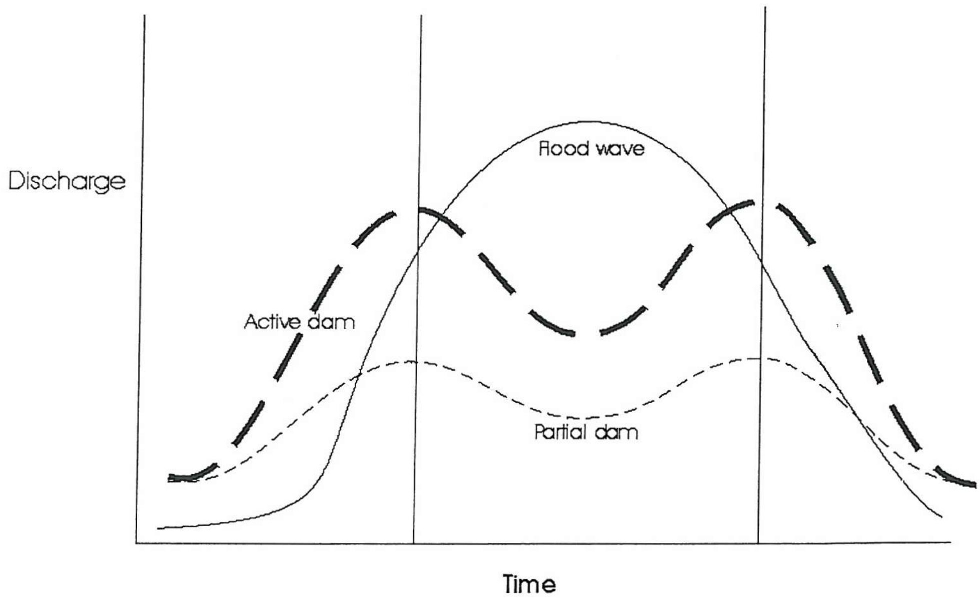


Figure 2.9 The reach-scale influences of different types of debris dams on the passage of a flood wave. Based on Gregory et al. (1985)

The main hydrologic effects of vegetation on overbank flow are described by Tabacchi et al. (2000); and illustrated in Fig. 2.10. Vegetation has a range of effects on floodplain hydraulics (for a more detailed discussion please see the next section). Organic material of any kind in the river channel tends to attenuate flood waves (e.g. Gregory et al., 1985; Fig. 2.9) and will frequently pond water upstream of debris accumulations (e.g. Keller and MacDonald, 1995; Piégay and Gurnell, 1997). Organic debris creates a hydraulic step that increases the local height of the water table, which significantly affects floodplain flow pathways (Gurnell and Gregory, 1995; Wondzell and Swanson, 1999). The effects of dams tend to decrease with increasing discharge (Figure 2.9, Gregory et al., 1985; Gippel, 1995; Keller and MacDonald, 1995). In high-energy or other active fluvial systems, where the connection between the channel and the floodplain is rapidly and frequently modified, hydrology will also rapidly alter (e.g. Wondzell and Swanson, 1999).

Floodplain hydrology varies at the catchment-scale and can be understood through models of gradients of energy, sediment and connectivity from upstream to downstream (e.g. Schumm 1977, Vannote et al., 1980, Burt 1997, and Marriot and Alexander 1999; see also Ward et al., 2001). Many of these are ecological and therefore conceptualise pathways of water and sediment that occur whether or not there is a definable floodplain.

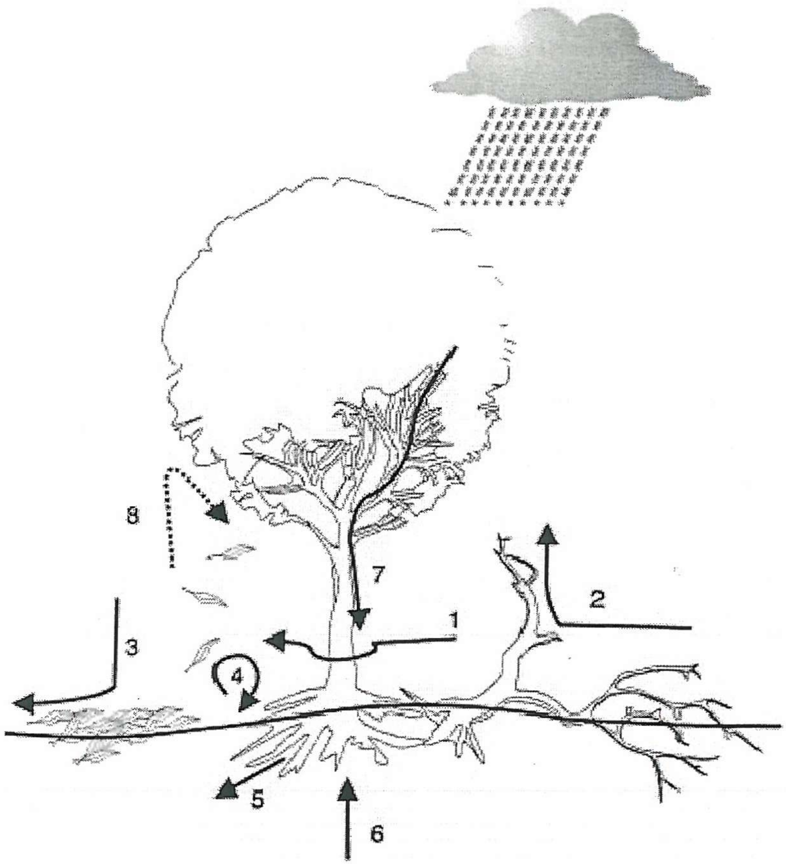


Figure 2.10 The impacts of vegetation on overbank flow (from Tabacchi et al., 2000). 1- form resistance provided by units of organic material; 2 – flow diversion by debris jams; 3 – sheltering of floodplain surface by litter to reduce inputs; 4 – increase of turbulence where roots are exposed; 5 – increase of substrate porosity around roots; 6 – increase of the capillary fringe by fine roots; 7 – stemflow; 8 – condensation of atmospheric water by leaves

2.2.4 Types of accretion on forested floodplains

The floodplains of the small, forested, lowland streams, which are the subject of this thesis, have not previously been investigated. Forest floodplain accretion usually falls into the 'other' category of Wolman and Leopold (1957). However, distinct forms of floodplain accretion exist according to physiographic setting. Three broad classes of forest floodplains can be envisaged within a longitudinal gradient of energy, sediment and biotic effects (Fig. 2.11): (i) small, steep headwater channels; (ii) large, high-energy piedmont channels; (iii) large, lowland channels with cohesive bank; finally, to contextualize this study, (iv) small, lowland channels with cohesive banks. Paralleling the downstream decrease in energy is a reduction in scientific understanding. Much research into fluvial geomorphology and mass-movement processes has been undertaken in small, steep, high-energy channels, and recent publications have enormously increased our understanding of piedmont systems, but lowland forested channels are less well researched and are poorly understood.

Upland channels are heavily dominated by gradient, with a combination of debris torrents, mass-movements of hillslopes and dam bursts creating extremely dynamic and heterogeneous environments (Heede, 1981; Hogan, 1987; Nakamura et al., 2000; Nakamura and Swanson, 1993). Vegetation is largely a dependent variable in such environments, and although trees are moved *en masse* by such processes, they affect geomorphology by stabilising hillslopes and providing temporary stability for debris dams (storing sediment).

Since 1990 there has been an enormous increase in research about high-energy forested piedmont rivers. Many investigations focus on the highly dynamic floodplains of sub-alpine rivers (e.g. Piégay and Salvador, 1996; Piégay and Marston 1998; Piégay et al., 1998; Gurnell et al., 2001; Ward et al., 2001). Undisturbed systems of this type are characterised by highly dynamic braids of vegetated islands. These currently exist on the Ain (Piégay et al., 1998), the Fiume Tagliamento, Italy (Gurnell et al., 2001; Ward et al., 2001), and used to occur in rivers such as the the Drac, the Garonne and the Isère (Hughes et al., 2001) but gravel extraction and hydroelectric abstraction have reduced lateral movement and floodplain activity. Similar high-energy systems occur in the Pacific Northwest on the Hoh River (e.g. Fonda 1974; Heller et al., 2001) and the Queets river (Fetherston et al., 1995; Abbe and Montgomery 1996) in NW Washington, and on the Squamish river, British Columbia (Brierly and Hickin, 1992; Hickin, 1984).

Forest floodplains of large, moderate to low gradient, low-energy rivers have been less frequently studied but enormous regional differences exist that appear to be associated with sediment type. For example, in the southwestern Great Plains area of the USA, sand-bed rivers have been subject to catastrophic floodplain stripping during high-magnitude events (e.g. Friedman et al., 1996; Friedman et al., 1998). Similar stripping was observed by Burkam (1972) on the Gila River, Arizona. During these events the floodplain was entirely removed, but over a period of 30-50 years, sedimentation and biotic factors have created a new forest floodplain. This type of floodplain, however, is heavily influenced by generally dry continental conditions with occasional high-intensity convective rainfall.

Of more relevance to this study, and relevant to an an extremely broad geographical area, are low-gradient forest floodplains in temperate areas with cohesive banks. Despite an extensive literature search, and although there are several papers about the biota of lowland forest floodplains, there are virtually no papers about the geomorphology of such areas. Brown (1997b; 1998) has studied the Gearagh (Ireland), an anastomosing river with cohesive banks in some detail. Yet there is just one study focused on the geomorphic implications of biotic and abiotic interactions in low-energy, gravel-bed rivers: McKenney et al. (1995). Vegetation within rivers on the Ozark Plateaux in Missouri and Arkansas is controlled at the catchment scale by drainage basin characteristics, and at the reach scale by channel pattern and fluvial energy (McKenney et al., 1995), but within discrete reaches propagules promote sedimentation on and stabilisation of mid-channel islands, and the study concluded that, 'many... roles of vegetation, including the effect of root strength on sediment stabilization, scour and flow damming, have not been adequately addressed for low-gradients streams,' p. 197.

While fluvial energy decreases downstream, therefore, vegetation progressively becomes more important in controlling fluvial processes. Biota can have a powerful effect on sedimentation (Hupp, 1992), on river bank stabilisation (Hupp, 1992; 1999), and on channel hydraulics (Darby, 1999; Darby et al., 1997; Gippel, 1995), but until now there has been no integration of research into a conceptual model of forest floodplains that can be applied across a broad spatial area. This represents a significant research gap: lowland rivers with cohesive banks occur widely in the UK, in Europe, in North America, and about their natural state there is virtually no scientific understanding.

Ward et al. (2001) suggested adopting a method for analysing such areas based on landscape ecology, an approach that can provide very useful conceptual linkages between spatially and temporally dynamic variables. This suggestion was proposed with a view to increase ecological understanding by examining how biotic variables are driven by abiotic factors. In return, geomorphologists are beginning to examine the effect of biotic elements on abiotic processes, but their aims are contrastingly geomorphological. We are lacking a conceptual model that succinctly combines these two areas. Clearly, the most efficient way to understand the interaction of biotic and abiotic variables is to consider them all, and this can be done within a conceptual model. Whilst recognizing that Fig. 2.11 does not fully address the problem, it goes some way to completing the geomorphic half of the bridge by considering a fairly generic and wide range of temperate environments influenced by vegetation. It accepts that vegetation both results from and controls geomorphic processes according to system characteristics, a similar approach to Gurnell et al. (2001) but within a much broader model. These issues are discussed further in chapter 5.

The hydraulic interaction between water and debris is extremely complex and no complete conceptual model currently exists. The modification of secondary flow by woody debris within a local area is highly variable, with flow acceleration in some areas and deceleration elsewhere (Newell, pers. comm. 2001). Some researchers have documented that debris dams significantly alter channel hydraulics (e.g. Gregory et al., 1985; Gippel, 1995). Dams also store sediment: Marston (1982) described that, when the stores of sediment provided by log dams are replete, sediment transmission occurs over the step. As the dams age and they begin to break down, sediment is released (Heede, 1981; Hogan et al., 1995). In some systems vegetative succession stabilizes floodplain islands, but the dynamism that transports sediments and creates these features also prevents their long-term stability, and they rarely store sediment for more than a century (Fetherston et al., 1995; McKenney et al., 1995; Abbe and Montgomery, 1996; Gurnell et al., 2001).

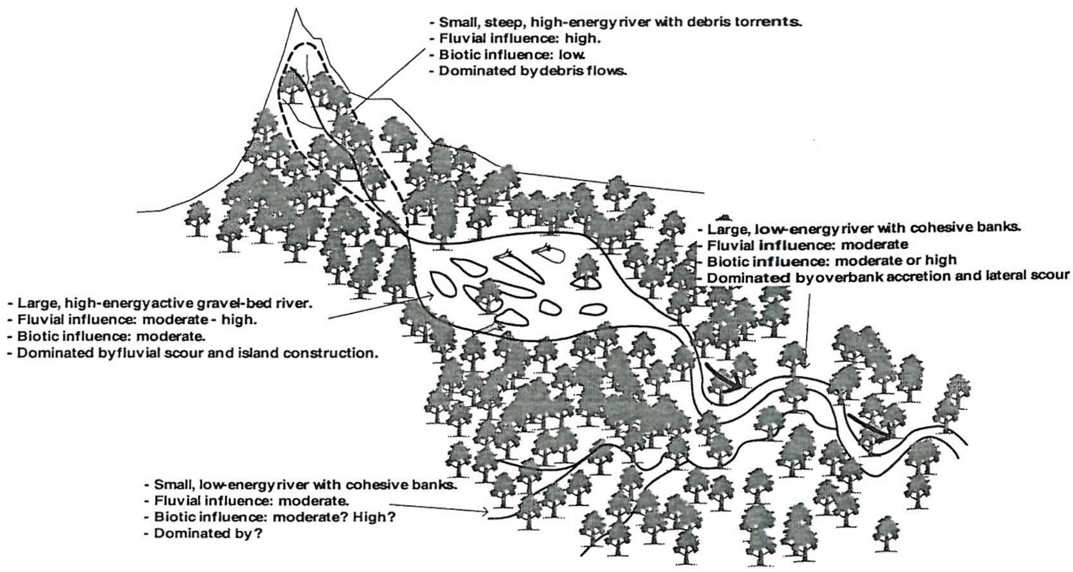


Figure 2.11 Four broad classes of temperate forest floodplains

Floodplain biota and overbank hydraulics

The first generic conceptual model of how biota affect hydrology and hydraulics was proposed by Tabacchi et al. (2000).Woody debris appears to have a variety of largely unquantified effects on overbank sediment deposition. Large masses of woody debris channelize flow between trees and other vegetation, so that ephemeral channels form; and these incise into the bank and floodplain surface (McKenney et al., 1995; Piégay, 1997; Piégay et al., 1998). Mobile debris jammed between the bases of trees and other vegetation increases roughness, reduces flow depths and shelters areas, thus promoting sedimentation. Piégay (1997) found that woody debris jams in the base of trees lowered the depth of overbank flow by 65 cm over a distance of 30 m. Log jams on the Muskawa and Squamish rivers, Canada, also divert overbank flow and prevent meander cutoffs (Hickin 1984).

Vegetation fundamentally controls floodplain roughness, which, assuming reach-scale slope to be constant, is the key control over water velocity (and, therefore, sediment transport and deposition). Roughness is defined by K. Richards (1990) as 'a composite term embracing all the frictional or retarding influences causing energy loss in fluid motion,' and is a composite variable that represents at least five types of resistance (Abrahams and Li, 1998), many of which are directly affected by forest biota (Table 2.5).

Numerical models provide insight into some of these effects. Two dimensional models have been employed by Fischer-Antze et al. (2001), who used momentum conservation equations to simulate the effects of flow around vegetation units that were represented as rigid cylindrical units. Vegetation changes the velocity distribution from a logarithmic to linear gradient up to the height of the top of the vegetation, with a return to a logarithmic profile above this point (Fischer-Antze et al., 2001), and flexible and inflexible grassy vegetation can increase water height of a given flood (e.g. Darby et al., 1997; Darby 1999).

Table 2.6 Types of resistance to fluid flow and the theoretical effects of forest vegetation, modified from Richards (1982; 1990); Abrahams and Parsons (1994); Abrahams and Li (1998); Kouwen, 1998; and Tabacchi et al., 2000

Type of resistance	Description	Importance on a forest floodplain
Grain resistance (grain roughness)	Resistance imparted by soil and microaggregates (results from shear and pressure forces acting on those grains)	Medium to high, depending on substrate
Form roughness		
a) from obstructions	The displacement of fluid forces by obstructions. Results in pressure differences between the upflow and downflow sides	Very high: roots, debris, deposited sediment, large clasts, trees and other vegetation all fulfill this function. Also depends on vegetation height and associated stiffness coefficient.
b) from channel morphology	The entire displacement of fluid flow (for example around a curve)	Medium to high: this depends on stage. At lower overbank inundation this would be of most importance
Wave resistance		
a) Free surface disturbances	Energy dissipated in maintaining an uneven water surface; energy lost through protrusions of obstacles into the flow	Medium to high as overbank flow tends to be shallow and turbulent. As stage increases this form of resistance probably also increases
b) Spill resistance	Abruptly diverging streamlines (e.g. in the lee of a tree) give a sudden reduction in velocity	High, particularly associated with trees and other relatively large, sessile objects
Rain resistance	Velocity retardation of the main flow as energy is transferred to an injected droplet to accelerate it to flow velocity	Probably low; forest canopies protect some areas entirely although stemflow may provide an input
Transport resistance	Acceleration of grains to flow velocity results in energy loss	Depends on available sediment load. Medium.

2.2.5 Floodplain evolution

The longest time over which floodplain evolution can be examined depends on the length of the available record, which in previously glaciated areas often coincides with the end of the last ice age. Studies of this sedimentary record allow the reconstruction of palaeoenvironments, often to determine palaeodischarge (Schumm, 1974; Brizga and Finlayson, 1990). An underlying assumption of such reconstruction is that the processes involved are deterministic, and that a particular sedimentary architecture results from a characteristic set of processes and sedimentation events, which in turn rely on a stable system. This is not necessarily the case because where internal system thresholds are crossed, a shift may occur from one state to another without climate change (cf. Brizga and Finlayson, 1990). Therefore, using contemporary studies to infer palaeodischarge from gradient, sinuosity and meander wavelength cannot be justified unless there is additional and independent supporting evidence (such as pollen records) of any environmental changes (Brown, 1994). Palaeoenvironmental reconstruction can also enhance understanding of rare or extinct geomorphology. For example, Brown et al. (1994) found that the floodplain of the River Soar used to be an anastomosing, multiple channel system because dense tree growth (*Alnus sp.*) inhibited lateral channel migration. There are few contemporary analogues for this vegetation-controlled low gradient meandering system (though see Harwood and Brown, 1994).

Several researchers have attempted to model long-term floodplain evolution at different spatial scales. Howard (1992; 1996) has modelled the long-term evolution of floodplain plan forms using relatively simple rules of lateral and vertical accretion, including versions of the James (1985) and Pizzuto (1987) models. An underlying principle of his sub-model of overbank deposition is that floodplain deposition rates decrease as the surface elevation increases over time (Wolman and Leopold, 1957; Nanson, 1980 – Cited in Howard, 1992), but this may not occur (see above).

Engineering and scientific investigations have led to the development of stratigraphic floodplain evolution models (Mackey and Bridge, 1995). Some of these models simulate two dimensions of stratigraphy, (e.g. Allen, 1979; Bridge and Leeder, 1979) and some three dimensional stratigraphy (e.g. Mackey and Bridge, 1995) between periods of 10^3 and 10^5 years. They have variously been used to evaluate the locations and interconnectedness of sandstone bodies deposited in the floodplain, to investigate the effects of changes in forcing factors, and to evaluate which control is dominant (Marriot, 1996).

Recent advances in computing have begun to allow the development of landscape evolution models in which the floodplain plays an important role, and within these vegetation tends to stabilize the landscape (Tucker and Slingerland, 1997; Vandenberghe, 1995). The evolutionary history of floodplains can be highly variable, and the same regional climate can make parts of the same system behave differently, resulting in floodplains in adjacent basins having significantly different sedimentary sequences (Brakenridge, 1980; Brown et al., 1996). Once disturbed, the time a floodplain takes to reach stability can be of the order of hundreds of years, so when rapid climatic shifts occur, such as at the end of the last glacial (Brown et al., 1994), a lag may occur in floodplain response. In addition, floodplains may respond in a non-linear way to changes in climate over millenial timescales (Brakenridge, 1980; Tucker and Slingerland, 1997), which implies that internal thresholds exist for which the conceptual models of floodplain evolution described above take no account.

One model of Holocene floodplain evolution that may be applicable to central England was proposed by Brown et al. (1994). The deepest basal sediments on the River Soar (Leicestershire) were coarse gravels laid down during the last glacial but, for the River Nene, the same basal sediments were several thousand years younger. This variation was attributed to local geomorphological controls, causing the two rivers to respond uniquely to the same forcing. During the late glacial (18,000 to 10,000 B.P.), gravels were reworked and overlaid by laterally active braiding channels, but these braiding systems became less active, channels became abandoned and subsequently filled in. From 10,000 to 6,000 B.P., the floodplains became more fine-grained and more heavily vegetated, which led to consolidation of the meandering channels. This increased their resistance to sudden, short inundation. Since 5200 B.P.

there was an increase in fine sediment input (a result of disturbance following agricultural and clearing activities on surrounding hillslopes) and a mantle of fine sediment was deposited overbank, and since around 2000 B.P. there has been little or no channel change. The balance between the modes of accretion therefore determines the floodplain sedimentology and geomorphology. However, it is clear that when climate changes occurs in association with less vegetation (as happened immediately after the end of the last ice age) channels can rapidly shift from one distinct type to another, sometimes non-linearly (Tucker and Slingerland, 1997). Thus, although climate or landuse changes drive floodplain evolution, system shifts can also occur by the crossing of internal thresholds; but no previous research has investigated how this response is likely to be tempered by dense forest vegetation.

2.3 Floodplain biodiversity and management issues

2.3.1 Ecological aspects of floodplain forests

Investigations into biotic-abiotic interactions were once neglected (Zimmerman and Thom, 1982), but within the last decade many new papers have been published on the subject (Fig. 2.12). Research has proceeded from two directions: from geomorphology, and from ecology, although neither has yet synthesised a coherent

A great deal of research focuses on how wood affects fluvial processes (Gregory 2000), particularly on how LWD influences channel morphology. Three themes of woody debris research are identified by Gregory, (2000):

(a) Function

(i) geomorphological processes; (e.g. Bilby and Likens, 1980; Fetherston et al., 1995; Hogan, 1986 and 1987; Hogan et al., 1995; Hupp, 1999; Hupp and Osterkamp, 1985 and 1996; Keller and Swanson, 1979; Piégay and Gurnell, 1997; Piégay et al., 1997;

Wallerstein and Thorne, 1996; Zimmerman et al., 1967);

(ii) extent and significance of debris (e.g. Gippel, 1995; Gregory et al., 1993; Gurnell et al., 2000; Marston et al., 1995; Montgomery et al., 1994; Piégay and Salvador, 1996; Shields and Gippel, 1996);

(b) Temporal and spatial change: debris budgets; debris dynamics (e.g. Gregory et al., 1993; Gurnell and Sweet, 1998; Piégay and Gurnell, 1997); and

(c) Management (e.g. Gregory, 1992; Gregory and Davis, 1992; Gregory et al., 1993 and 1994b).

More recently, a new approach to conceptualising stream ecology has been advocated (Ward et al., 2001), but this concentrates on the hydrological links between the channel and floodplain and their importance for habitat and species diversity. Although geomorphic processes fundamentally control most new floodplain habitats (e.g. McKenney et al., 1995; Gurnell et al., 2001; cf. Bendix and Hupp 2000), no conceptual model exists that integrates established floodplain concepts (e.g. Wolman and Leopold 1957) with forests and ecology.

An environmental gradient exists on floodplains between areas of high energy and disturbance and low energy and stability (Brown, 1997; Brown et al., 1997; Gurnell, 1997; Ward et al., 1999; Bendix and Hupp, 2000; Tockner et al., 2000). There is a division between (i) high energy areas and 'r' selected species (having high fecundity, rapid lifecycle, and able to colonise new sediment); and (ii) lower energy areas which contain more 'k' selected species (having a lower fecundity but living longer and preferring already vegetated surfaces) (Brown et al., 1997). The decrease in energy away from the channel and to the floodplain defines a hydraulic gradient that can vary both laterally and longitudinally. A second and equally if not more important variable than disturbance is a resources gradient from scarce to abundant (Ward et al., 1999) and this is in part associated with sediment type and regime of disturbance

(Bayley, 1995). Hupp and Osterkamp (1996) state that the dominant controls on vegetation distribution are (i) species tolerance to geomorphic disturbance and, in an opposing direction, (ii) species competition, which implies that species competition is low where geomorphic process is high and vice versa. Although this pattern occurs within small space and time scales, larger areas are both geomorphologically active and species rich (cf. Power et al., 1995; Bendix, 1998; Gurnell et al., 2001). The intermediate disturbance hypothesis (Petraitis et al., 1989; Bendix and Hupp, 2000) suggests that species diversity will be highest where disturbance is neither extreme nor lacking. However, as Petraitis et al. (1989) demonstrated, population dynamics are only stable under certain (fairly narrow) conditions; Bendix and Hupp (2000) heavily underline that high biodiversity does not always result from deterministic processes; and explain how patterns of vegetation can be equifinal.

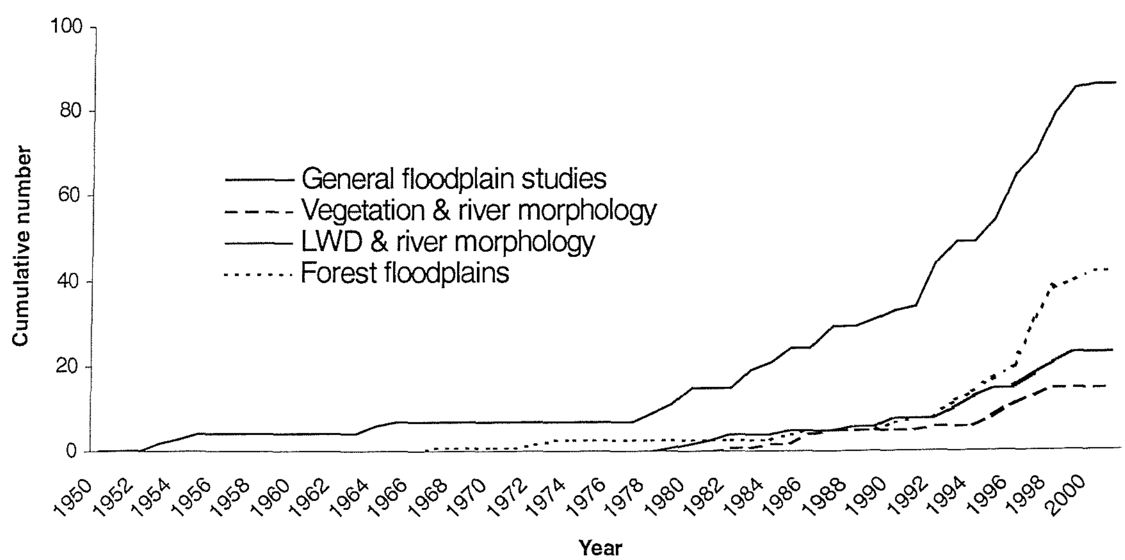


Figure 2.12 General floodplain research has been established since 1952, but investigations focused on biotic-abiotic interactions, beginning around 1980, are relatively recent

Vegetation grows where conditions are most suitable and different biota will therefore characterise different areas. Three main factors influence the environmental characteristics of floodplain habitats: (i) substrate type (defined by fluvial processes); (ii) hydrology (wetness, defined by several variables); and (iii) disturbance (Bendix, 1998; Hupp and Osterkamp 1996; Hughes, 1997; Bendix and Hupp 2000; Hughes et al., 2000; Deiller et al., 2001). Colonisation of any area also depends on propagule transport, which partly depends on species reproduction (fecundity, type of seed dispersal), and partly on mechanisms of movement (water, wind, fauna, rhizome development). The key to whether vegetation establishes, prospers and modifies the local environment, therefore, is whether conditions at a given site are suitable for long enough for the plant to reproduce (Bendix and Hupp, 2000).

High-energy areas are often subject to frequent disturbance (Schnitzler, 1994; Fetherstone et al., 1995; Brown et al., 1997; Gurnell, 1997; Lane and Richards, 1997; Gurnell et al., 2001) and are characterised by coarse-grained sediment, which, due to its lower surface area: volume ratio, contains fewer nutrients than more fine grained sediment, thereby making these areas more difficult to colonise. Therefore "r" selected species such as *Salix sp*. will be successful in these environments due to their inherent ability to be successful on temporary, bare sediments of varying quality (Brown et al., 1997). On the other hand, low energy, fine-grained environments, which tend to be subject to less frequent or less dynamic disturbance, contain more fine grained sediment such as silt, clay and organic matter, have a higher surface: volume ratio for particle adsorption and are generally more fertile. Thus they are more suited to "k" selected species, which, although more slow growing, tend to survive for longer, thereby outlasting their "r" selected counterparts and dominating the patch. In low-energy cohesive systems, therefore, vegetation may begin to dominate over geomorphic variables.

Areas left undisturbed will undergo seral succession, where the invasive plants ("r" selected species) give way to "k" selected species of increasing size, longevity and adaptation. With each cycle of growth and dieback, the substrate will be modified, with inputs of organic matter creating more friable and fertile soil. In temperate forested systems the succession will locally vary according to environmental conditions and species assemblage, but is likely to vary from an initial cover of grass or other ruderal species through shrubs and soft woods to hard wood species. Schnitzler (1994), Marston et al., (1995), Pautou et al., (1997), Piégay (1997), Piégay and Salvador (1997), Piégay et al., (1998), and Hughes et al., (2001) all noted that forests along the French Rhone, Ain and Ubaye rivers have undergone such succession since the 1950s. The Rhone has been regulated since that time and the successional forest cycles which depended upon periodic flood disturbance have since been lost (Deiller et al., 2001). Rural-urban population shift since WWII on the Ain and Ubaye has left forests effectively unmanaged and vegetative succession has occurred (Marston et al., 1995; Piégay and Salvador, 1997; Piégay et al., 1998).

Environmental gradients of disturbance and process vary systematically through the catchment, whether in high-energy systems (Marston et al., 1995; Brown et al., 1997; Gurnell, 1997; Gurnell et al., 2001), or relatively low-energy rivers (McKenney et al., 1995). Ward et al. (2001) identify many concepts of stream ecology that describe longitudinal gradients.

However, lateral and longitudinal gradients at the catchment-scale are modified by intrinsic local variables, which are either geomorphical (for example, valley slope, type and supply of sediment) or ecological (for example, type of vegetation, input of dead wood). Extremely sharp energy gradients exist where vegetation, debris or topography divide zones of high and low activity (Schnitzler, 1994; Piégay, 1997; Piégay et al., 1998). High energy areas are not restricted to the main river channel because ephemeral channels can exist on the floodplain which have the same effect (Piégay et al., 1998). Lowland (bottomland) rivers in North America vary according to local reach characteristics, for example where there is influence from local bedrock obstructions, and this affects the availability of suitable germination surfaces for tree seedling establishment (McKenney et al., 1995; Scott et al., 1996). Alluvial Oak and Elm *(Querco and Ulmus sp.)* forests on the upper Rhine which are subject to a high disturbance regime have substantial growth of large trees distant from the channel with faster growing softwood species closer to the high energy channel (Schnitzler, 1994). Patterns of vegetation therefore control and buffer inputs of fluvial energy. Indeed, overbank flows may well be confined to where there are fewest immobile vegetation units such as trees (Piégay et al., 1998).

Spatial gradients are modified by the temporal variability of processes and vegetation across sub yearly to millennial timescales (Hughes, 1997: Ward et al., 1999; Fig. 2.13). Ward et al. (1999) advocates using habitat turnover time (from geomorphic processes) to structure studies of biodiversity. Bendix (1998) echoes this view, stating that individual floods decrease immediate biodiversity but when considered over periods of more than five years an increase is observed. Several authors have correlated the height of the floodplain, consequent duration and depth of inundation, to vegetation type (Bren, 1988, cited in Gurnell, 1997; Marston et al., 1995; Scott et al., 1996; Hupp and Osterkamp, 1996; Hughes, 1997). Ecological timescales of interest are therefore heavily influenced by geomorphic process. Spatiotemporal hierarchies of floodplain process and vegetation (Hughes, 1997; Ward et al., 1999; Fig. 2.13) therefore oppose Schumm and Lichty's (1965) concept of vegetation as an independent variable over timescales of less than 10 years.

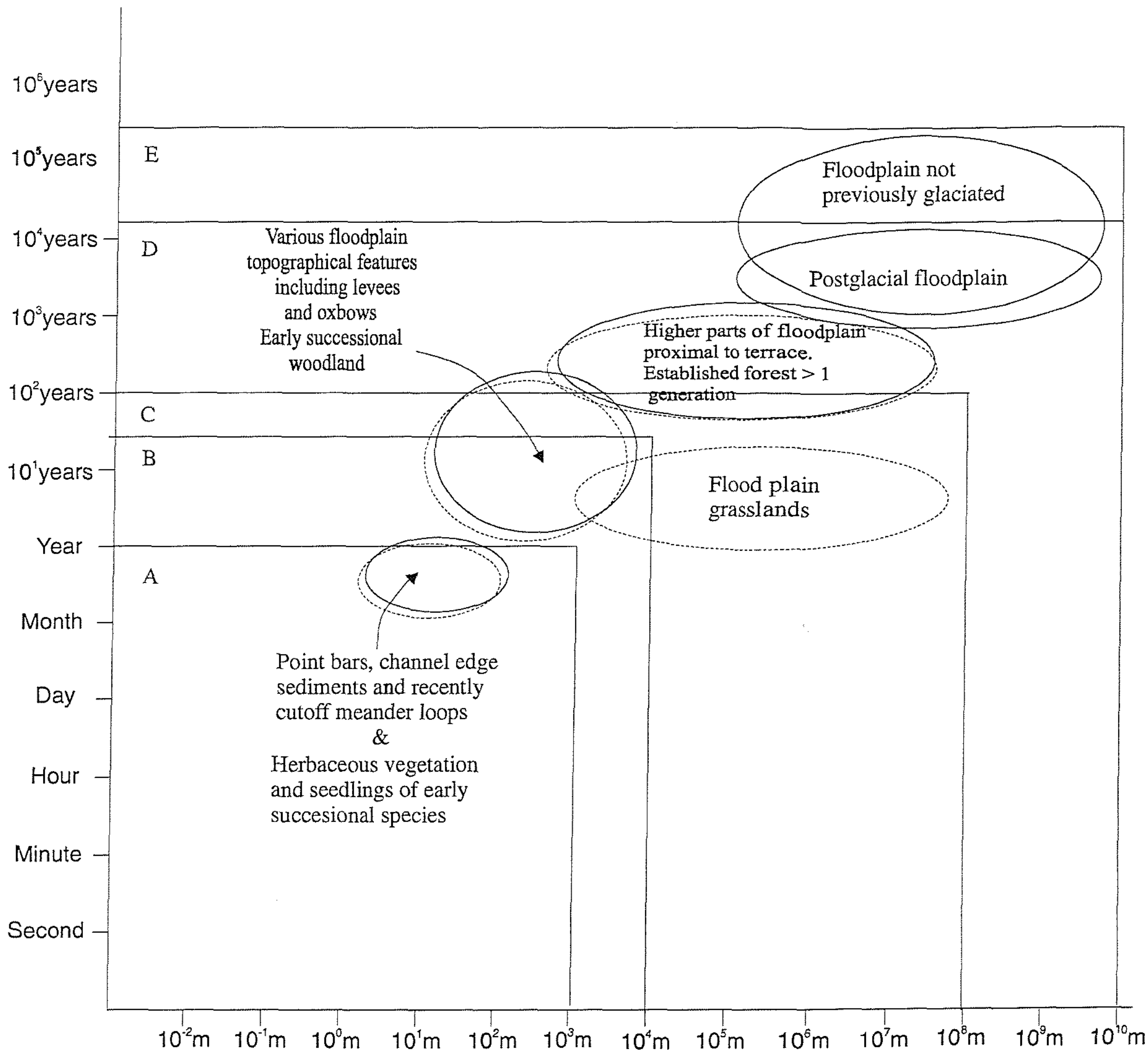


Figure 2.13 The organisation of floodplain components and processes as a spatiotemporal hierarchy (From Hughes, 1997)

The interaction of flooding and floodplain vegetation

I Environmental conditions and seedling establishment

Optimum environmental conditions for vegetation establishment vary according to species, but the probability of germination is typically highest on bare (i.e. recently formed), moist and fertile substrate which is protected from flooding until reproductive age is reached (Hupp and Osterkamp, 1985; 1996; Scott et al., 1996; Bendix and Hupp

2000; Hughes et al., 2000; Hughes et al., 2001). Germination requires water, but most seeds are adversely affected if inundated for more than around 30 days (Toumey and Durland, 1923), though some seeds remain viable after submersion of more than 30 months (Kozlowski 1982). The formation of suitable areas therefore depends not only on substrate quality but also on the previously discussed spatial and temporal characteristics of geomorphic processes. There can even be differences of habitat preference within the same species: Hughes et al., (2000) found that within black poplar, (*Populus nigra* L. subspecies *betulifolia* (Pursh) W. Wettst.) seedlings, females preferred wetter and more nutrient-rich areas than males.

II The morphological and physiological responses of vegetation to flooding

Kozlowski (1982) reviewed the importance of flooding on tree growth. In essence, flooding tends to decrease tree growth by causing stomata to close and photosynthesis to decrease, roots to be less permeable and soil mineralogy to change adversely. Waterlogging causes chemical changes in the soil, and toxic compounds are generated from various sources: from the roots themselves (Ponnamperuma, 1972); from the chemical action of the water on the soils; and as a by product of microbial action, particularly under redox conditions (Kozlowski, 1982). The response of trees to flooding varies between species, and some are able to cope with high levels of anaerobic respiration in water logged areas. Metabolical changes defend against changes in soil chemistry, and physiological changes, such as the growth of adventitious roots, allow trees to cope with higher water levels.

Timing of flooding is critical to plant survival. When inundation occurs, stomatal apertures close (Regehr et al., 1975: cited in Kozlowski, 1982), which prevents CO_2 uptake, making long periods of inundation difficult to endure during the growing season, although the same trees may be able to survive for longer periods if they are dormant. Nutrient uptake is decreased during flooding, and some nutrients such as nitrogen are actively leached out of the soil (Kozlowski, 1982). Extremely prolonged flooding leads to root rot where species of fungus tolerant of low oxygen conditions (such as Phytopthora) thrive. This leads to certain physiological changes, such as when roots grow vertically down during the summer but die when water tables rise during the winter, and this makes trees susceptible to wind throw (Sanderson and Armstrong, 1980: cited in Kozlowski, 1982; Harmon et al., 1986).

The age of the plant in question also determines the effect of the flood water. Established trees are likely to be much more able to survive flooding than seedlings (Kozlowski 1982), and of the established trees those most vigorous are likely to survive, with older specimens more susceptible to flooding. Different species are better adapted to survive flooding. Studies from the Pacific Northwest region of North America have shown that certain species of Alder such as red alder *(Alnus rubra)* can survive flooding better than others such as sitka alder *(A. viridis)* (Batzli and Dawson, 1997) because it extends adventitious roots that maintain its ability to fix nitrogen, even during prolonged inundation. Certain species, such as the black cottonwood, (a subspecies of the balsam poplar *(Populus balsamifera))*, however, may be yet better adapted to flooding dominated regimes, since it has been found to be more adaptable to flooding than Prairie cottonwood *(P. deltoides)* and narrowleaf cottonwood *(P. angustifolia)* (Kranjcec et al., 1998). Kozlowski (1982; pp. 149-150) lists species tolerant and intolerant of prolonged flooding.

The impact of flooding on soil chemistry and plant health is dependent in part on the flow of water across and through the floodplain (see section 2.3.1). Ponded water has a limited supply of nutrients and oxygen, and by virtue of its ponded state is likely to become detrimental to the soil and plants after only a short time: oxygen can be depleted in a few hours if water is stagnant (Kozlowski, 1982). Flowing water, on the other hand, contains a greater level of nutrients and oxygen, and may also be able to prevent the buildup of adverse compounds (Kozlowski, 1982; Burt, 1997). Experiments demonstrate that roots become less permeable to water uptake when surrounded by water containing CO_2, and this is reversed when oxygen is added (Chang and Loomis, 1945, cited in Kozlowski, 1982) Therefore, the most dangerous time for trees would be prolonged, ponded inundation during the growing season, and the least dangerous would be occasional inundation during dormancy. Concurrent with this, Richards et al., (1996) and Hughes et al., (1997) found that soils that were wet (i.e. saturated) for longer than seven consecutive days lead to lowest growth rates of *A. incana* seedlings, though growth inhibition also occurred if drought was experienced.

Trees respond to flooding with morphological and physiological changes such as formation of lenticels (loosely-packed masses of cells in the bark of a woody plant, visible on the surface of a stem as a raised powdery spot, through which gaseous exchange occurs), and the regeneration of roots as a response to death or rotting, including the formation of adventitious roots (large structurally and physiologically important roots protruding from one of the main roots) at an elevated level (Kozlowski, 1982). The formation of such roots has been linked to the opening of stomata and an associated increase in photosynthesis.

Metabolic reactions to flooding include transfer of oxygen from aerial portions of the tree to the submerged portion, with some species able to adapt such that they avoid anoxic conditions at the roots by accelerating ethanol production to use as anaerobic source of energy. Certain species are also able to survive elevated levels waste products from anaerobic respiration such as ethanol or lactic acid and these appear to be more successful at surviving flooding than others (Kozlowski, 1982).

Altering the flooding regime of a given system will almost certainly change the species assembly on the floodplain (Bendix and Hupp, 2000; Schnitzler, 1994). This may originally manifest itself through death of established trees and growth of "r" selected species, usually soft woods. Flooding regime may also vary across the floodplain in addition to being a function of upstream control: a new channel incising into the floodplain may lower the local water level and this environmental stress may alter the floristic composition of the area.

III Direct physical effects of flooding

Bendix (1998) notes that 'studies of the effects of floods on riparian vegetation… have pursued questions that were either time independent, stressing patterns of vegetation as quasi – equilibrium responses to the distribution of flood severity… or successional, stressing post flood seral stages….Relatively few studies have addressed the immediate impact of floods – namely, the degree and kind of difference in vegetation after a flood,' (Stromberg et al., 1993; cited in Bendix, 1998).

Large floods can destroy plants. Water either directly kills vegetation by breaking it, by burying it, or by scouring and uprooting it. (Gay et al., 1998; Piégay et al., 1998; Bendix and Hupp 2000). Floating woody debris may flatten or break shrubs or grasses; and in steep streams subject to debris flows, whole trees can be uprooted (Hogan 1987; Nakamura et al., 2000). The immediate impact of a flood, therefore, is to reduce species diversity, and over short timescales a flood can have a detrimental impact on floodplain biodiversity. The concept of increased biodiversity as a function of the effects of flooding (e.g. Salo et al., 1986) works only when one examines medium term (>5 <100 yr) timescales over which ecological processes operate (Bendix, 1998; Ward et al., 1999). Hughes (1997) observes that vegetation patterns can be predicted from a combination of variables including local elevation (topography), soils, sediment type and geomorphological landform and exposure to flood disturbance, which implies that the studies she cited observed vegetation patterns which were adjusted to the prevailing flood regime. Conversely, Bendix and Hupp (2000) caution that vegetation patterns are not deterministic (see section directly preceding this).

The spatial impact of a flood on vegetation can vary through the catchment but also within individual reaches (McKenney et al., 1995; Bendix, 1998). Although a flood with a recurrence interval of around ten years had a negligible impact in one area of Sespe Creek, California, its impact elsewhere was significant (Bendix, 1998).

IV Types of forested floodplain

Distinct types of floodplain vegetation units occur, depending on the area in question; these are outlined in Table 2.7. However, because river floodplains are 'among the most species rich environments known.' (Ward et al., 1999, p.125), mainly due to their dynamism (Gurnell, 1997; Hughes, 1997; Ward et al., 1999; Hupp, 1999), this table can only provide some of the dominant species. Though the actual existence of forested floodplains is somewhat scattered, there is a clear gradation from Alpine through continental to lowland units (Wenger et al., 1990; Brown et al., 1997).

Table 2.7 Types of vegetation assemblages on forested floodplains in Europe, adapted from Brown et al., (1997) and Schnitzler (1994)

	Description	Dominant species	Characteristics	Location	Source
(1)	Alnus rubra scrub	Alnus rubra, Stellaria nemorum, Alchemilla vulgaris, Crepis paludosa, Gallium mollugo, Geranium sylvaticum	Small streams, shallow soils, percolating groundwater	Subalpine / continental	Brown et al., 1997
(2)	Salix alba scrub	Salix viminalis, Cardamine amara, Rumex obtusifolius, Solanum dulcamara, Urtica diorica, Valariana officinalis, Anthricus sylvestris	Active channels, high rates of erosion and deposition with coarse sediment	Piedmont	Brown et al., 1997
(3)	Alnus incana woodland	Sambucus nigra, Prunus padus, Fraxinus excelsior, Picea abies, Rubus fruticosus, Aegopodium podagraria, Brachypodium sylvaticum, Cirseum oleateum	Intermediate energy rivers with coarse mineral soils, permanently high groundwater	Montane and continental	Brown et al., 1997

(3 a)	150 year old flood forest	(1) Fraxinus excelsior, Prunus padus; Populus alba	Fairly species rich, but disturbance dominated	Rhineau, south of Strasbourg	Schnitzler, 1994; Deiller et al., 2001
(3 b)	Forest unflooded for 30 years	(2) Cornus sanguinea, Prunus Padus, Corylus avellana	Very species rich because not all nutrients are used within 30 years	Marckolsheim to Lauterbourg	Schnitzler, 1994; Deiller et al., 2001
(3 c)	Forest unflooded for >150 years	(3) Fraxinus excelsior, Acer pseudoplatanus, Quercus Robur	Fewer species due to lack of nutrient input	Marckolsheim to Lauterbourg	Schnitzler, 1994; Deiller et al., 2001
(3 d)	Mesophilic terraces	(4) Lonicera xylosteum, Tilia cordata, Corylus avellana	Rarely flooded high and sandy terraces dominated by shrubs	Terraces on the margins of the Rhine	Schnitzler, 1994; Deiller et al., 2001
(3 e)	Ill – Rhine confluence	(5) Fraxinus excelsior, Acer pseudoplatanus, Corylus avellana	Subject to a more acidic, fine grained sedimentary composition	Small areas of the Ill – Rhine confluence	Schnitzler, 1994; Deiller et al., 2001
(4)	Alnus Glutinosa woodland	Salix sp., Populus nigra, Prunus padus, Sambucus nigra, Quercus robur, Filipendula ulmaria, Humulus lupus	Relatively stable channel, fine organic rich soils and peats	Maritime continental and lowland	Schnitzler, 1994
	NVC W4b Sallow carr	Betula pubescens – Molinia caerulea woodland with Juncus effusus or J. acutifloris sub - community	Channel stability and grazing pressure	New Forest Lowland	Peterken et al., 1996
	NVC W5b Alder carr	Alnus glutinosa – Carex paniculata woodland with Lysimachia vulgaris sub – community	Channel stability and grazing pressure	New Forest Lowland	Peterken et al., 1996
(5)	Fraxinetalia communities	Acer pseudoplatanus, Populus alba, P. canescens, P. tremula, Prunus avian, Quercus robur, Tilia platyphyllos, Ulmus laevis and U. minor	Channel stability, fine organic rich circum neutral soils, occasionally flooded	Continental and lowland	Brown et al., (1997)
(5 a)	NVC W7 Ash rich stands	Alnus glutinosa, Fraxinus excelsior, Lysimachia nemorum woodland with Urtica dioicia sub community (7a) or Carex remota sub community (7b)	Channel stability, fine organic rich circum neutral soils, occasionally flooded	Continental and lowland	Peterken et al., 1996
	Ain floodplain forest	Populus nigra, Salix alba, Alnus glutinosa, with an understory of Salix eleagnos, Crataegus monogyna	Structure of forests on meanders of the Ain river, France. Subject to protection from trash lines in lower areas of trees	Meanders of the Ain upstream of Lyon	Piégay and Marston (1998); Piégay et al., (1998);
	Pannonian hardwood forest	Fraxinus angustifolia	Hungarian forests dominated by F. angustifolia have been replaced by white poplar	Hungary, along the Danube, Drava and Raba rivers.	Weiger et al., 1990

2.3.2 Management

Contemporary management of forested floodplains is not well documented, probably because these areas are so rare. Historical management has been through clearance (Sterba et al., 1998) and, in limited areas, coppicing (Peterken et al., 1996). Recent work has focused on how restoration of forest floodplains would be undertaken (e.g. Tockner et al., 2000; Hughes et al., 2001; Ward et al., 2001).

The Forestry Commission which oversees much of the forest areas in the UK, notes the importance of Ancient and Semi- Natural woodlands, including the some of the remaining natural floodplain forests (Forestry Commission, 1993; Peterken et al., 1996). These are managed in accordance with the UK Forestry Standard (Forestry Commission, 1993) and the Forests and Water guidelines (Forestry Commission, 1993), to maintain and restore natural ecological diversity, aesthetic value, genetic integrity of populations of native species; and to provide a renewable resource (Forestry Commission, 1993). Plantations are managed according to the UK Forestry Standard (Forestry Commission, 1993) as a sustainable resource in compliance with the U.N. Conference on Environment and Development (in Rio de Janeiro, 1993). In relation to restoration, the creation of 'new native woodland' (using locally native tree and shrub species that are matched to the site) is now Forestry Commission policy, and follows similar guidelines to those for the Ancient and Semi-Natural woodlands. The riparian zone ('the land immediately adjoining the aquatic zone and immediately influenced by it,' where the aquatic zone is 'the ground frequently or permanently under water, forming streams, rivers, ponds and lakes' (Forestry Commission, 1993) includes damp forest floodplains. Its management 'must aim to protect and encourage the diversity of these rich habitats for the benefit of the whole forest'. Riparian vegetation applies 'to all features characteristic of riparian land, including headwater source areas, terraces, floodplains, swamps and carrs,' and should be managed so as to 'maintain open or partially wooded conditions such that bankside vegetation thrives, thereby minimising bank erosion and opening up the water to sunlight… Trees should not be planted on, or allowed to regenerate into, ecologically rich open ground habitat' (Forestry Commission, 1993).

2.3.3 Restoration

Restoration is defined as 'the complete structural and functional return to a pre-disturbance state'; rehabilitation, on the other hand, is 'the partial structural and functional return to a pre disturbance state' (Cairns, 1991), and enhancement is 'any improvement of a structural or functional attribute' (National Research Council, 1992; Brookes, 1996). For the sake of simplicity, restoration as used here simply implies some improvement to a lesser or greater extent, and with or without reference to a pre-disturbance condition, of a floodplain or river. The goals of restoration will vary between countries and organisations undertaking the task. Increasing biological diversity is likely to be the main aim of many projects. This can be sustainably assured only if the geomorphological and hydrological processes that generally drive the system are returned to functionality. Because processes vary dramatically between systems (see above; Bendix and Hupp, 2000), different restoration techniques will be required.

Restoration of floodplain forests could initially be quite difficult because they are still poorly understood. Regional and international diversity is very high. To ensure project success, therefore, local "benchmark" floodplains need to be identified (Ward et al., 2001). Even recognition of the full diversity of floodplain forests is no easy task: stream studies in Europe and in North America evolved studying modified rivers with 'cleared' floodplains (Ward et al., 2001). Many benchmark forest floodplains have been studied in steep environments (e.g. Nakamura et al., 2000), and several in piedmont continental environments (e.g. Gurnell et al., 2000; Gurnell et al., 2001; Ward et al., 2001) but very few in lowland, cohesive systems. A conceptual model that incorporates floodplains, forests and regional diversity would provide valuable generic guidance for restoration efforts.

For any restoration project, it is necessary to have a clear understanding of how fluvial and biological processes should link to each other in the system under consideration (Hughes et al., 2001). River restoration is itself a very young area, and the best practice is still emerging (Brookes, 1996; Sear, 1994). Catchment-scale influences on local variables need to be assessed; most restoration projects focus on reaches or short sections of a river (e.g. Sear et al., 1998; Adams and Perrow, 1999); and the goal of many projects has been the attraction of increasing the ecological value of a restored area, often for a specific species such as Salmon or Crayfish (e.g. Verdonschof et al., 1998). In Denmark and England more than 95 % of river channels are modified to some extent (Brookes, 1995), and many have been that way for centuries (Sterba et al., 1998). Therefore, there are few baseline forest floodplains to capture the attention of those undertaking restoration, and it is not surprising that so many projects have been based on restoring a meandering planform within a wet floodplain grassland. If any reach-scale restoration is to be successful, the hydrological processes that drive the system must function with catchment hydrology. As floodplain forest matures, it will almost certainly alter floodplain hydrology and geomorphology and these changes must also be taken into consideration: they should be part of the project goals.

Although floodplain turnover in piedmont systems is high; and in steep, mountainous catchments even higher (Nakamura et al., 2000), lowland floodplains are much less dynamic. Restoration of such diverse areas will therefore require fairly separate techniques, and more intervention is likely to be required in lowland forest floodplains, both as a consequence of their relatively quiescent nature; and because the pattern of vegetation, one of the main variables, must be restored. Decades or even centuries might be required to return the full functionality of a forest floodplain; biological diversity might take longer still. The reconnection of the floodplain to the river will require intervention. The financial support for any restoration project is unlikely to last beyond the duration of active modification so it is necessary to get it right first time! Restoration of 'cleared' rivers has proven rather difficult and forest floodplains initially appear to be even more so. However, it is not inconcievable that a system left alone will self-balance. The medium-disturbance hypothesis (Petraitis et al., 1989) suggests that biological and fluvial linkages might self-restore given sufficient time and hydrological connectivity. It may therefore be necessary to re-establish some initial condition of floodplain connectivity, and to seed trees, before adopting a non-intervention approach to let the system re-establish natural equilibrium. However, positive results could take years or decades to emerge. Biological diversity is even less determinate than geomorphological diversity (Petraitis et al., 1989; Bendix and Hupp, 2000), so there is no guarantee of exact outcomes. Nevertheless, the flexible approach that is being increasingly adopted by water managers in many countries could provide the key to restoring forest floodplains to full functionality in a variety of environments (Hughes et al., 2001).

Restoration significantly affects the characteristics of the fluvial system, and while it might provide ecological and recreational benefits, the flood defence or capacity for land drainage can be significantly compromised (Buise et al., 1998; Cals et al., 1998; Downs and Thorne, 1998). Usually, the aim is not only to (i) increase the lost ecological value of a river, but also to (ii) generate recreational potential, all the time having to account for (iii) the flood defence and drainage issues associated with that area. The natural river-floodplain system is deeply linked (Adams and Perrow, 1999;

see above sections), but disassociation of the river from the floodplain is often the idea behind river training and drainage works. Thus there is a likely conflict between achieving (i) and (ii) without compromising (iii). If the floodplain is inundated it will increase the frequency of flooding at that site and slow the speed of the flood wave down the channel (Kronvang et al., 1998), therefore reducing flooding risk downstream, albeit at the expense of flooding an area upstream. Thus there has been a drive for restoration strategies to take careful account of the impacts they have, and a number of integrated studies have been undertaken in order to more fully understand the impact that it has on a reach (e.g. Kronvang et al., 1998).

The benefits of restored floodplains include buffering of agricultural runoff (e.g. Fugsland et al., 1998), by nitrate retention, acidity reduction, adsorption of metal ions (Correll, 1997; Siggers et al., 1999), trapping of suspended sediment and slowing of flood waters. Forest floodplains also trap sediments and associated dissolved material in some areas, though the channelisation of flows means that it may be scoured from elsewhere, particularly in fairly high energy piedmont-river floodplains (see Piégay et al., 1998; Piégay and Bravard, 1997). However, fine-grained anastomosing systems have a greater number of channels to trap sediment, including blind ends and debris dams (Harwood and Brown, 1993). This sedimentation consolidates the banks and can therefore reduce rates of lateral migration and may control channel instability (Brown et al., 1994). The debris dams that are a characteristic feature within forested floodplains trap coarse sediment (see, for example, Heede, 1981), pond water and, by diverting water overbank, may increase the contact between the fine sediment carried in suspension and the floodplain surface. There has been very little research into these effects in lowland forested floodplains, but it is assumed that the beneficial effects of non forested floodplains will be increased in forested environments.

River restoration involves a certain amount of re-coupling of the channel to the floodplain, but this is not usually undertaken to the fullest extent possible (Brookes, 1996). The floodplain can be used to its full potential as an area for increasing the morphological and ecological value of rivers, but this requires a clear understanding of its role in the fluvial system (Brookes, 1996), thereby implying restoration or rehabilitation rather than enhancement. Such understanding can be difficult for any type of floodplain, but is more so for forested areas because they are relatively rare (Schnitzler, 1994).

The practicality of restoring floodplains is questionable (Adams and Perrow, 1999; Brookes, 1996). In addition, forest floodplains add to the complexity and time to recovery. There are four main areas that hinder the restoration of floodplains: (i) the scientific complexity of the floodplain systems, which is poorly understood (see earlier sections); (ii) lack of scientific understanding means that it is difficult to predict what will happen in a given scenario, which poses a significant problem for those undertaking the works; (iii) existing land management and planning has to be reconciled with proposed changes, and gaining the approval of the number of different organisations involved can be very difficult; (iv) informal, but overridingly practical institutions, for example market value of the land; and what is an acceptible change (Adams and Perrow, 1999). Understanding the full range of floodplains, including those which are forested, allows a more holistic understanding of where the limits of non forested systems lie, thus addressing problem (i). Although non forested flood areas have clear benefits for nutrient retention, buffering agricultural runoff, ecological value and so on, forest systems are likely to be better yet at fulfilling these functions. Therefore, although fraught with the difficulty of the lack of a baseline, and representing an even greater challenge than non forested floodplain restoration alone, forested floodplains provide a greater probability of benefits should they be restored.

2.4 Summary

Complex biotic and abiotic variables interact in a comprehensible manner to create forest floodplains. To fully understand the linkages involved it is necessary to take a wider perspective than is current either within contemporary geomorphological or ecological thought. Forest floodplains are controlled both by geomorphic and ecologic variables and there are fundamental links between water, sediment and vegetation. To consider one aspect, when explaining their evolution, is a subtle failure to understand the system. Conceptualising these apparently complex systems is nevertheless quite possible because there are coherent interactions of biotic and abiotic variables.

Clear catchment-scale changes occur. There are downstream changes, such as the alpine to mediterranean shift along the Fiume Tagliamento, Italy (Gurnell et al., 2000; 2001), and there are lateral changes, for example a decrease in flooding away from the channel (Hughes, 1997). Both patterns are locally modified and overriden by reach-scale variables (e.g. McKenney et al., 1995).

At least four types of temperate forest floodplain can be discerned (Fig. 2.11) within a conceptual model similar to that of Schumm (1977):

(i) Source streams: steep, headwater streams characterised by catastrophic mass-movements;

(ii) Transfer streams: large, high-energy rivers (often piedmont), characterised by a wide, braiding floodplain with island development in association with vegetation (many of these have been impacted by gravel extraction or hydrological regulation);

(iii) Sink streams: large, lowland meandering rivers with cohesive banks, about which relatively little is known; and

(iv) Small, low-gradient meandering rivers with cohesive banks draining lowland areas, about which virtually nothing is known.

Vegetation affects geomorphic processes differently within each zone. In the uplands, geomorphic processes that are driven by high slope and runoff are very dominant, often physically destroying the channel and the log steps and debris dams that store sediment and alter channel hydraulics, but the wood is often deposited within a snout matrix where lower valley gradients occur (e.g. Hogan et al., 1995). In piedmont zones biota stabilizes parts of the floodplain and promotes island development (e.g. Gurnell et al., 2000). Finally, although vegetation significantly modifies floodplain and channel hydraulics, its exact influences over the processes operating in lowland systems remains unclear. Because these are the geomorphically least active parts of the network, biota could begin to vie with inherent process mechanics to be the dominant control. The research outlined in this Chapter illustrates that relatively little is known about the interrelation of biotic, fluvial and floodplain processes; and more information is required, especially from the lowlands, to generate a catchment-wide understanding of these interactions.

Following the intermediate disturbance hypothesis, (Petraitis et al., 1989), biological diversity is likely to be greatest in high-energy braiding and island-development reaches: little physical disturbance in lowland areas prevents high habitat turnover and diversity; and more geomorphic disturbance in upland areas prevents stable habitats from forming. However, local patterns of floodplain processes and vegetation are not always deterministic: a degree of equifinality may be associated with why vegetation is present at a particular location (Bendix and Hupp, 2000). Hence, system dynamics are not necessarily predictible. Also, floodplain forest systems may take decades to evolve, and self-sustainance appears to be fundamentally based on the interaction between process and biota (e.g. Marston et al., 1995). The understanding and restoration of forest floodplains therefore face myriad challenges.

Fluvial science and riparian ecology developed through the study of natural systems that were already heavily impacted by humans (Ward et al., 2001). From this view, geomorphologists are attempting to understand and explain systems that go beyond the foundations of their subject, which is why the greater understanding provided by inter-disciplinary links is so important. A successful conceptual model of forest floodplains has to consider the spatial and temporal dimensions of both ecological and geomorphic processes. This requires a fundamental reconfiguration of the existing conceptual model of floodplains. A preliminary model is proposed in Fig. 2.11, which highlights that the study of lowland forest floodplains has been particularly neglected, and this is where the thesis is addressed.

Chapter 3
Lateral accretion and the geomorphology of a wooded lowland floodplain

3.1 Introduction

The model of lateral accretion and vertical accretion described in chapter 2 (Wolman and Leopold, 1957) has frequently been used to explain the formation of lowland floodplains. Lateral accretion is driven by in-channel hydraulic structures, and vertical accretion is caused by the deposition of sediment overbank during flooding. Both, therefore, are caused by the interaction of three geomorphic actors: channel form; hydraulic structures; and hydrology. Chapter 2 also described how each of these actors can be modified by vegetation, which is therefore a variable that has a theoretical capacity to modify geomorphic processes and influence floodplain formation. For this reason, vegetation should be considered when investigating the formation of forest floodplains. However, no previous assessments have been made of how biotic variables affect either the lowland floodplain model described by Wolman and Leopold (1957), or the lowland forested floodplain model described at the end of chapter 2 (see Fig. 2.11). Indeed, few studies of lowland forest floodplains exist, and so floodplain research is lacking the conceptual structure that will allow understanding of how biota influences floodplain processes. The aim of this chapter is to begin assessing how floodplain processes are determined by forest vegetation. This was achieved through a survey of floodplain geomorphology, and from this assessment the processes of formation were inferred. This assessment lays a foundation for further research (chapter 4) and leads to the final construction of a conceptual model of lowland floodplain geomorphology (chapter 5).

The first half of this chapter describes the floodplain geomorphology of the Highland Water, a forested lowland stream in the southern England. The geomorphology was assessed within a baseline survey that covered 58% of the catchment (Fig. 3.1) that was undertaken between October and December 1998. The main scientific advantage of the survey was that it began to test the Wolman – Leopold (1957) model by assessing whether lateral or vertical accretion occurred on the Highland Water floodplain. In fact, lateral erosion and accretion were observed infrequently, especially in the channels that were least disturbed (most natural), suggesting that these processes were not important for floodplain formation. However, this conclusion needed further verification because the processes had been observed in a rapid qualitative fashion, and their overall importance could not be assessed. The reconnaissance survey indicated that lateral accretion had occurred at several locations within channelised sections of the river, but was less obvious in the natural sections, despite a meandering planform. While evidence of lateral accretion existed at several points through the catchment, there was only one active site of overbank flow and deposition, within which overbank processes were highly complex. Therefore, while it was possible to undertake another survey to identify the location and extent of lateral accretion at the catchment level and thereby evaluate its importance, more detailed experiments would be necessary to investigate processes of overbank accretion, and these are described later in the thesis (chapter 4).

The second half of this chapter therefore describes a second survey that specifically investigated the spatial distribution and rate of lateral accretion. Two years after the first, this survey quantified river bank erosion and in-channel deposition. A resurvey of the floodplain was undertaken at the same time in order to provide information on how the floodplain geomorphology had changed, which was especially relevant because the period between surveys included a period of exceptional flooding, generated by the wettest winter since UK Meterological Office records began.

This chapter therefore fulfils two functions. First, it introduces the field-based research that underpins this thesis, describing the geomorphology of a lowland forest floodplain. Secondly, at a more strategic level, it takes this research and links it to the current focus of this thesis described in chapter 2 - a general consideration of floodplain formation, represented by the Wolman and Leopold (1957) model - and from both sources synthesizes geomorphic concepts that take firm account of biotic influences on floodplain processes. The relevance of both models for floodplain research as a whole is discussed in chapter 5.

The surveys were essentially based on visual interpretations, so photographic records of typical floodplain and channel features were made. The resulting photograph album contains 25 images, and to avoid making the text too cumbersome it is presented in Appendix A.

3.2 Geomorphological survey

3.2.1 Aims and objectives

The aim of this survey was to define the geomorphology of a lowland forested floodplain. The specific objectives were (1) to identify features that affected floodplain processes; and (2) to identify floodplain morphological elements as a starting point for building a conceptual model of a forest floodplain. To address these objectives, the methodological phases were quantification of geomorphic variables; and subsequent spatial analysis (Fig. 3.2).

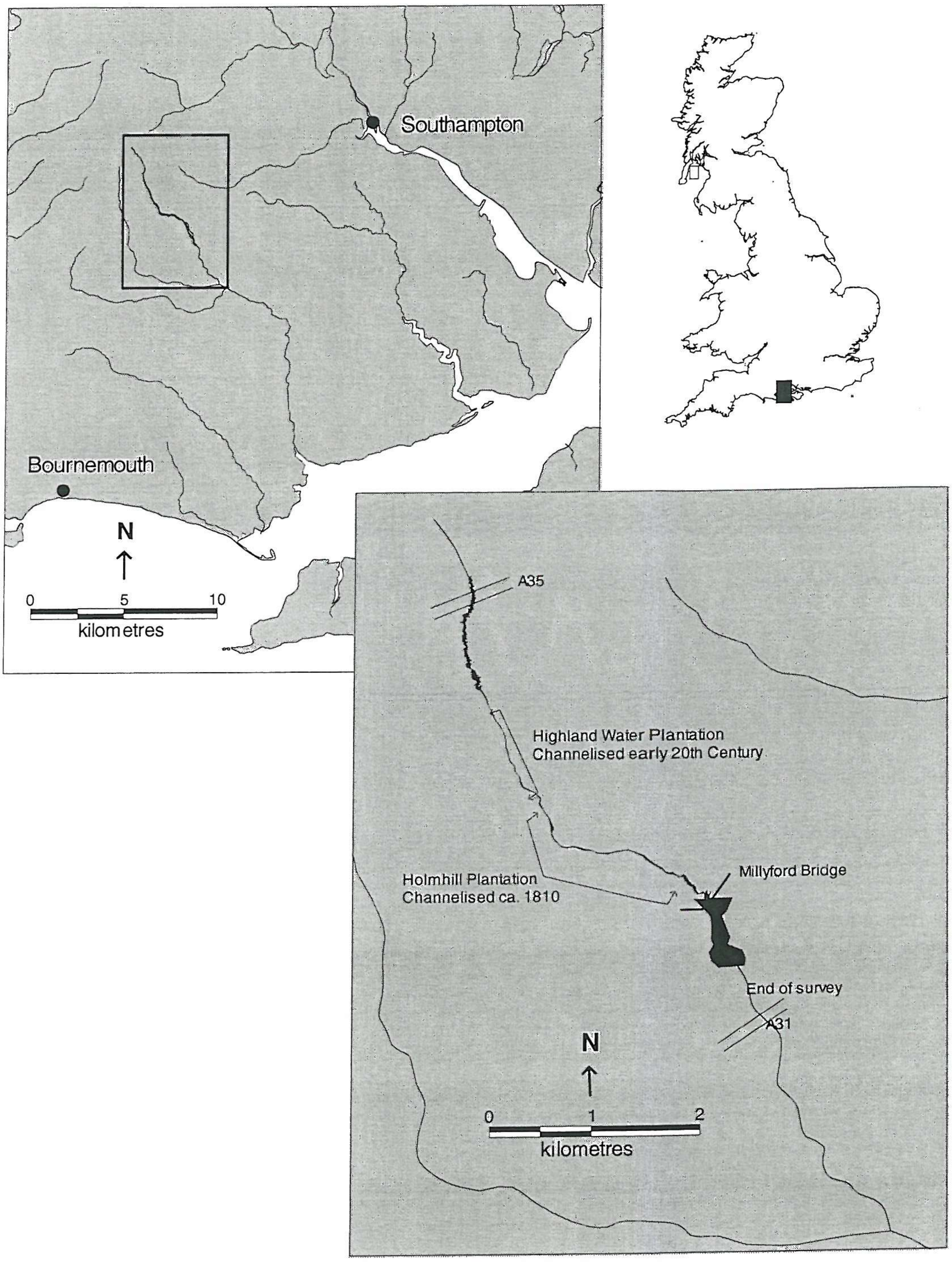


Figure 3.1 The location of the reconnaissance survey: the black shading represents the surveyed width of the presently active floodplain (see text for how the edge of the floodplain was identified)

Phase I: Reconnaissance survey

Hypotheses (determine what data to collect)

↓

Floodplain corridor survey

↓

Spatial representation of floodplain variables (display in GIS)

Phase II: Associations between variables

↓

Hypotheses of causal mechanisms

↓

Identification of sites where associations and mechanisms occur (GIS)

↓

Detailed process investigation (hypothesis testing: Chapter 4)

Figure 3.2 Strategy for a catchment survey of floodplain geomorphology

3.2.2 Methodology

Data collection

At the time of the survey, a literature search highlighted that no catchment-scale surveys of forest floodplain geomorphology had been attempted, so there was no established methodology to base this survey on. The survey aimed to collect spatially-referenced floodplain data, for which several techniques were considered. Although highly accurate, field surveying using a level or total station would have proven very time-consuming for a catchment survey, and was immediately rejected. Remotely sensed images of the area showed that neither the river channel nor the floodplain surface could be identified under the canopy of trees, which precluded the remote collection of information. A geomorphological map based on field sketches could have provided the necessary useful information, but was likely to be time-consuming to carry out for several kilometers of forest floodplain. Also, detailed sketch maps made entirely in the field from one starting point would also have been prone to spatial errors. Part of the aim was to quantify the width of the floodplain and to map it for spatial display and analysis. Field mapping was therefore rejected.

A new technique had to be devised that gave the spatial location of the river and floodplain at continuous or frequent intervals. The continuous spatial collection of riverbank and planform data is time-intensive (German, 2000), and would have made the task unachievable over a short time. Therefore, a stratified survey procedure was adopted.

On a 1:2500 scale 1952 Ordnance Survey map of the Highland Water, which was enlarged twice to 1:833, the floodplain was split into segments within which two types of geomorphic information were collected: (i) physical measurements of generic floodplain features (floodplain, trashline and channel widths; bank height and composition); and (ii) presence or absence of geomorphic features (e.g. relict channels, overbank deposition). The planforms on the map indicated that part of the Highland Water had been channelised (Fig. 3.1). Channelised planforms were essentially straight, whereas more natural sections (here termed 'natural') meandered. To account for this change in planform, natural sections were split into transects spaced 20 m apart and channelised sections were split 50 m apart.

Where each transect crossed the river, width measurements of the channel (to bankfull), trashline (as defined by floodwater-rafted debris) and floodplain (to terraces or nearest confining break in slope) were taken (the rationale for these is explained subsequently, and is listed in Table 3.1). Transects were run perpendicular to the river channel, and therefore obliquely cross the floodplain (Fig. 3.3). This decision was based on the need to accurately determine channel width, whilst perpendicular floodplain width could be determined from the digitized floodplain map to be created later. Distances were measured with a pacing stick, using a compass bearing where necessary, towards stationary landmarks such as trees. Visual estimates of bank height, angle and composition were also made for each transect. A survey sheet was completed for each transect (Fig. 3.4) and this ensured that the same set of variables was observed.

Secondly, frequency counts of floodplain features were undertaken for each transect. Geomorphic features commonly found on lowland floodplains and described in the literature (see Table 2.4 in chapter 2) were recorded (Table 3.1). The survey also aimed to identify any 'other' lowland forest floodplain features that had not been previously described in the literature, and a space was left to record these on the survey form. Hypotheses about the origin of these features could then be formulated for testing in later chapters (Fig. 3.2, Phase II). Finally, the larger features and changes in planform were sketched on the basemaps. Because the locations of each feature was known (within a given transect and on the basemap), they could be later georeferenced to the river and floodplain. Finally, an inventory of geomorphic elements was compiled from the survey.

Table 3.1 Information collected during the baseline survey

Information	Data collected	Interpretative comment
Measurements		
Floodplain area	Paced measurements of floodplain width (to the margin); width of the inundated area between trashlines; channel width	Used to calculate the areas of floodplain, recent inundation and channel; and to reconstruct geomorphic floodplain reaches
Overbank flow	Widths (later reconstructed to areas) and frequency counts	Flooding limits were determined by proxy indicators such as the presence of leaf litter and twigs at the edge of the flow
River channel	Width, depth, apparent stability (eroding or not), estimate of sinuosity, type of modification	Changes in channel geomorphology later used to reconstruct fluvial reaches
Bank characteristics	Visual estimates of bank height, angle, cover (as with floodplain cover); composition; sketch of profile; stability	These provide a second assessment of channel processes
Counts		
Floodplain features	Frequency counts, field classification	Visual observations of sediment deposition; scour; flow pathways picked out by depositional forms, sand shadows and flattened vegetation
Large geomorphic floodplain features	Frequency counts, field classification and location	These provide evidence of current or former activity (e.g. flood channels, pools, meander cutoffs, abandoned channels)
In-channel debris dams	Frequency counts, field classification and location	Classified into active (hydraulic head); complete (no hydraulic head but spanning the channel); partial or lateral deflector dam; and High Water (HW; as where a fallen tree spans the channel) dam, this scheme being modified from Gregory et al. (1985) and Wallerstein et al. (2001)
Floodplain cover	Estimates of the proportion and type of cover; location. Visually estimated: 0 = none r = isolated individuals 1 = up to 5 % 2 = 6-25 % 3 = 26-50 % 4 = 51-75 % 5 = 75-100 %	Determining the relative area of types of landcover informs about species assemblages

The survey was undertaken between 22 October and 17 December 1998: this ensured that any recorded changes were spatial not seasonal. The surveying period lasted 25 days and covered a length of 5.3 km along the floodplain (Fig. 3.1). The upstream limit of a floodplain can be difficult to identify (Nanson and Croke, 1992, Nakamura and Swanson, 1993, Marriott and Alexander, 1999), so to avoid problems with floodplain definition, only floodplain that had clearly been fluvially created was surveyed. Around 58% of the length of the Highland Water was covered, providing a significant sample of floodplain features at the scale of this catchment.

Data analysis

Data were input to a GIS (ArcInfo v.7.1 running on Solaris UNIX machines) for spatial display and analysis. Transect centrepoints were digitized from the 1:833 basemaps; relative to these, X and Y coordinates representing the location of the channel, trashline and floodplain were calculated in a spreadsheet using trigonometry; these calculations produced six points per transect (two each for the channel, trashline and floodplain margin). Three polygons were digitized from these points, representing river plan form, area recently inundated and the floodplain. Once the GIS had been set up using ArcInfo it was transferred to MapInfo v.6.5 running on a desktop PC, which was used to calculate the areas covered by the channel, recent flooding and floodplain.

The original survey sequence was split up into reaches based on changes in fluvial geomorphology; for example, natural and channelised reaches (German et al., 2001; German, 2000; Universities of Nottingham, Newcastle and Southampton, 1998). Geomorphically homogenous fluvial reaches are a response to local driving variables such as valley slope, regolith, hillslope sediment supply, anthropogenic disturbance or management (German et al., 2001; McKenney et al., 1995). The mapping of geomorphic reaches permits an assessment of how reach-scale controls on fluvial geomorphology are distributed throughout a catchment. Although surveys of this type have previously focused on the channel, floodplains can also be divided into geomorphic reaches (e.g. McKenney et al., 1995) if they have been created by and are in balance with fluvial processes (ie. a genetic floodplain as described by Nanson and Croke, 1992 and Marriott and Alexander, 1999). This dataset therefore identified geomorphic partitions inherent within both the river and floodplain. These divisions were then used to see if there were clearly defined differences in the attributes associated with each reach (Table 3.1), and whether these were associated with changes in the specific characteristics of each reach as a basis for developing hypotheses that explain causal mechanisms.

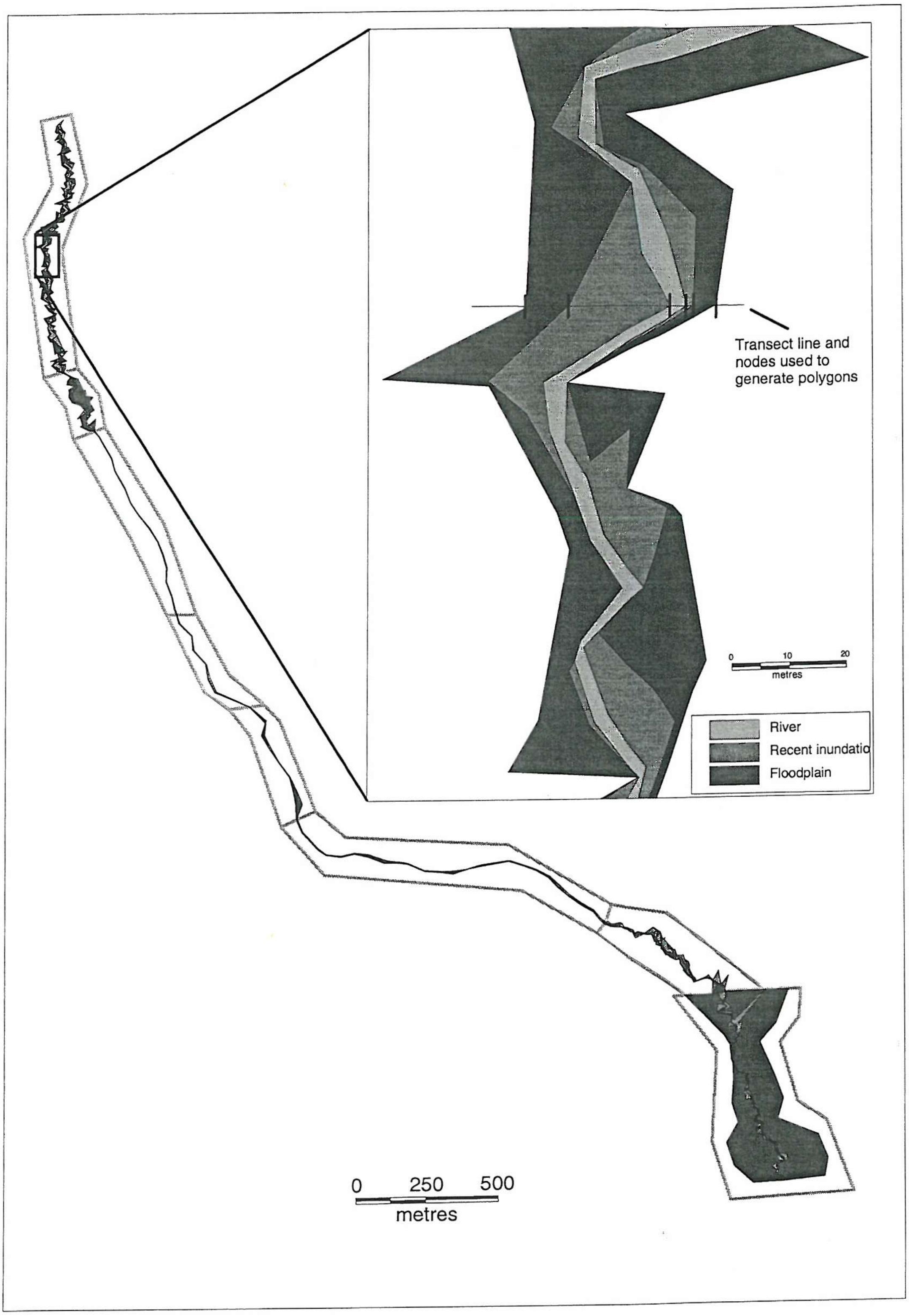


Figure 3.3 Schematic of method used to survey river, inundated area and floodplain. Geomorphological fluvial and floodplain changes are marked by the divisions within the grey polygon

DATE____________ SECTION ID________________

FLOODPLAIN

Valley floor width ________________

Surface hydrology ________________

Land use ________________

Vegetation

Type	Cover	Height (m)
None		
Litter		
OD		
Moss		
Grass		
UGrass		
Shrubs		
Decid		
Conif		
Mixed		

The lines below were used to record transect widths

Trashline ________________

Terraces ________________

Overbank deposits ________________

Spatial extent OB depsts ________________

Floodplain features ________________

LATERAL RELATION OF FLOODPLAIN TO VALLEY

Form ________________

Sinuosity (from map) ________________

Activity

None	
Meander progression	
Increasing amplitude	
Progression and cutoffs	
Irregular erosion	
Avulsion	
Head cuts	
Bank cuts	

CHANNEL

Width (m) ________________

Feature ________________

No/type of Dams ________________

Lateral OD ________________

Depth ________________

Eroding/depositing ________________

BANKS

	LEFT	Sketch (L)	Right	Sketch (R)
Vegetation				
Vegetation height				
Height (m)				
Angle				
Stability				

Figure 3.4 *Survey sheet used for floodplain transects*

3.2.3 Results from the geomorphological survey

This section initially describes the reaches of river and floodplain identified during the survey, and therefore provides an overview of the geomorphic controls throughout the study area. Following this is a short section describing how in-channel debris dams play a key role in the functioning of floodplain processes: this addresses the first aim (quantify features influencing floodplain processes). The final part addresses the second aim of identifying floodplain morphological elements with a summary of what these features were and an interpretation of their origin.

Table 3.2 Physical characteristics of fluvial geomorphological reaches

Reach (type)	Mean channel width (m)	Mean channel depth (m)	Mean bank height (m)	No. of sections	Counts of overbank *deposition*
1 (natural)	3.14	0.43	0.67	52	26
2 (natural)	3.50	0.53	1.71	3	0
3 (channelised 1960s)	3.10	0.25	1.73	6	0
4 (channelised post 1870)	3.80	0.40	1.71	4	1
5 (channelised pre 1870)	2.60	0.26	1.52	3	0
6 (channelised pre 1870)	4.90	0.35	1.43	13	2
7 (natural)	4.54	0.58	1.04	25	14
8 (natural)	3.80	0.73	1.24	39	29
Natural section means	**3.75**	**0.57**	**1.17**	**29.75**	**17.25**
Channelised section means	**3.53**	**0.32**	**1.60**	**6.50**	**0.75**
Means for all sections	*3.67*	*0.52*	*1.38*	*17.85*	2

Geomorphic reaches and features

The most evident influence on the channel and floodplain of the Highland Water was channelisation (sections that are here referred to as 'channelised') (Fig. 3.5). Nevertheless, downstream changes in the character of the floodplain and river were also evident: the widths of the river and the floodplain increased with distance downstream (Fig. 3.5). Overall, eight geomorphological reaches were identified, of which half (reaches 3-6) were channelised (Fig. 3.5; Table 3.2). Within the unmodified natural sections, the changes in fluvial and floodplain processes and geomorphology were usually caused by human influence. For example, reduction in floodplain area between reaches 1 and 2 was a result of reach 2 being incised following the channelisation of reach 3. In contrast, the morphology of the channelised sections bore the imprint of past modification, with higher banks, narrower and shallower active channels, and virtually no overbank deposition (Table 3.2).

The floodplain morphology in reach 1 did not appear to have been directly managed, and was therefore fairly natural. Good hydrological connections to the surrounding heathland were provided by several small tributaries that promoted strong links from the hillslope to the floodplain and the floodplain to the river. These hydrological inputs also caused boggy areas to exist within 29 % of surveyed sections. But reach 1 showed little evidence of significant overbank deposition: although trashlines were very common (Table 3.3), they often occurred across flat parts of the floodplain near the channel (photo 1), implying that overbank flow was shallow and slow. Secondly, although small debris dams (photo 2) were relatively common (1.83 per 100 m) compared with elsewhere (Table 3.4), they caused only small areas of overbank flow to occur (photo 1a). There were no areas of extensive overbank accumulation (i.e. where significant overbank deposition was taking place). Shallow flood channels (activated only during flooding and therefore termed 'ephemeral') were widespread (photos 3 and 4) but poorly defined: they were often curtailed by the river meandering across the full width of the relatively narrow floodplain (average width 26.47 m; photo 5). Meander cutoffs (photo 6) were evident, although they were not as common as elsewhere (cutoffs were occurring in 12% of the sections, compared with 16% and 15% for reaches 7 and 8 respectively; see Table 3.3). These cutoffs had in some cases led to a relict main channel that was periodically reactivated (photo 7), and in one location cutoff activity had led to a near-anastomosing planform. As a result of this activity, the floodplain topography in this reach was often complex (photo 8).

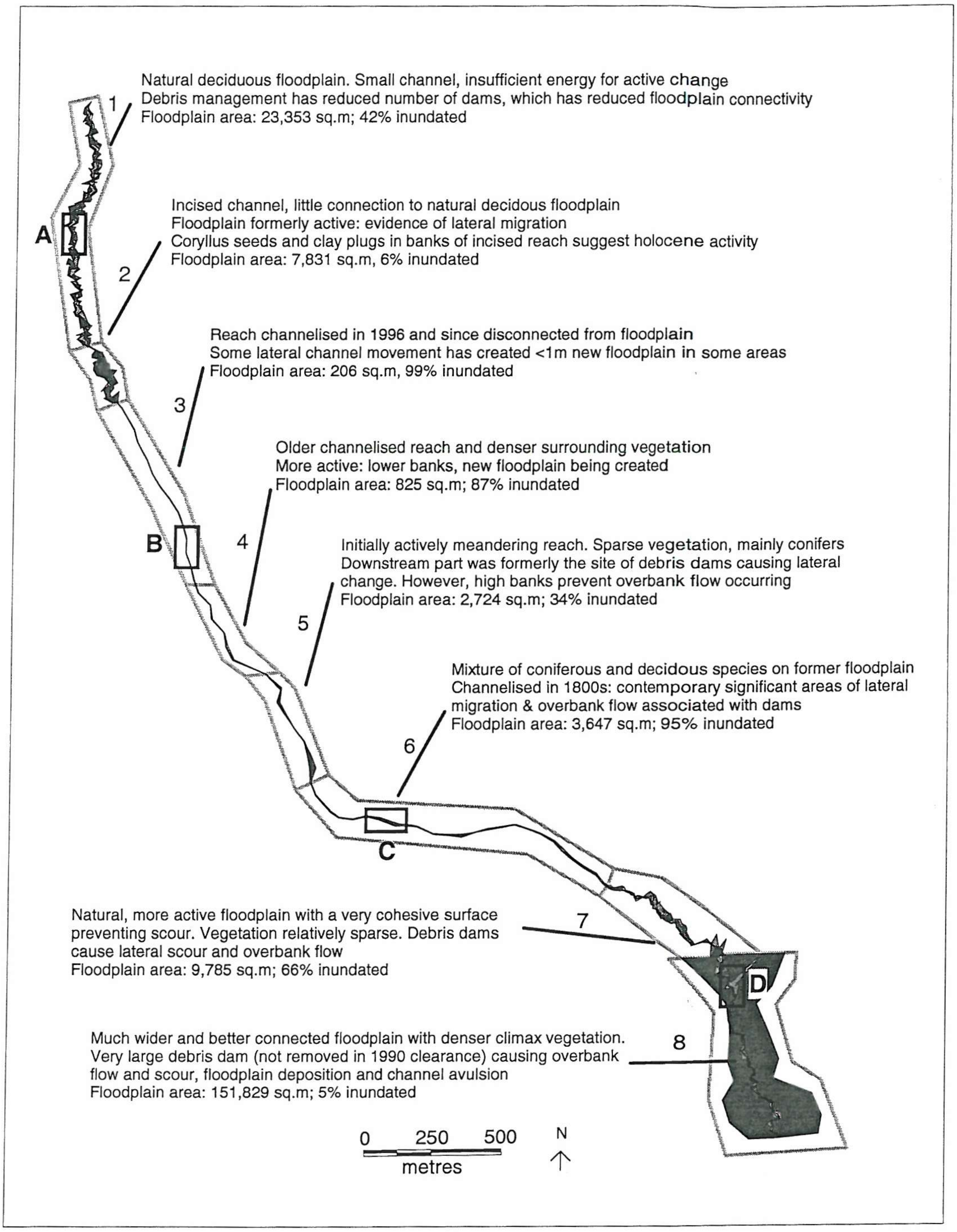


Figure 3.5 Geomorphological floodplain reaches along the Highland Water

The floodplain in reach 2 was similar to that immediately upstream (Table 3.3): it too did not appear to have been directly modified, but it was disconnected from the channel by high banks (1.17 m compared with 0.67 m upstream) because channelisation from reach 3 had caused upstream incision (photo 9). The bank heights for this and the next section were therefore very similar (reach 2 was 1.71 m and reach 3 was 1.73 m), despite a very different floodplain geomorphology (Table 3.3). Incision has led to the exposure of clay plugs that cause steps in the water surface profile (photo 10).

Table 3.3 Inventory of geomorphological floodplain features found along the Highland Water

Reach	No. of sections	Geomorphological features ranked in order of frequency. Percent of sections in which feature occurs is bracketed
1	52	Trashlines (81 %); Overbank deposition (50 %); Ephemeral channels (29 %); Bog (29 %); Relict channels (17 %); Progressing meander cutoffs (12 %); Small tributaries (10 %); High water dam (6 %)
2	3	Trashline (33 %); High water dam (33 %)
3	6	Channelisation (100 %); Trashline (100 %); Relict channels (33 %); Bog (17 %)
4	4	Channelisation (100 %); Trashline (75 %); Relict channels (25 %); High water dams (25 %)
5	3	Channelisation (100 %); High water dams (67 %)
6	13	Channelisation (100 %); Trashline (77 %)
7	25	Trashlines (60 %); Overbank deposition (56 %); Ephemeral channel (28 %); Bog (20 %); Relict channel (20 %); Progressing meander cutoffs (16 %); High water dams (12 %)
8	39	Trashlines (77 %); Overbank deposition (75: 13 % causing extensive overbank deposition), Ephemeral channels (46 %); High water dams (31 %); Bog (23 %); Progressing meander cutoffs (15 %); Relict channel (5 %)

The floodplain in reaches 3-6 can be regarded as inactive (photo 11) due to channelisation in the early 20th Century, which had decreased the bed level of the river by at least 0.5 m (photo 12): bank heights varied between 1.43 and 1.73 m, but within the undisturbed reaches (1,2,7 and 8) this range was 0.67 to 1.38 m. Little hydrological transfer from the river to the former floodplains occurred, as evidenced from trashlines confined to the channel. The active floodplain was confined to the engineered channel and compared with the natural sections, few floodplain features occurred (Table 3.3).

The floodplain surrounding the channelised sections was usually overgrown with vegetation (photo 11), and widespread needle litter or vegetation indicated a complete absence of fluvial or hillslope processes. Indeed, the channel that had been abandoned following modification was usually evident on the former floodplain (photo 13). This channel gave an indication of the height of the water table: in reach 3 it was near the (former) floodplain surface and the old channel formed a pond (photo 13), partly filled with woody debris (logging spoil and windthrow). Within reaches 4 and 5, however, the old channel was usually dry. Reach 6, channelised in 1810 (Stagg, 1990), had lower banks than other modified sections (1.43 m) and the abandoned channel was occasionally reactivated by floodwater, although dense floodplain vegetation prevented erosion (photo 14).

Table 3.4 Numbers and types of debris dams per reach

Reach (type)	Active dams	Complete dams	Partial dams	HW dams	Total dams	Dams/100m*
1 (natural)	10	4	5	4	23	1.83
2 (natural)	1	0	0	0	1	1.67
3 (channelised 1967)	0	0	0	0	0	0.00
4 (channelised post 1870)	0	2	2	1	5	2.00
5 (channelised pre 1870)	0	0	1	2	3	0.67
6 (channelised pre 1870)	1	3	2	0	6	0.92
7 (natural)	4	2	1	3	10	0.56
8 (natural)	3	9	2	12	25	1.79
Total for natural reaches	17	15	8	19	59	1.72
Total for channelised reaches	2	5	5	3	15	0.85
Means for natural reaches	4.50	3.75	2.00	4.75	15.00	N/A
Means for channelised reaches	0.25	1.25	1.25	0.75	3.00	N/A
Totals for all reaches	19	20	13	22	74	1.28

* not including HW dams because their geomorphological influence is minor (see Gregory et al., 1993).

The river banks in the modified sections were usually a cohesive clay-sand matrix and fluvial energy was dissipated over a larger cross-sectional area, so lateral scour was unlikely to occur. Nevertheless, in discrete locations in-channel debris dams had altered channel hydraulics sufficiently to scour the bed and banks, which provided sediment for adjacent deposition, and this process has resulted in the formation of short, low (0.2-0.4 m above the river bed) sections of new incipient floodplain (Fig. 3.5; photos 15-17).

The natural reaches 7 and 8 were similar to reach 1, but lay in wider sections of the valley: the average floodplain width in reach 8 was 218 m (Table 3.2). The increasing distance downstream was visually correlated with deposition that was concentrated over a small portion of the floodplain; and a reduction in the frequency of trashlines contrasted with more overbank deposition; 75% of sections in reach 8 were depositing, compared with only 50% in reach 1 (Table 3.3). The thickness of deposits also increased with increasing distance downstream, perhaps indicating a greater sediment supply: in reach 7, frequent splays of fine sediment several millimetres thick were evident (photo 18); and much of the upstream part of reach 8 was mantled with deposits up to several centimetres deep.

Reach 8 was heavily influenced by a large debris dam that fully blocked the channel (photo 19), evidently causing frequent and sustained overbank flow (photo 20) and extensive overbank deposition (Photo 18). The dam has been in existence since at least 1993 (C.T. Hill, 2001, pers.comm.), but was not recorded during a survey of wood undertaken in 1990 (Gregory, 1992). The floodplain hydraulics in reach 8 were complex because the overbank discharge caused by the dam was hydraulically disrupted as it flowed through and around a variety of shapes and sizes of unevenly distributed surface obstructions (trees, other vegetation, dead wood and microtopographic obstructions). Although complex, overbank flow was usually oriented down-valley and often formed coherent ephemeral flood channels. Overbank sediment deposition, which occurred downstream of surface obstructions, between adjacent flood channels and in ponded areas, was associated with these channels, although no sorting was immediately apparent.

In the downstream part of reach 8, close to the end of the survey section, without the influence of the dam, but with much of the water diverted into an adjacent tributary, overbank processes of water flow and sediment deposition "switched off," and the trashlines were always close to, or in, the channel. The local distribution of overbank flow was therefore closely related to the local effect of in-channel debris dams in this reach.

The distribution of in-channel debris dams

The significance of in-channel debris, demonstrated most spectacularly in reach 8, suggested that the catchment distribution of debris loading was of particular importance for floodplain processes. Debris dams of any type were most common in the natural sections – this is most evident from normalised values: there was a mean value of 1.72 dams per 100 m length of natural river, compared with 0.85 in channelised sections (Table 3.4). The number of dams was more variable within the channelised reaches, with no dams in reach 3 and the maximum for the entire survey of 2.00 per 100 m in reach 4. Many dams in channelised reaches bridge the channel (High Water or HW dams; terminology from Gregory et al., 1985); or partly block it (partial dams); or, if a complete dam occurred, it did not alter the water surface profile. Debris dams in the channelised reaches therefore tended to be less hydraulically efficient than in natural reaches. This change is probably caused by a combination of two factors.

Firstly, the formation of in-channel dams depends partly on the discrepancy between the average channel width and the average length of pieces of woody debris entering the channel (Gregory et al., 1993). Considering this, a possible explanation for this difference in dam density is that within the plantation (see Fig. 3.1 for location), tree management (ie. the trimming of small branches and removal of small trees) has reduced the input of wind-thrown branches and twigs to the channel. Instead, in-channel debris is more likely to be whole trees that have been undercut or subject to windthrow and have then toppled across or fallen into the channel (photo 21). Such pieces of debris probably exceed the average channel width and, on average, are probably longer than those derived from natural sections. A single large piece of plantation debris, which may be significantly wider than the channel, is less likely to trap floated organic material and create a step in the water surface profile than an accumulation of many smaller intermeshing pieces of debris in natural sections.

Secondly, the plantations are mainly coniferous and no fall of broad leaves occurs. Dams in natural reaches therefore have an immediate source of material to seal small gaps within a matrix of LWD. Indeed, natural reaches had many more dams that completely blocked the channel, and these often caused a step in the water surface profile (noted during the survey as active dams). Overall, therefore, the affects of debris dams appear to be greatest in the natural reaches.

A conceptual model of floodplain geomorphology

The information on the number and type of floodplain features was summarized into an inventory (left column of Table 3.5). The generic features of this forest floodplain were: trashlines; overbank deposits; ephemeral channels; bogs; relict channels; progressing meander cutoffs; small tributaries; high water dams; and three other types of in-channel debris dams. A simple list like this can be used to directly compare this floodplain to any other, but on its own provides no deeper understanding. An interpretation of the geomorphic origin of each feature is necessary before they can be conceptually linked. An initial attempt to provide geomorphic understanding is provided by the right column in Table 3.5, which lists the possible origin of each feature based on field observations. The processes that form each feature were then linked to build the initial conceptual model of forest floodplains presented in Fig. 3.6. This model was then used to identify conceptual and physical areas for further investigation.

Table 3.5 Features and implied geomorphological process

Feature	Process
Trashline	FLOODING: Movement of material on floodplain to demarcate maximum recent limits of inundation.
Overbank deposition (no differentiation in this survey between areal and s/s deposition	DEPOSITION: movement of material onto floodplain that remains after cessation of flood.
Ephemeral channels	UNCERTAIN: one or combination of following: (1) scour into floodplain surface; (2) linear deposition to create intermediate low-lying areas; (3) relict channels being maintained by overbank flow.
Bog	PONDING: impermeable layers in floodplain stratigraphy causing perched water tables to occur.
Relict channels	FORMER CHANNEL MOVEMENT: channels may be naturally abandoned or disconnected due to channelisation.
Progressing meander cutoffs	SCOUR ACROSS MEANDER NECKS: overbank flow follows the shortest route with the greatest slope. Hence, velocity is high and scour occurs. Often roots are exposed across the neck and ephemeral channels are created (See ephemeral channels).
Small tributaries	SURFACE EMERGENCE OF THROUGHFLOW: Relatively small inputs that express no discernable channel before joining the main river. These drain surrounding heathland or forest.
Disconnected floodplain	CHANNELISATION OR INCISION: over deepening of main river channel to improve local drainage and increase the amount of land available for silviculture. At the upstream end of an area of modification a headcut works back upstream to incise natural channel. Both of these reduce the hydrological connection between the main channel and the floodplain.
Complete dam	PONDING: in-channel accumulations of wood cause a step in the water surface, locally storing water, sediment and energy upstream and dissipating it through the surface of the dam and via erosion of river banks. During floods these dams promote spatially heterogeneous patches of overbank flow.
Active dam	VELOCITY REDUCTION AND ENERGY DISSIPATION: in-channel accumulations of wood reduce the velocity of channel flow and dissipate energy. May promote bed scour or bank erosion. May also promote overbank flow by locally reducing channel capacity.
Partial dam	FLOW CONSTRICTION: lateral accumulations of wood block part of the channel (but do not cross it), cause acceleration of flow within the rest of the cross-section; and promote energy dissipation at the dam, but increases bed and bank scour.
High water dam	WINDTHROW: fallen tree crossing the top of the river channel. Modifies pathways of overbank flow. Also, and although it initially does not affect flow, as it breaks up it may, depending on the size of individual pieces of wood, create a debris dam (see complete, active and partial dams).
Lateral organic debris	ENERGY DISSIPATION: Scattered pieces of wood aligned along the edge of the river channel increase channel resistance.

The model divides the river from the floodplain and separates features from process. The origin of the floodplain surface morphology at the heart of this thesis provides the central point for this model of evolution. Note that processes are driven by discrete events and are not continuous: the model aims to outline processes that occur during flooding, although in one part a longer timescale is embodied by the slow breakup of in-channel debris dams.

Channel and floodplain processes are spatially and conceptually separate, but the overbank discharge of water provides a transient physical link. Biota have a direct effect on fluvial processes because they are the source for in-channel debris dams and these disrupt the secondary flow helices that promote lateral erosion, point bar deposition and floodplain creation (cf. Thorne and Furbish, 1995). The channel is therefore shifted from a state of hydraulic dominance, driven by the effects of channel morphology, to a state where the local hydraulic effect of debris literally causes drowning.

Through this hydraulic impact, in-channel accumulations of LWD have an indirect effect on overbank flooding. The reduction in channel area by a dam causes ponding and the local inundation of the floodplain surface at discharges below bankfull. The resulting pathways of overbank flow are often confined within ephemeral floodplain channels, which were characteristic features of the natural reaches 1, 2, 7 and 8. These ephemeral channels flowed down valley, running parallel to the main stream where it was relatively straight, (photo 3) or flowing across the necks of meander loops (photo 4). They were usually fairly shallow (around 10 or 20 cm, although sometimes up to 50 cm deep) and sometimes interconnected as they ran between trees. Flow along the channels was controlled at the micro scale by trees, patches of vegetation and floodplain debris dams. The disruption of overbank flow by organic material, especially trees, had two effects. Firstly, biota sometimes caused shelter and deposition in the form of wake deposits (sand shadows). Secondly, biota (especially trees) could reduce the cross-sectional area of the micro channel, which in some locations led to flow acceleration and scour (photo 22). Either of these processes could be used to explain the formation of the ephemeral channels, and requires further investigation.

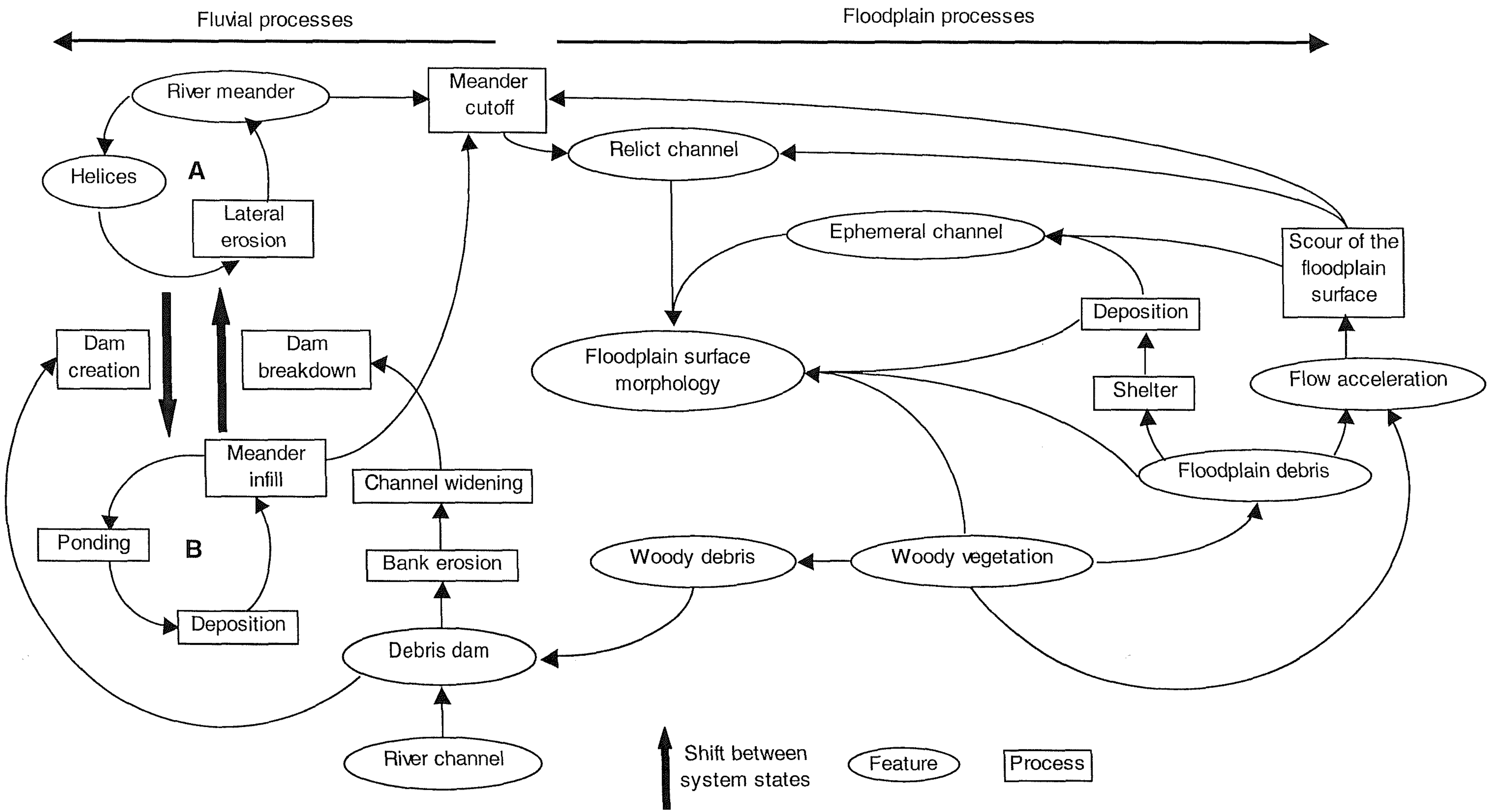


Figure 3.6 Conceptual model of a forest floodplain based on published literature and the information collected from geomorphological surveying

The processes of erosion and deposition that occur during overbank flow can modify the existing floodplain morphology – abandoned channels could either be maintained by scour or filled with deposited sediment, depending on their position relative to the specific routing of overbank flow; and ephemeral channels could be formed as a result of scour, deposition or both. Visual observations (photo 8) suggested that the floodplain morphology was highly variable across small spatial scales (< 1 m), but the factors that lead to this heterogeneiety `are undefined and require further investigation.

This model can only explain floodplain processes in the natural sections of the Highland Water because the river banks are too high in the channelised sections. The real-world applicability of the model can therefore be tested by applying it to different types of floodplain, for which a catchment-scale classification is required.

Floodplain typology

At the catchment scale, the natural reaches were more geomorphically diverse than the channelised reaches (Tables 3.4 and 3.5). Where they were large enough, in-channel debris dams provided a major local control on the distribution of overbank flow in natural reaches, and this theoretically promoted spatially variable floodplain processes, leading to complex surface topography (see the discussion immediately above). Within channelised sections, however, the dams could not usually eject water overbank because the channel was too deep, and floodplain geomorphological diversity in these areas was consequently relatively low (Table 3.4), although relict features (most notably former channels) were easily identifiable. Out of the eight sections, four 'types' of floodplain geomorphology could be identified (Fig. 3.7): "A" - natural headwater reaches; "B" - relatively recently channelised sections; "C" - older channelised sections; and "D" - natural downstream reaches.

Type "A", the headwaters, were surrounded by, and drained, heathland, with deciduous trees on the floodplain, and had a relatively narrow valley and low-flow channel. Within these sections, ephemeral channels (EC) were fairly common (also see Table 3.4), and the active zone occupied by floodwaters was on average ~ 15 m wide, although there was little evidence of overbank deposition. The zone occupied by flood waters could have been much wider, but there were no large debris accumulations that blocked the channel to bankfull, thereby causing such floodplain flow.

Type "B" reaches had been channelised between 1870 and 1967, and this over-deepening and widening has disconnected the river from an artificially-drained floodplain covered with plantation woodland. The low-flow channel was relatively wide (Table 3.2) but, during flooding, there was very little increase in its width (as quantified by width of the trashline) due to the high banks. The floodplain in these areas was covered by dense coniferous woodland between which the abandoned former river channel meandered. Dams occurred fairly frequently in these channels.

Older channelised sections, type "C," were also surrounded by plantation and had originally been over-deepened and widened (before 1870), but some parts have since recovered to create short, narrow sections of new floodplain (Fig. 3.7; photos 15-17). Those sites with the greatest lateral accumulation were linked to significant bank erosion associated with debris dams. These sections therefore have a narrower low-flow channel but a wider flood-channel than the more recently channelised areas.

Finally, in the downstream reaches lies the wider type "D" floodplain, with deciduous trees and longitudinally variable but sometimes laterally extensive overbank flow. The longitudinal distribution of overbank flow is strongly controlled by debris dams, the formation of which is promoted by an input of wood from the surrounding mature deciduous forest. The lateral distribution of overbank flow, however, is controlled by ephemeral channels, and vertical accretion (VA) occurs in between these (Fig. 3.7). The floodplain in this reach is the most natural and most active of the surveyed sites.

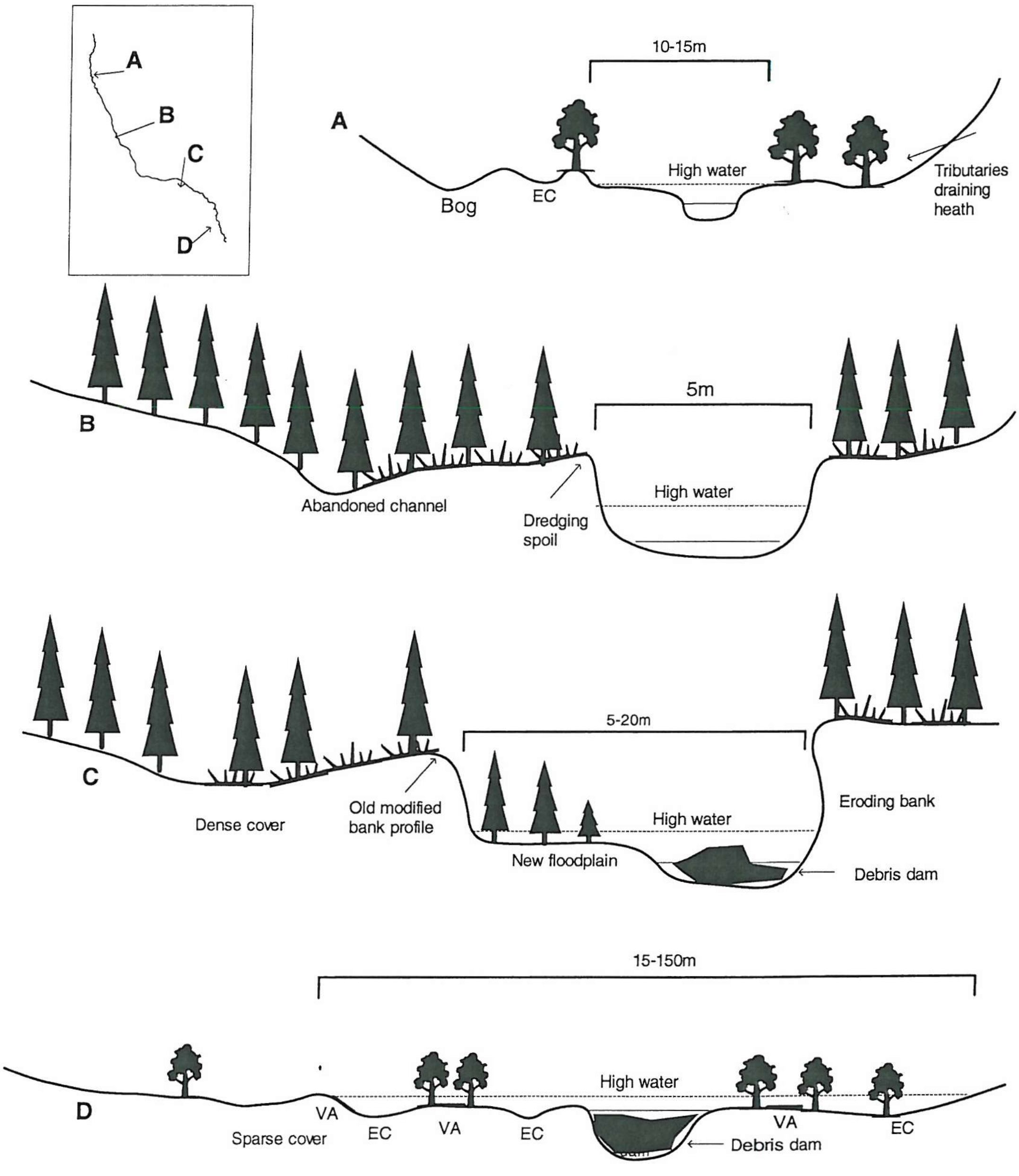


Figure 3.7 Downstream changes in floodplain character. EC (ephemeral channel); VA (vertical accretion); see text for definitions and discussion. Although these diagrams are only illustrative, note that the vertical scale is exaggerated four times for clarity

Two types of woodland covered the floodplain: plantation (either coniferous or coniferous-deciduous mix) or deciduous (afterwards termed 'natural'). The vegetation on all natural sections of floodplain was determined by Peterken et al., (1996) to be NVC type W7: this contains beech (*Fagus sylvatica*), and blackthorn (*Rubus fruticosus*). Less frequent are Alder (*Alnus glutinosa*) and Ash (*Fraxinus excelsior*). The assemblage is defined to have sub-communities of Yellow Pimpernel (*Lysimiachia nemorum*) and Common Nettle (*Urtica dioica*) (Peterken et al., 1996). However, the field survey identified that Pedunculate Oak (*Quercus robur*) and Holly (*Ilex aquifolium*) are common, while Bramble (*Rubus fruticosus*) and Bracken (*Pteridium aquilinium*) compose much of the ground flora, particularly in the downstream sections.

Fences around the Holmhill and Highland Water plantations prevent most livestock, with the exception of deer, from entering and grazing the floodplain surface. Correspondingly, vegetation is very dense in the channelised sections, particularly in reach six. In contrast, there was very little physical cover of the surface in the heavily grazed natural sections: floodplain cover in the natural reaches was composed mainly of mature trees, brambles and isolated patches of bracken.

The reach-scale conceptual model presented in Fig. 3.6 cannot be applied across the catchment to all the types of floodplain described in Fig. 3.7, mainly due to management influences (especially channelisation but also forest type). The survey and analyses were both undertaken at the catchment scale, but it is at the reach scale (and below) that fluvial processes operate, and it is at this level that further research is required. The following discussion considers both scales and concludes with a plan for the rest of this chapter.

3.2.4 Discussion

Floodplain geomorphology at the catchment scale

The catchment offers a natural and useful spatial perspective from which to consider how vegetation changes fluvial processes (Abernethy and Rutherfurd, 1998). This survey has identified that broad-scale changes in the character of the Highland Water and its floodplain result either from human intervention or a downstream change in processes: channelisation, debris clearance and grazing create four distinct types of fluvial and floodplain geomorphology (Fig. 3.7). Much of the unmodified, type "A" floodplain was fairly inactive, and although some overbank flow occurred in this area, there was often little or no evidence of recent overbank sediment deposition. Overbank flow can occur more extensively in type "D" sections. A good example of this lies within reach 8, where a very large dam in-channel debris has for nearly a decade promoted sediment deposition across a discrete area of floodplain. However, the processes within the channelised sections, types "B" and "C" were significantly affected by channel modification: high banks usually prevented overbank flow and fluvial energy was instead focused on bed and bank erosion; therefore, new patches of floodplain have been created. The most active section of the floodplain of the Highland Water lay around the in-channel debris dam in reach 8.

In the Highland Water where the main channel is frequently blocked by woody debris (Table 3.4), floodplain evolution was unlikely to be determined by a combination of lateral migration and successive layers of overbank deposition. Instead, a new model where floodplain processes are strongly influenced by vegetation is proposed in Fig. 3.6. This model suggests that biota, whether living or dead, affects fluvial and floodplain processes, and the spatial distribution of biota is likely to be an important factor for floodplain evolution. The occurrence of debris dams in the

Highland Water changes systematically downstream, peaking around 2.5 km from the drainage divide and decreasing thereafter (Gregory et al., 1993). Gregory et al., (1993) report that in 1990, most debris dams were cleared from the channel by the Forestry Commission in order to improve fish passage. Gregory et al. (1993) then calculated that debris clearance on the Highland Water is likely to have reduced present debris loadings to around 15% of the potential undisturbed level. Gregory (1992) derived a budget of woody debris for the Highland Water, and suggested that, after debris clearance, input processes were potentially able to produce similar debris loadings to pre-clearance levels within 5-10 years. While this survey did not quantify the loadings of debris, the numbers of active and complete dams in 1998 (1.28 per 100 m) was less than that reported by Gregory et al. (1995), who recorded an average of 3.7 dams per 100 m of channel. The post-clearance value was 1.15 dams per 100 m (Gregory et al., 1993). Thus, there has been only a minor increase in debris dam density in the eight years since clearance. Assuming a linear increase in dam numbers, the channel will take 157 years to recover from debris clearance. While these calculations are based on a very small number of data points, they do indicate a high sensitivity of low-gradient forested streams to disturbance. Yet how important is debris and vegetation to floodplain morphology? The rest of this chapter aims to begin answering this question by examining the distribution of lateral and vertical accretion in the Highland Water.

Reach-scale processes of floodplain geomorphology

The potential effect of vegetation on processes of lateral and vertical accretion is detailed by the floodplain process model presented above in Fig. 3.6. The model therefore differs from that of Wolman and Leopold (1957) by explicitly considering how in-channel and overbank processes are affected by biota. Firstly, lateral accretion may, in effect, be 'switched off,' or at least reduced, by in-channel debris. Secondly, overbank flow (and sediment deposition) can be controlled by the pattern of floodplain vegetation and debris.

In-channel debris locally dominates channel processes, disrupting helices of flow (Thorne and Furbish, 1995), meander migration and lateral floodplain reworking. Also, debris dams may cause in-channel deposition of fine sediment as water is backed up behind an obstruction (e.g. Hogan, 1987). Two possible scenarios can be envisaged in the life of a debris dam. In the first, the dam blocks the channel and causes a step in the water surface profile. Water is ponded upstream and the water and energy slopes are reduced, leading to sediment deposition upstream. Water is routed over, through and around the dam, and rapidly falls into the channel downstream: flow acceleration over a small area of the bank causes scour. Alternatively, if a gravel lens occurs within the bank adjacent to the dam, water can instead be routed into and through the adjacent floodplain, causing undercutting of the banks and leading to a lowering of the floodplain surface (Davis and Gregory, 1994). Depending on the location of erosion and the stability of the dam, these processes of bank erosion could cause its destabilization and breakup: a negative feedback loop. The result of this scenario is a series of localised changes in the cross-section and planform that is not necessarily related to intrinsic fluvial variables such as discharge or valley slope.

In the second scenario, the ponding caused by the dam does not erode the river banks and enlarge the channel, and instead overbank flow occurs. Overbank flow vectors are controlled by vegetation, principally trees, along definable routes. The localised nature of overbank flow caused by an in-channel dam is conceptually likely to act in a different way to the inundation of the entire floodplain that would occur during a large runoff event. Firstly, inundation occurs over a relatively small area; and secondly, because dams could promote overbank flow at discharges less than bankfull, overbank processes are active for longer. During a large flood when the active channel includes the floodplain, the water surface slope closely approximates to the valley gradient. During a lower-magnitude event where only those areas of the floodplain inundated as a result of in-channel debris are active, the water surface will slope from elevation of the upstream ponding to the elevation of the floodplain downstream of the dam (including any areas where flow is constricted by vegetation), and is therefore likely to be steeper, with a greater stream power. In essence, water can be considered to flow onto the floodplain and around the dam to return within a short distance to the main channel. At the point of re-entry, water accelerates down the river bank, cutting into it.

In the Highland Water, two factors appeared to promote the formation of debris dams large enough to block the channel: (1) debris input from upstream and (2) channel constriction (either laterally from trees growing either side, or vertically from trees growing across the channel, or both). Debris management has reduced the amount of dead wood in the river, while channelisation has resulted in a wider, straighter and deeper channel that debris cannot block (Fig 3.2 and Table 3.2). Before these modifications, some of which took place almost two centuries ago, a much stronger hydrological connection probably used to exist between the floodplain and the channel. Following clearance in 1990, the number of debris dams is still low. Therefore, the site where the large dam in reach 8 promotes overbank flow, though relatively rare when compared with the rest of the floodplain, can therefore arguably be considered to be representative of the most 'natural' floodplain processes that occur along the Highland Water.

3.2.5 Conclusions and rationale for future work

The inventory of features and geomorphic floodplain assessment provided by this survey represent novel geomorphic information about lowland forest floodplains. This information has been synthesized into a conceptual understanding of how floodplain change is associated with biotic elements (Fig. 3.6). Vegetation and especially woody debris in the channel and on the floodplain appear to modify the core processes of floodplain geomorphology. Indeed, the resulting processes bear little or no superficial resemblance to the lateral and vertical concepts of floodplain creation presented by Wolman and Leopold (1957). Woody debris dams block the channel, causing channel enlargement and, in some instances, overbank flow. Trees, dead wood and other vegetation appeared to determine the vectors of overbank flow more than fluvial processes. The spatial pattern of vegetation and woody debris therefore controlled the spatial distribution of floodplain creation processes at all scales from the catchment to the reach and possibly sub-reach levels.

However, these abiotic-biotic floodplain linkages were significantly disrupted by management. Half of the surveyed length of the Highland Water has been channelised, and despite the fact that nearly 200 years have passed since modification in some areas, only limited fluvial recovery has occurred. The floodplain has remained effectively disconnected from fluvial processes within channelised sections, but localised foci of channel change do nevertheless exist within those sections that were associated with in-channel accumulations of woody debris. Via debris clearance, management has also reduced the number of dams that promote overbank flows of water and sediment in natural sections. Even eight years after clearance, there were 65% fewer dams than before. Channelisation and debris clearance have effectively led to floodplain process dormancy. Only in one location had an in-channel debris dam reached a sufficient size to promote overbank flow and accretion.

These conclusions are the outcome from a reconnaissance level characterization of fluvial and floodplain geomorphology. The processes of in-channel and overbank accretion that are implied from this survey here appear to differ strongly from those suggested by Wolman and Leopold (1957) but no quantitative evidence was collected to evaluate this concept. Therefore, the rest of this thesis is dedicated to testing whether lateral and vertical accretion do influence the formation of the Highland Water floodplain. To begin with, a second survey was undertaken to quantify the extent and type of fluvial erosion and deposition (thus defining whether lateral channel movement was responsible for floodplain evolution). This second survey also covered the same variables and area as the first, allowing an investigation of change to be determined, and forms the second section to this chapter. More detailed experiments were necessary to evaluate vertical accretion of sediment on the Highland Water floodplain, and these are described in chapter four.

3.3 Lateral migration and floodplain change

3.3.1 Introduction

The conclusions above (3.2.5) defined the aims of this survey:

(1) To quantify lateral migration in the Highland Water;

(2) To quantify catchment-scale change in fluvial and floodplain character.

Lateral migration of a river causes erosion occurs on the outside of meander bends and deposition on the inside (Allen, 1970; Fig. 2.5). To assess whether lateral erosion occurs on the Highland Water, it was necessary to separately quantify bank erosion caused by (1) fluvial processes and (2) in-channel accumulations of woody debris. In practice, all types of bank erosion were surveyed because this allowed careful distinction to be made between erosion caused by fluvial scour, debris scour or other entrainment processes such as geotechnical collapse or animal poaching. At the same time, the number and size of in-channel bars were assessed to quantify in-channel deposition. Through the measurements of erosion and deposition, an assessment could then be made of the spatial frequency of processes of lateral migration, and its location relative to in-channel debris. Changes in planform were sketched onto basemaps and a comparison of these with the historical river location (determined from ordnance survey maps) provided information on the distance and rate of lateral river movement. Because this second survey covered the same floodplain variables in the same area as the first, inter-survey comparison provides information about the temporal and spatial change in geomorphic reaches of the river and floodplain. Although only a two year period separated the surveys, it included the wettest winter on record, and it can therefore be argued that it represents the period during which significant floodplain changes are most likely to occur.

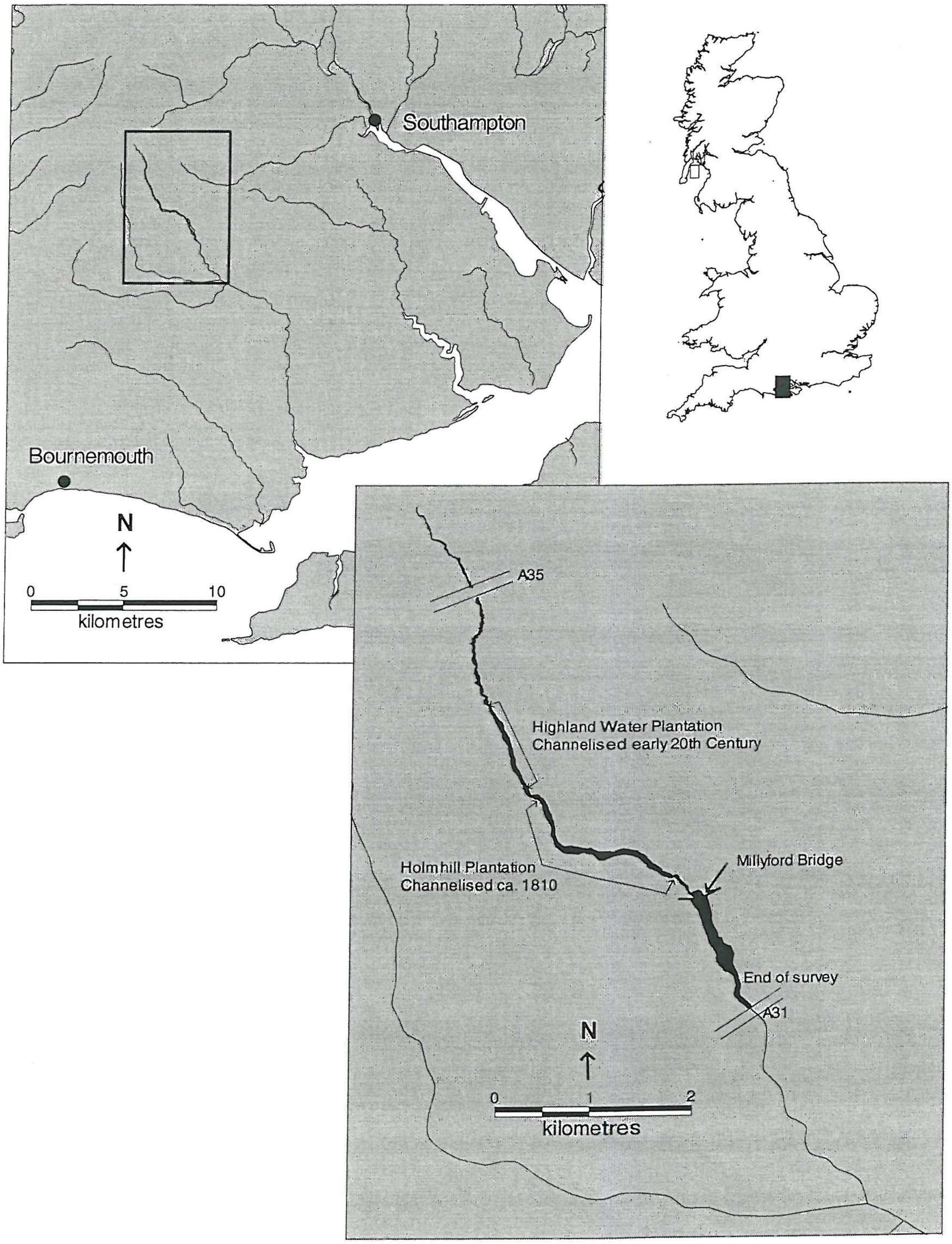


Figure 3.8 The location and extent of the second survey, which extends further up- and downstream; and follows the width of the former floodplain through channelised sections

3.3.2 Methodology

Data collection

This survey followed a similar basic pattern to the first, but was modified to efficiently address the new aims. In order to test the Wolman-Leopold (1957) model of floodplain formation, assessments were visually made of the type and severity of bank erosion and in-channel deposition. Although the method used in the first survey provided useful planform data, the continual traverses of the floodplain were very time-intensive. Also, the survey required here was to be focused more on channel process, and a new method was devised based on the previous survey and on work by German et al. (2001). Rather than pacing the widths of the channel, trashline and floodplain, planforms were carefully sketched onto base maps. Nevertheless, visual estimates of bank heights and widths were made because this allowed comparison between surveys. According to the first survey, in-channel debris dams caused hotspots of fluvial change but were associated only infrequently with overbank floodplain activity. This implies that channel processes are more sensitive to the geomorphological influence of woody debris than the floodplain, and a potential result of this would be the existence of more fluvial reaches than floodplain reaches. This difference between fluvial (channel) change and floodplain change is here termed 'floodplain sensitivity,' and was tested by separately recording geomorphic fluvial and floodplain reaches. Thus, the most important parts of the new survey structure were that the channel was surveyed separately from the floodplain, and that instead of pacing the widths of the channel, zone of recent inundation and floodplain, sketch maps were made.

Fluvial reaches were again split by geomorphic criteria: that is, where there was a discernible change in fluvial character; here this was carried out in the field and a survey form completed for each reach (Fig. 3.9). Instead of using transects, records of fluvial variables were directly noted for each reach. While walking along the river, the location, type (fluvial, geotechnical, animal poaching) and severity (low, medium or high relative to other areas of the river; photos 23-25) of bank erosion were carefully marked on the same base maps used for the reconnaissance survey. Visual waymarks were provided by roads, tributary inputs, land boundaries and by the planform of the river itself. Hence, the extent of erosion could easily be sketched to a high degree of visual accuracy upon the map.

Frequency counts were made of in-channel deposits: for each bar, the area (m^2) and types of sediment deposited (clay, silt, sand, coarse gravel, medium gravel, organic material) were recorded on the fluvial record sheets (Fig. 3.9). This provided an estimate of the amount of deposition within each reach.

Floodplain reaches were also split in the field where there was a discernible change in floodplain character. A repeat was made of the information collected during the earlier survey, and this information was recorded on a second survey form (Fig. 3.10). One of the outputs from the initial reconnaissance survey was an inventory of floodplain features, and an area of each survey form was used to prompt the surveyor to visually check for these within every floodplain reach. Any acceleration of processes by local variables (e.g. increase in overbank discharge from an in-channel debris dam) was also noted.

The survey began in mid February 2001, but completion was delayed until October 2001 by Foot-and-Mouth Disease restrictions. The survey area was extended upstream until a discernible and active floodplain was no longer evident. The basemaps of contemporary channel planform, areas of inundation and valley width were digitized in MapInfo v.6.5 on a desktop PC and the resulting polygons split into geomorphic reaches for reach- and catchment-based spatial queries.

Survey error

The technique of estimating distances in the field is subject to observer error. The two types of estimation subject to error here were visual estimates (of bank heights and widths); and the field sketches made of the planform, trashline and floodplain. To assess error associated with the visual estimates bank heights estimated in the previous survey were compared with those from the corresponding reaches of this survey (Table 3.6). The average difference between estimates was 0.11 m, with a standard deviation of 0.15 m. This equates to a coefficient of variation of 0.08. The technique is therefore precise to within 8%, and although this is no guarantee of accuracy, estimations will nevertheless highlight real changes in bank height and channel width.

Table 3.6 Error associated with the visual estimates of bank heights

Bank height (m) 1998	Reach	Bank height (m) 2001	Reach	Difference (m)
0.67	1	0.5	6	-0.17
0.71	2	1	7	0.29
1.73	3	1.8	8	0.07
1.71	4	1.9	9 and 10	0.19
1.52	5	1.7	11 and 12	0.18
1.43	6	1.4	13 to 22	-0.03
1.07	7	1.3	23 and 24	0.23
1.24	8	1.35	25 and 26	0.11
Mean of all bank heights = 1.31 m			S.D. = 0.150	
Coefficient of variation = 0.08				

The sketch maps of channel, trashline and floodplain location were subject to two types of error: (1) in the estimation of the width of a feature; and (2) in sketches of their location on basemaps. The survey in 1998 had measured channel, trashline and floodplain width more accurately than this survey because a pacing stick had been used. The first survey therefore had potential to be a relatively accurate dataset to which the sketch maps could be compared and error quantified.

The next step was to decide whether to use the channel, trashline or floodplain planforms derived in 1998 to quantify sketchmap accuracy in 2000. Because the first survey identified that woody debris in the channel and on the floodplain tended to determine the pathways of overbank flow, and because woody debris is itself variable in time and space, the location of the trashline was unlikely to be comparable between surveys. During the first survey, the width of the active floodplain was measured and in the channelised sections it was invariably confined within the channel. In contast, sketches of the disconnected floodplain adjacent to the channelised reaches were made during the 2000 survey. This change in survey strategy prevented direct comparison of floodplain widths for the full length of both surveys. Thus, channel planform was the most viable subset of the data that could be used to compare surveys. An additional source of error is the fluvial change that occurred between surveys. However, the planform was not only similar between surveys, but also to that found upon the 1953 basemaps. This slow planform change is nevertheless recognised as a small potential flaw in the error estimation.

For both surveys, the channel planform exists in the GIS as a polygon. For the first survey, each node or vertex on the polygon represents a 'real' location that had been surveyed on the ground. These nodes were derived from transects taken at 20 m intervals along the channel (for natural sections) and every 50 m (for channelised sections). Each node represents an accurate bankline location that was compared with the planform sketched in 2000. The 1998 and 2000 polygons of the channel were overlain, and the difference measured between a node and the nearest point of the sketched, digitized planform using the MapInfo ruler tool. The discrepancy in channel location was measured at 366 locations (the full length of the 1998 survey). The average difference from 1998 to 2000 was 2.066 m; the standard deviation 2.072 m (n=366). While translating these one-dimensional errors into a 2-D value that can be applied to planform errors is not straightforward, they are significantly less than the typical channel, trashline or floodplain widths, and therefore represent an acceptable error.

Data analyses

To define whether lateral migration occurred, and if so how important it was, two analyses were undertaken. First, a crude sediment budget was derived for each fluvial reach, which provided some insight into reach stability and whether different sections of the river had a net loss or gain of sediment. The total length of erosion per reach was summed and multiplied by the average bank height to give an area of erosion (m^2). The areas of all the bars in the channel were also summed into an area of deposition from which the area of erosion was subtracted. Thus, for each fluvial reach, the area of sediment deposition was compared to the area of bank erosion, which provided an estimate of the net sediment balance per reach, highlighting those with a net gain or loss, and provides an assessment of sediment dynamics that can be used to infer reach change. An inherent assumption of this technique is that the area of eroded river bank is directly comparable to the area of in-channel deposition, which in effect ignores the third spatial dimension of depth. Clearly, the depth of a given area of bank erosion is unlikely to be very similar to the depth of in-channel bars, and the depth of bars and erosion may not be constant between reaches: these are recognised limitations. Nevertheless, while the technique provides only a general estimate of the sediment balance per reach; it does allow inter-reach comparisons to be made. Other inter-reach comparisons were made with the proportion of each reach that was eroding, and with the type of erosion.

Catchment		River		Reach Code		Map Number	
Date		Surveyor		Survey conditions			

Photograph Codes	Orientation (°)

Description:-

Flow conditions Low flow ☐ M. flow ☐ High flow ☐ Bank height [m] Water width [m]

Bank characteristics

Bank material (D/✓)	Clay		Si/cl		Silt/sand		Sand		Gravel		Organic		Artificial		Obscured	
Bank vegetation (%)	Algae		Moss		Grass		Reeds		Shrub		Roots		Tree			
Roots (D/✓)	Fibrous		Adventitious		Mature		Tap									
Bank profile	Overhang		Vertical		Steep		Moderate		Gentle		Flat					
Bank structure (D/✓)	Cohesive		Non-cohesive		Composite		Eroding cliff									
Erosion process (D/✓)	Fluvial		Geotechical		Tree scour		Debris scour		Subaerial		Poaching					
Toe status	Bare		Vegblock		Gravel		No accumn		Undercut		V. colonisation					

In - channel characteristics

Bed material (D/✓)	Fines		Sand		F.Gravel		C.Gravel		Wood		Organics		Artificial		Obscured	
Bed vegetation cover	%															
Debris	Lateral		Active		Complete		Partial		Spanning							
Debris type (D/✓)	Windfall		Sawn log		Twigs		Litter									

	Gravel		Sand		Silt		Organic	
	Stable	*Unstable*	*Stable*	*Unstable*	*Stable*	*Unstable*	*Stable*	*Unstable*
Micro (<1m²)								
Meso (1-10 m²)								
Meso (10-50 m²)								
Macro (>50 m²)								

	Flow type (D/✓)
Pool	
Glide	
Run	
Riffle	
Dam fall	

	No impact	D/S scour	Bank scour	Pond u/s	Sediment
Debris dam					
Bridge					
G.S					
Outfall					
Tributaries					

Access - grazing

	Left bank						Right bank					
Fencing	None		Semi-effective		Effective		None		Semi-effective		Effective	
Access	Poor		Intermediate		Good		Poor		Intermediate		Good	
Grazing	None		Slight		Heavy		None		Slight		Heavy	

Figure 3.9 Survey form used for geomorphic river reaches

The second analysis aimed to quantify the rate of lateral migration. As discussed above, the survey error was probably greater than the amount of planform change between surveys. Therefore, planform change between 1998 and 2000 could not be used to calculate rates of lateral movement. However, the channelised planforms illustrated on the basemaps were straight and of a fairly regular width, which suggested that they represent the channel location at the time of modification. In the field, the original channelised location was evident either where no planform change had occurred, or where the channel had migrated away from its original location to abandon the channelised bank. These original planforms were evident on the basemaps, which represented the channel location at the time of modification, and a comparison of these with the contemporary planform described from the sketch maps provided a distance of lateral movement. The distances were measured in MapInfo using the ruler tool and these were divided by the time since modification to give a rate of lateral movement.

Catchment		River		Reach Code		Map Number	
Date		Surveyor		Survey conditions			

Photograph Codes	Orientation (°)

Description:-

Flow conditions Low flow ☐ M. flow ☐ High flow ☐ Bank height ☐ m Water width ☐ m

Channel form characteristics

Channel	Multichannel		Single channel		Meandering		TM		Channelised		Recovered channelised		
Old channel	Infilled		Active		Not apparent								

Floodplain characteristics

FP landuse	Conif		Decid		Mix		Felled		Heath		Scrub					
	Wetland		Urban		Road/path		Lawn		Urban		Amenity					
FP material (D/✓)	Clay		Si/cl		Silt/sand		Sand		Gravel		Organic		Debris		Obscured	
FP cover (%)	Bare		Litter		Moss		Grass		Shrub		Bracken		Trees		Heather	
Veg species (D/✓)	Alder		Oak		Beech		Conifer		Holly		Blackthorn		Other			
Tree age, structure	Young		Med/mature		Mature		Over mature		Homogenous		Clustered					
FP features	Pools		Trashline		ECs		Sheltered areas		Sand shadows							
FP process	EC scour		Areal scour		Avulsion*		Cutoff*		Overbank flow							
Extrinsicntrol (+/-)	D. Dams		Sediment plug		BP		Channelisation		Terrace		Tree					
Erosion processes	EC scour		Biogenic		Tree throw		Litter dam scour		Channel scour							
Other	*Cm relief*		*Variability*		*Sand dep*		*Silt dep*		*Clay dep*		*Organic dep*					

* S = semi avulsed or cut off; C = completely avulsed or cutoff

Floodplain activity

Debris type (D/✓)	*Windfall*		*Sawn log*		*Twigs*		*Litter*

Activity	Eroding	Depositing	Sheltered (no change)	Not inundated
High				
Medium				
Low				
None				

	Flow type (D/✓)
Pond from channel obst	
Pond from FP dams	
EC scour	
Slow flow	
Backwater (pool)	

	No impact	Control fp flow	Sediment
Debris dam			
Bridge			
G.S			
Outfall			
Tributaries			

Figure 3.10 Survey form used for geomorphic floodplain reaches

3.3.3 Results

Floodplain and channel morphology

This section describes the reaches of river and floodplain identified during the survey, and therefore provides a catchment context for the study of lateral processes described later. No significant change in the broad geomorphological character of either the floodplain or channel were apparent between the surveys, despite an extremely wet intervening winter. A typology similar to that in Chapter 3 was established, but with four times more fluvial reaches (Fig. 3.11a; Tables 3.6 and 3.7). These new fluvial reaches were a result of either extending the survey (e.g. reaches 1-5), or of a finer differentiation of the effect of in-channel dams on river morphology (e.g. reaches 12-20 & 25-31). A similar floodplain typology was established to that in Chapter 3 (Fig. 3.11b), in addition to which two new types were defined (Fig. 3.12): headwater channels, with a floodplain 6-18 m wide that was ill-defined and with no evidence of overbank flow; and incised channels near the downstream end of the survey area, where the flooding was confined within bankfull, and which were fairly active with frequent in-channel deposits of gravel.

In floodplain reach 1, a headwater floodplain, a narrow (5.9 m wide) flood zone was discernible but there was no contemporary evidence such as deposition that this feature was created by fluvial processes (fluvial reaches 1-3). The narrow channel (0.35 m wide) was liable to be blocked by organic debris, and provided insufficient energy to prevent large macrophytes, including trees, from growing into it and locally creating blockages.

Downstream from the headwater section was floodplain reach 2 (fluvial reach 4), which was on average 17 m wide and contained a narrow (5.22 m) belt of recent inundation bounded on both sides by deciduous forest. Between this natural section and the next (floodplain reach 4 and fluvial reach 6) lies the floodplain reach 3 (fluvial reach 5), which was modified, having been culverted under the A35. Ponding occurs upstream of the culvert entrance results in overbank flow and deposition of sand and silt. The low area of overbank flooding for this section (Table 3.7) reflects the fact that around two-thirds of the length of this reach is culverted, thus reducing the mean width of the inundation zone.

Floodplain reach 4 (fluvial reach 6) did not display evidence of management, and was fairly natural. The floodplain was bounded on both sides of the valley by relatively steep slopes of heathland, and, at 31.8 m wide on average, was still relatively narrow (see Fig. 3.12). Trashlines occurred within a zone an average of 11.8 m wide that frequently ran parallel to the river: variations in the width of this were fairly small (an example of this is presented in Fig. 3.13). However, the floodplain surface topography in this reach was complex (photo 8), and there was evidence of meander cutoffs (photo 6), ephemeral channels (photos 3 and 4), abandoned channels that were frequently reactivated (photo 7), and in one location the channel was almost anastomosing.

Further downstream, the heathland that surrounded floodplain reach 4 was replaced by the dense coniferous woodland of the Highland Water plantation (Fig. 3.12a). Before the plantation, an entrenched fluvial reach 7 (bank height 1-2 m; photo 9) had disconnected floodplain reach 5 from the channel. Bed scour had revealed clay plugs that were controlling the long profile by creating a step in the water surface profile (photo 10). This section was incised because it led into the most recently channelised part of the river (floodplain reach 6 and fluvial reach 8), which formed the most heavily impacted length surveyed (photo 12): river banks were high (2 m), and although the former floodplain had an average width of 46 m, it was disconnected from current fluvial processes (photo 11): the active channel and trashline occupied the same area (photo 12). At the downstream end (fluvial reach 9), the channel had undergone lateral movement of up to 7.6 m since its modification ca. 1910 (Table 3.8); the floodplain surrounding this fluvial reach remained inactive.

The upstream and downstream boundaries of fluvial reach 10 were defined by the Highland Water and the Holmhill plantations, respectively (Fig. 3.12a). While this fluvial reach had a meandering planform that appeared to be natural (sinuosity 1.94, compared with 1.15 and 1.21 for the reaches in the plantation up- and downstream, respectively), it was incised because it lay between the deepened sections within the Highland Water and Holmhill plantations. This reach was also the most laterally active site on the river, with fluvial scour of the bank toe, leading to geotechnical collapse and adjacent point bar deposition (photo 25).

The ten fluvial reaches within the Holmhill plantation (11-21) underlined the planform variability of a section that was channelised in 1810: sinuosity varied from 1.06 to 1.48. Floodplain reach 7, which was covered by less dense plantation woodland than floodplain reach 6, contained fluvial reach 11 that had five short (average 40 m) sections of lateral change, creating small areas of incipient floodplain (photos 15 and 16). While fluvial reach 12 had no clear evidence of change since its channelisation in 1810 (sinuosity 1.21), reaches 12-19 were more variable (average sinuosity = 1.30; Table 3.7); indeed, reach 16 had undergone up to 13 m of lateral movement (photo 17; Fig. 3.13; Table 3.9). Associated with this increase in lateral channel activity was a change in floodplain character, from the dense coniferous stand within floodplain reach 7 (photo 14), to the mixed, more open woodland of floodplain reach 8.

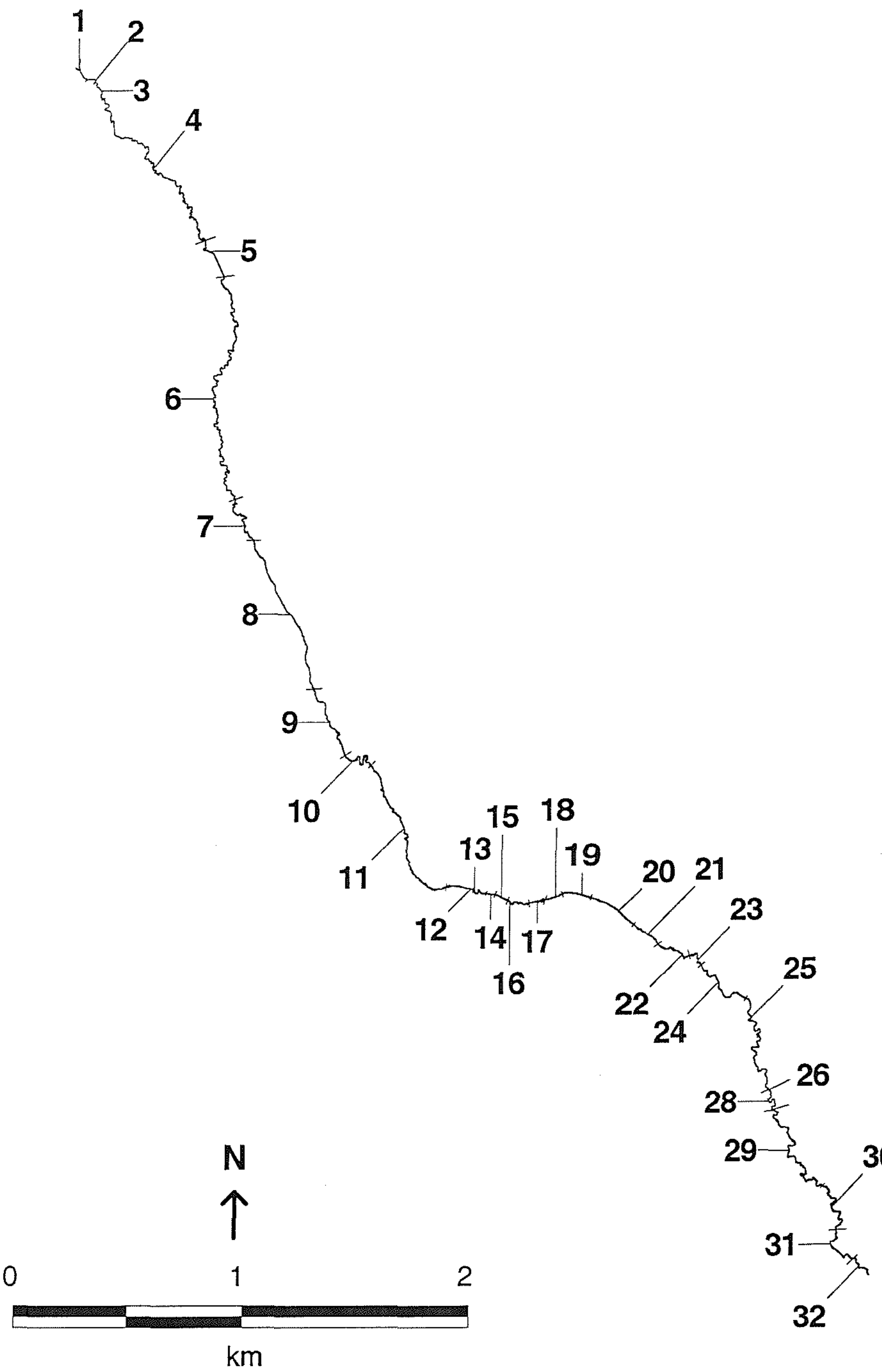


Figure 3.11a Geomorphic channel reaches

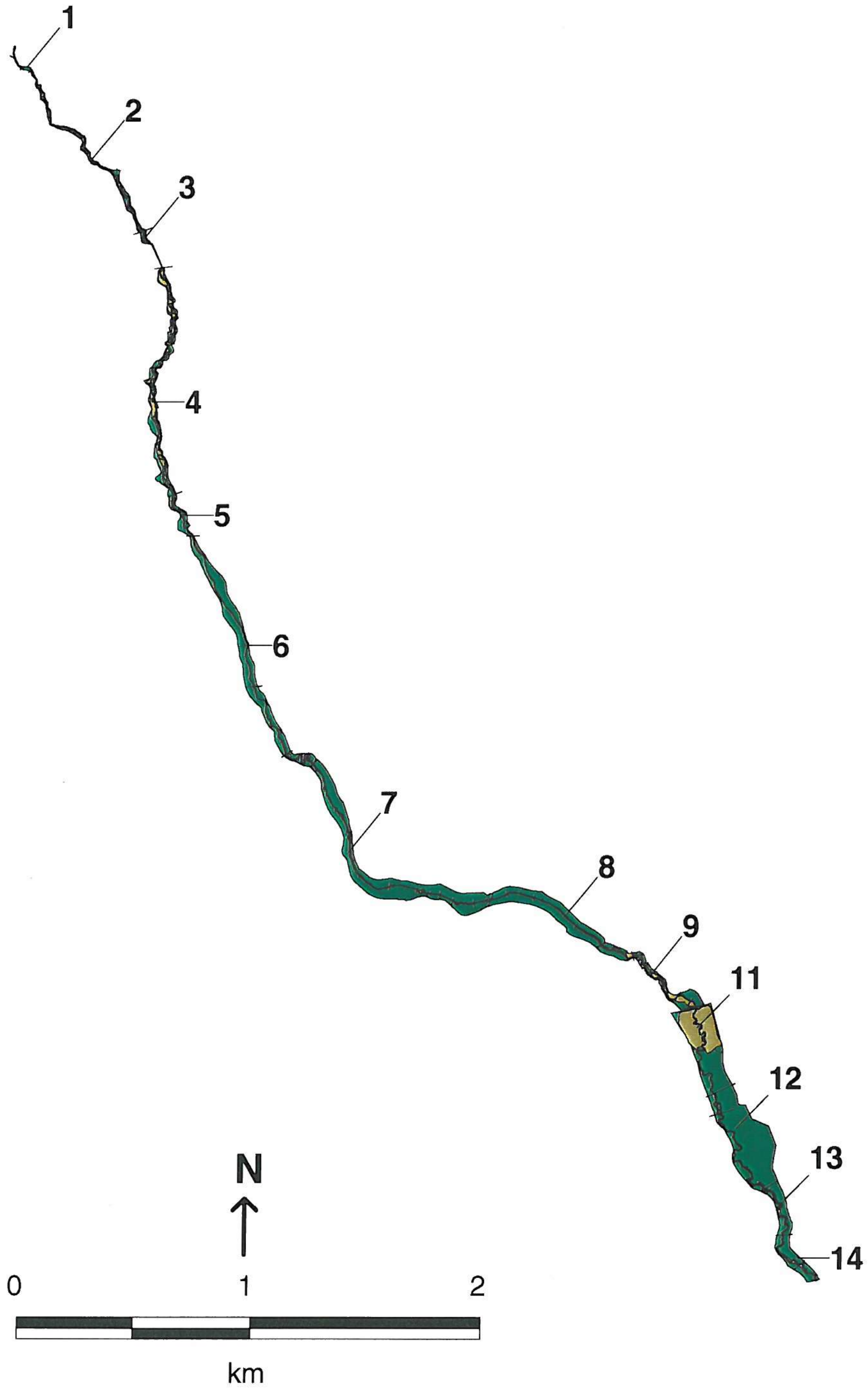


Figure 3.11b Geomorphic floodplain reaches. The floodplain is green; areas of flooding are brown.

Table 3.7 Descriptions of fluvial reaches

Reach	Description
1	Steep, small headwater stream. Floodplain poorly defined
2	Small headwater stream. Floodplain poorly defined
3	Small headwater stream. Definable floodplain but no overbank flow.
4	Channel size increasing and floodplain more evident. Overbank flow common.
5	Ponded area upstream of culvert: extensive overbank deposits
6	Long natural stretch of floodplain with definable zone of overbank flow but very little deposition
7	Natural reach with disconnected floodplain
8	Channelised reach with no floodplain
9	Channelised reach with no floodplain
10	Laterally unstable reach with overbank flow and deposition
11	Channelised reach with short sections of new floodplain
12	Inactive channelised reach
13	Actively meandering reach, formerly channelised but with up to 15m of lateral accretion
14	Semi-active channelised reach
15	Inactive channelised reach
16	Active meandering reach, formerly channelised but with up to 6m of lateral accretion
17	Former channelised reach – now meandering but no evidence of current process
18	Inactive channelised reach
19	Active meandering reach, formerly channelised, with 1 – 3 m of lateral accretion
20	Channelised reach with lower banks and short sections of lateral movement
21	Channelised reach with evidence of overbank flow
22	Natural floodplain with overbank flow but little accretion
23	Natural floodplain with increasing overbank flow ponded by bridge
24	Natural floodplain with diverse morphology and increasing evidence of overbank deposition
25	Extensive overbank flow promoted by debris dam: spatially variable depositon. Study site.
26	Natural but less active section of floodplain below debris dam
28	Tortuously meandering section with overbank flow acros meander necks
29	Less active reach with flood water largely remaining within the channel
30	More frequent overbank flow around the main channel
31	Higher banks and wider channel prevent much overbank flow; evidence of recent lateral movement.
32	Partly incised reach leading to road bridge; active lateral erosion but floodplain is poorly connected

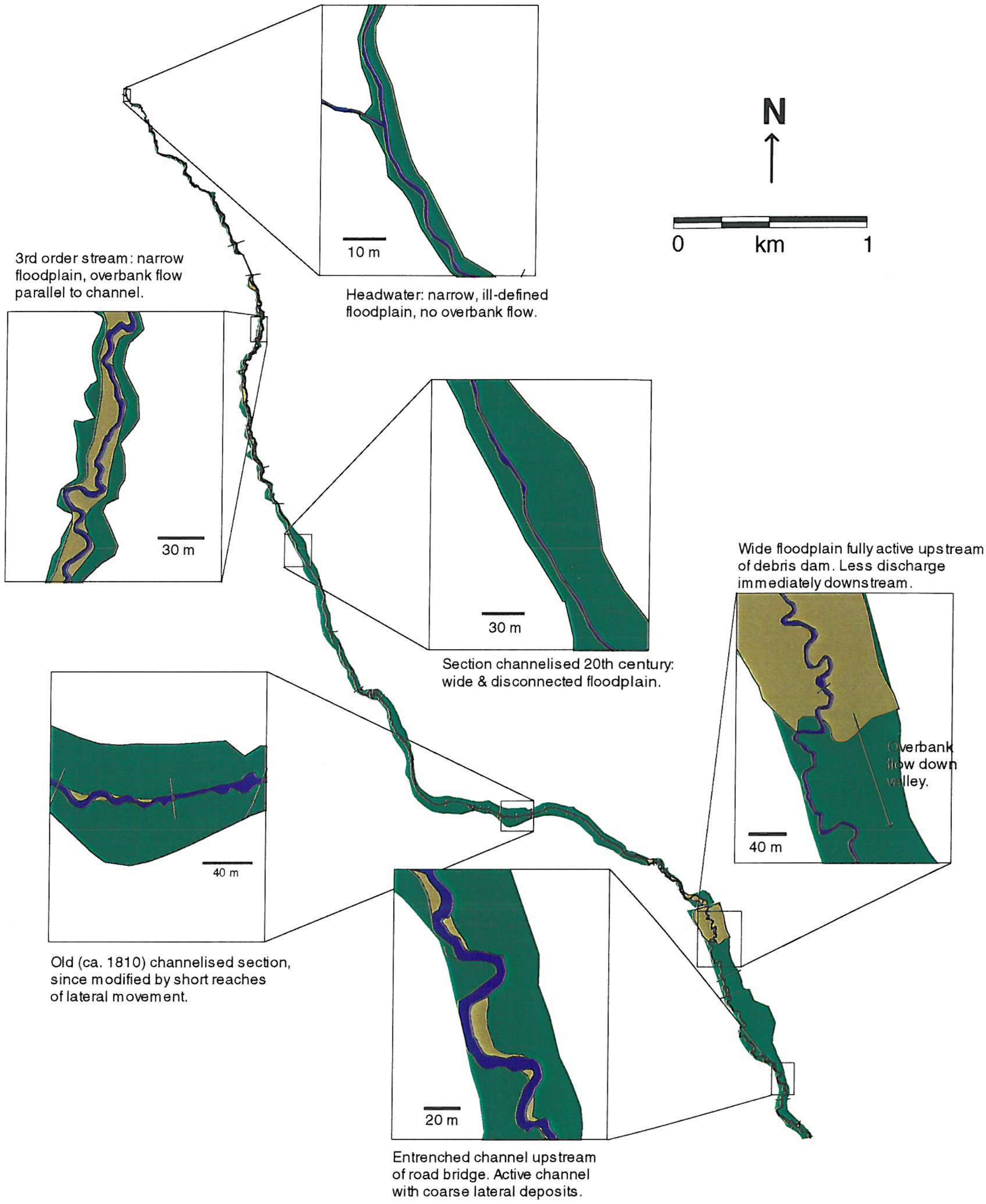


Figure 3.12 Forest floodplains of the Highland Water. The floodplain is green; areas of recent flooding are brown.

Table 3.8 Summary information about fluvial reaches

Reach	Distance downstream (km)	Sinuosity	Average width of surrounding floodplain (m)	Average width of flooding (m)	Percent recently flooded	Width of active channel (m)	Bank height (m)
1	0	1.34	5.9	0.65	9.7	0.35	0.25
2	0.18	1.31	13.1	0.72	100	0.35	0.25
3	0.29	1.31	9.5	0.84	56.3	0.45	0.30
4	1.47	1.53	17.5	5.22	40.9	1.00	0.45
5	1.70	3.23	5.5	6.00	4.9	1.00	0.40
6	3.23	1.57	31.8	11.79	66.6	2.00	0.50
7	3.46	1.12	30.2	3.61	80.7	2.00	1.00
8	4.20	1.06	45.8	2.51	68.1	2.50	2.00
9	4.58	1.15	41.1	3.58	61.2	2.50	1.80
10	4.82	1.94	42.0	6.92	50.1	3.00	2.00
11	5.58	1.21	58.7	4.57	36.8	3.00	1.90
12	5.72	1.21	81.6	3.11	16.6	2.50	1.50
13	5.82	1.48	51.1	6.58	61.9	2.50	1.30
14	5.87	1.14	66.7	4.00	0	2.50	1.50
15	5.93	1.07	58.2	3.73	0	2.50	1.80
16	6.04	1.27	87.6	5.93	38.5	5.00	1.30
17	6.13	1.16	68.6	5.42	4.7	5.00	1.40
18	6.22	1.06	55.9	3.26	22.4	4.00	1.20
19	6.34	1.15	63.4	3.91	9.6	2.75	1.50
20	6.56	1.07	63.1	3.55	10.6	2.50	1.60
21	6.70	1.07	58.4	6.38	11.8	6.00	1.20
22	6.89	1.23	42.0	12.15	13.2	4.50	1.10
23	7.01	1.80	35.7	10.49	25.6	5.00	1.30
24	7.33	1.31	50.0	16.17	16.5	4.00	1.30
25	7.60	1.52	146.4	94.75	1.4	4.00	1.30
26	8.16	2.35	94.8	1.88	16.2	3.00	1.40
28	8.59	1.67	156.3	6.97	7.5	3.00	1.40
29	9.21	1.50	134.7	1.37	26.9	5.50	1.40
30	9.52	1.68	60.5	9.86	28.6	4.00	1.30
31	9.76	1.43	62.9	8.87	5.6	4.50	2.50
32	9.90	1.45	47.4	6.91	52.1	3.75	2.50

Towards the end of the Holmhill plantation, the effects of channelisation became less evident: the banks were lower (1.1 m instead of around 1.5 m, which was more typical for the upstream channelised section) and overbank flow became more extensive (average flooding width 6.58 m). Once beyond the plantation boundary (fluvial reach 22), the width of recent overbank flow increased to 12 m. The sinuosity also increased, from 1.07 in reach 21 (within the plantation) to 1.80 in reach 23. This change from channelised to natural was also reflected by a shift from a disconnected floodplain, which had mixed woodland and dense surface cover (floodplain reach 8, photo 14), to the unmodified floodplain reach 9, which had a heavily-grazed, more open deciduous woodland, and, as noted above, a stronger hydrological connection, as indicated by a greater average flooding width. The extent of overbank flow was further increased where the channel was constricted by road bridges (fluvial reach 24; average flooding width 16 m) or debris dams, such as that in fluvial reach 25 where the average flooding width was 95 m (photos 19 and 20).

Indeed, the largest area of flooding recorded was in fluvial reach 25 (floodplain reach 11), which contained the experimental site detailed in the next chapter. The zone of overbank flow here was very wide (95 m), and the in-channel debris dam (photo 19) had caused ponding upstream as far as Millyford Bridge. Although the in-channel debris dam had significantly increased floodplain hydrological connectivity (see chapter 4), the cover of the floodplain was otherwise similar to that found within floodplain reaches 9-14. The corresponding fluvial reaches were 25-30, and these had a consistent bank height (around 1.4 m), but were otherwise variable: sinuosity ranged from 1.43-3.73, and the channel width from 3-5.5 m. Thus, in this natural section, bank heights and floodplain cover did not appreciably change, but channel planform, width and area of overbank flooding were the most variable recorded.

Towards the end of the surveyed section (fluvial reaches 31 and 32), the channel cut into steep right-bank terraces. It finally became entrenched and disconnected from the adjacent floodplain reach 14 (bank heights increase to 4-5 m), and coarse in-channel deposits became frequent. Finally, the Highland Water flows under the A31 (Fig. 3.8), which is where this second survey ended.

Bank erosion and channel deposition

The majority of the surveyed river banks were stable (that is, they presented no evidence of erosion): in 20 reaches less than half of the banks were eroding (Fig. 3.13; see below for definitions of erosion types). Reaches where more than half the banks were eroding were uncommon (7 of 32 reaches); and only within reaches 2 and 7 were most of the length of the banks eroding. The most significant areas of bank erosion were associated with recent channelisation (more than 50% of the banks were eroding within the channelised reaches 6-8,9,10 and 13). The greatest bank erosion was recorded in the headwaters (the whole length of reach 2 was eroding), but this was a local effect: the channel ran across a clay plug, the cohesion of which prevented lateral movement, steepened the local profile and promoted minor fluvial scour for the length of the reach (110m). The older channelised sections 12-22 and the natural sections 5 and 23-28 were relatively stable and bank erosion was uncommon (<25% of the bank).

The most severe type of bank erosion, a diagnostic of which was rapid recent bank retreat with many exposed roots, also occurred within the recently channelised sections 7-13 (Fig. 3.13). Bed level change (as evidenced by an incised channel with higher banks on both sides and disconnected floodplain: see Tables 3.7 and 3.8) had also promoted severe bank erosion in reach 32. Otherwise, bank erosion was relatively minor (ie. small patches (<0.5m^2) of bare bank juxtaposed with moss and other vegetation). Minor bank erosion was common within natural and undisturbed sections (1-4,16-21,22-28; Fig. 3.13). Areas of medium erosion, where the bank was free from vegetation but had not retreated rapidly (usually evidenced by exposed but intact fragile roots on top of, or within, the bank) tended to associate with areas of instability, marking the transition between these and adjacent stable areas (reaches 7-11,29-30). These generalisations must, however, be treated with caution because bank height and composition caused changes in the area and lateral depth of the same erosion type observed in different areas, and these variables were not recorded during the survey.

Bars covered less than 25% of the river bed in 28 reaches (Fig. 3.14); ten reaches (a third of the total) had between 25 and 50% of the bed covered by bars (3,4,10,13,16,22,28-31); and only in reach 32 was more than half of the bed covered by bars. Deposition was most common at or downstream of locations where the channel was undergoing erosion (10,13,16,22,28-31). Relatively more deposition was observed in the headwaters, where more than 25% of the bed was covered by bars, which was a result of local influences (reach 3 because of upstream erosion in reach 2; reach 4 because of ponding under a road culvert). Note that direct comparisons of bank erosion and bed deposition are not valid because the area of river bed varies independently of the areas of river banks per reach: these data should be treated as very general indicators of prevailing processes.

The most significant factor to affect bank erosion and channel deposition was channelisation. The oldest stretch of channelised river was created around 1810, and this lay within the Holmhill plantation (Stagg, 1990; see Fig. 3.12). The Highland Water plantation was channelised between 1875, with a short section immediately downstream of fluvial reach 6 being modified in 1967. These sections of relatively recent modification were eroding more than the older channelised reaches downstream (compare reaches 7-11 with 19-21 on Fig. 3.13). The older channelised reaches downstream (14-21) were relatively stable. Other more subtle variables also affected bank stability, such as road culverts, bridges and clay plugs. In the absence of such controls, the natural channel, which had cohesive banks and occasional debris dams, experienced short sections of minor bank erosion, implying slow lateral movement.

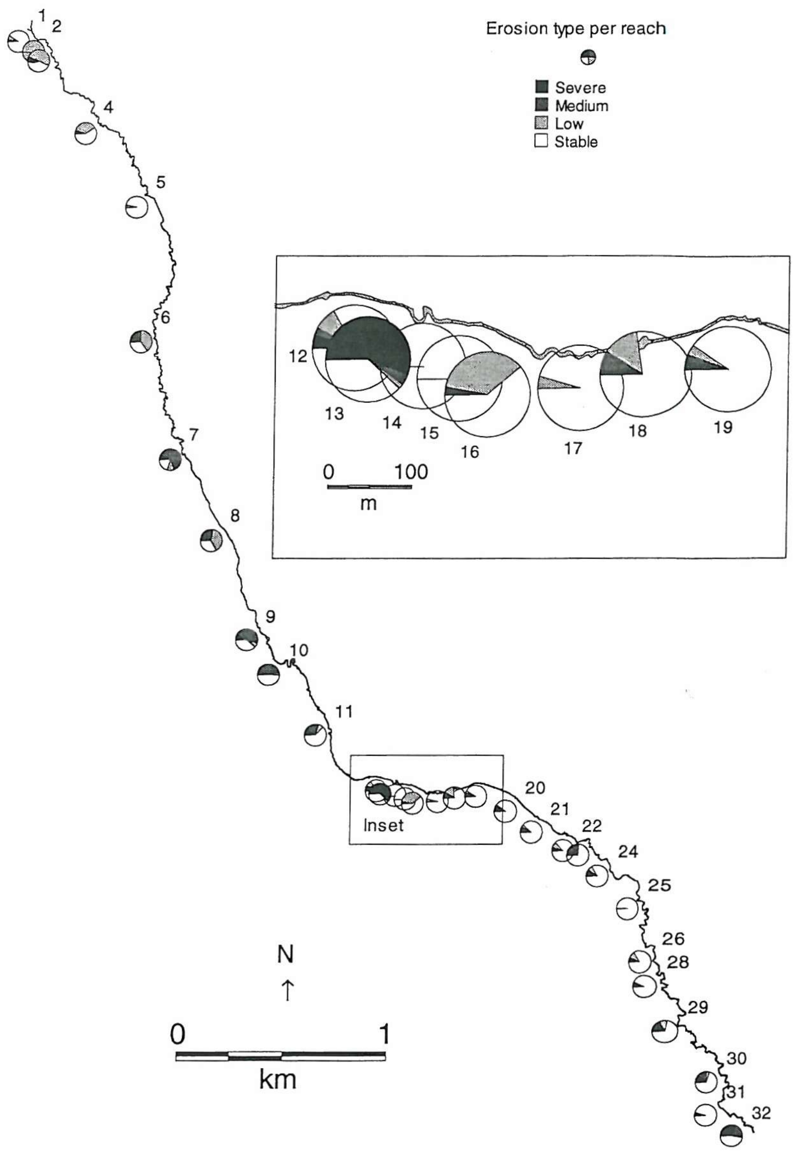


Figure 3.13 The proportion and type of erosion for each reach: see text for definitions of stability and erosion types

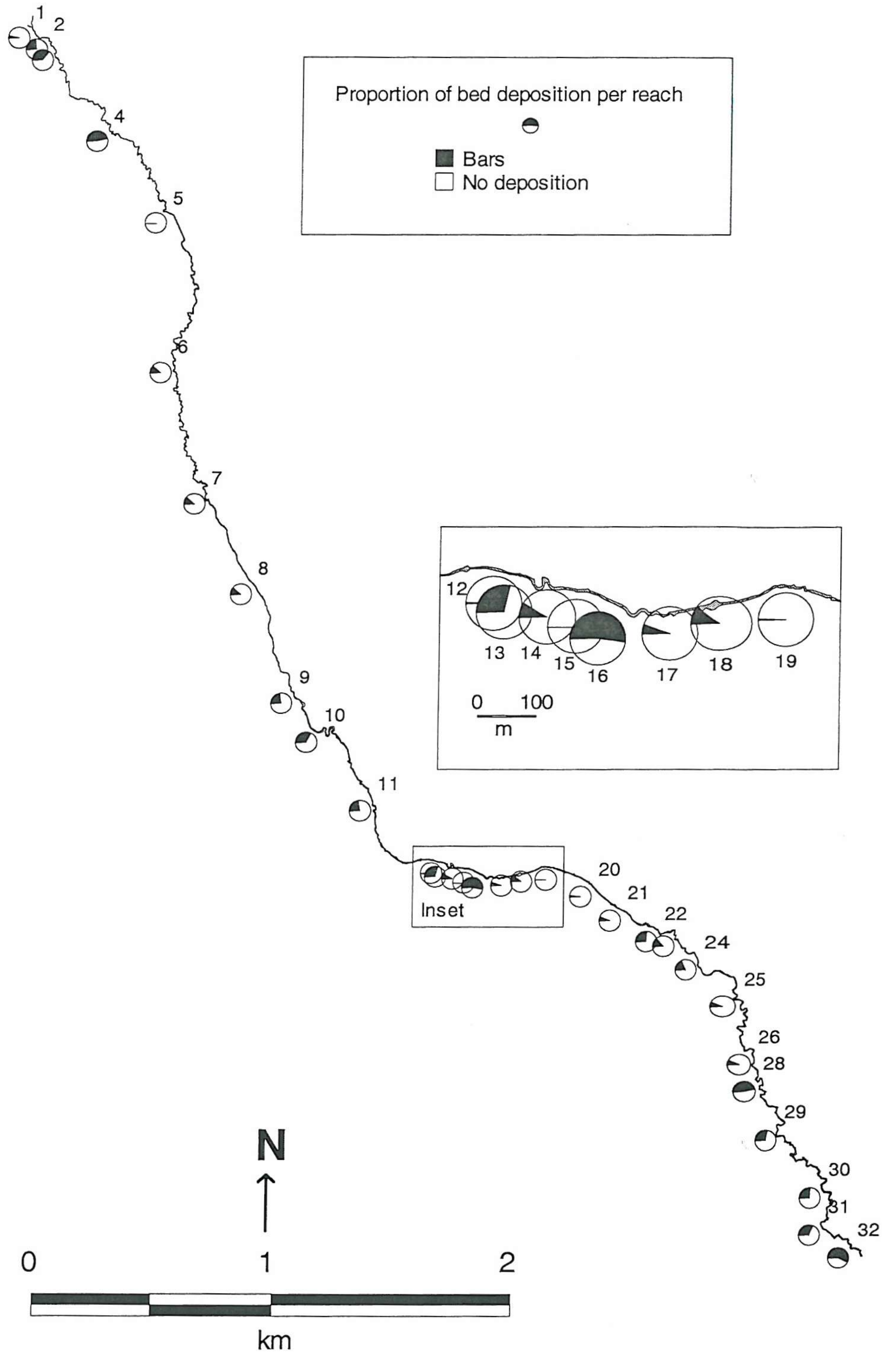


Figure 3.14 The proportion of river bed covered by bar deposits

Influences of debris dams on overbank flow and bank erosion

Within natural fluvial reaches, as the spacing of dams within a reach increases and they become less frequent, the area of overbank flow also increases (Fig. 3.15). This surprising result, albeit with very weak correlation ($R^2 = 0.46$) is probably due to the fact that a minority of large dams promote most overbank flow, and that the more numerous smaller dams have less impact on channel and overbank processes. Although no data on the size of dam was collected that allow this hypothesis to be tested, some support is provided by the dam that causes 25,000 m^2 flooding, which is the site of the largest dam studied in Chapter 4. Within channelised sections, a weaker reverse trend is presented, where as the spacing between in-channel debris dams increases, so too does the area of overbank flow (Fig. 3.15). Nonetheless, 12 reaches that were free of debris dams also experienced overbank flow (Fig. 3.15), and 7 of these were within the plantation where the only small areas of new floodplain created by lateral movement existed (see section below). As reflected by such a weak correlation between dam spacing and flooding extent, debris dams in the main channel were not the only influences on overbank flow: where the river was channelised, overbank flow onto the former floodplain surface could not occur, and floods were confined to new areas within the channel. While the area of overbank flow appeared to be weakly linked to the frequency of debris dams, no correlation existed between the spacing of in-channel debris dams and the amount of bank erosion. However, the spatial patterns of erosion (Fig. 3.13) illustrate that channelisation did create reaches that were prone to bank instability. Thus, extensive erosion was not especially related to the presence of dams, which were instead more likely to promote short sections of channel diversity, (e.g. fluvial reaches 13-19).

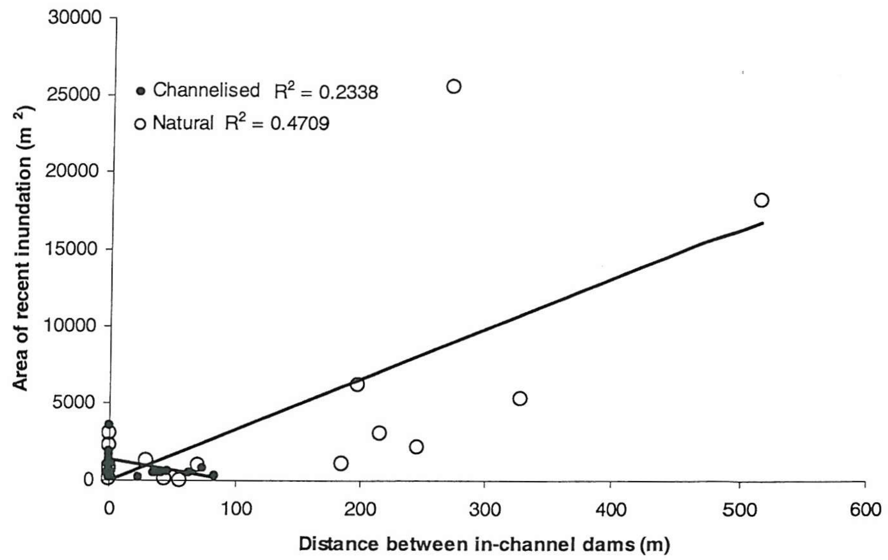


Figure 3.15 The effect of debris dam density on the area of overbank flow

Lateral migration of the channel from 1810 – 2001

Despite the wettest winter since Meteorological Office records began, little overall change in channel morphology was evident in the time interval between the two surveys. This forested channel with cohesive banks was largely static 15

in terms of lateral response, even after an extreme period. Within natural sections, very small amounts of lateral change might have occurred, but a qualitative visual assessment was insufficient to quantify these. However, an estimate of the long term rate of lateral movement in channelised reaches was made from channel movement, quantified from digitized fieldwork maps. The sketching and digitizing both allow errors to occur, and considering these, the values of change are estimated to be accurate to within 2.1 m. The distance of the original channelised line from the contemporary planform divided by the time since modification provides estimates of the average rates of channel migration that range from 0.8 to 9.5 cm/yr (Table 3.8).

Although most contemporary erosion occurs within channels modified ca. 100 years ago (Fig. 3.13), the older channelised sections have generally been the most active in terms of lateral accretion (Table 3.9). The river in these sections therefore appears to have evolved to become a stable if not natural channel following channelisation nearly 200 years ago. The more recently channelised sections, particularly those modified ca. 100 years ago, still appeared to be adjusting to the change. This again underlines the slow rate of lateral movement and accretion in this lowland forested channel.

Table 3.9 Rates of lateral movement.

Fluvial reach	Distance channel movement (m) Mean	Max.	Years since channelisation	Rate of channel movement (cm/yr) Mean	Max
1-8	0	0	N/A	0	0
9	4.8 (n = 5)	7.6	Ca. 125 - 50	Ca. 3.84 - 9.6	15.2
10	6.2 (n = 4)	10.4	191	3.2	5.4
11	3.7 (n = 19)	7.1	191	1.9	3.7
13	8.2 (n = 3)	13.3	191	4.3	7.0
14	2.1 (n = 1)	2.1	191	1.1	1.
16	3.3 (n = 5)	6.2	191	1.7	3.2
19	2.3 (n = 3)	3.4	191	1.2	1.8
20	1.5* (n = 2)	1.8*	191	0.8*	0.9*
21	2.7 (n = 1)	2.7	191	1.4	1.4
22-32	0	0	N/A	0	0

* change within error bounds is considered to be undetectable at the precision levels employed in this study

3.3.4 Discussion

The lateral erosion within the natural reaches of the Highland Water, 24 to 30, was not enough to be detected using this walk-through survey. Reach 6, another natural section of the river, also experienced only small amounts of lateral erosion. The modified reaches 9 - 21 had, however, experienced lateral erosion and had the river had migrated up to 13.3 m from the original channelised course (Table 3.9). Thus, in the absence of disruption from previous management, the Highland Water underwent little lateral erosion. Although the older channelised sections currently appear to be fairly stable, the recovered floodplain does not have the same geomorphological diversity as natural sections.

Where the river has been channelised, it is less sinuous than the channelised sections; (Table 3.8). Thus, the thalweg length is shorter and, although the bed of the river was lowered (to increase floodplain drainage), the valley gradient would have remained the same. A shorter river length therefore falls over the same vertical distance, increasing overall slope. This in turn will increase stream power, which is a physical measure of the potential sediment transport capacity (Bagnold, 1966). These anthropogenic changes to stream power could explain why lateral accretion has occurred within channelised sections. However, the cross-sections of the channelised reaches were generally wider and shallower than the natural reaches (Table 3.2): the average width-depth ratio of channelised sections was 11.3, compared with 6.5 for the natural sections. Therefore, while the channelised sections had a slightly greater slope, the increased stream power was distributed across a much wider cross-section. The channels would probably have been deliberately over-engineered in this way in order to prevent channel change.

Nevertheless, channel change has occurred and new floodplain has been created. The contemporary examples of change in channelised sections are associated with in-channel debris dams. Firstly, if the dam partly or completely blocks the channel but does not create a step in the water surface profile, then for a given slope and discharge the stream power must be applied to a smaller cross-section. This focus of fluvial energy over a smaller area will promote a higher bed shear stress and could cause bed or bank erosion. Secondly, an active dam ponds the water and stores kinetic energy upstream, dispersing stream power over the dam face, over the bed downstream, or at the adjacent banks, all of which can then become loci for channel change. Finally, if a dam completely blocks the channel then it may promote overbank discharge of water and sediment, effectively energizing floodplain processes, although this process appeared to be limited to the natural reaches where river banks are lower.

Trees and other vegetation provide the source material for in-channel debris dams, locally altering the cross sectional area, slope and flow hydraulics of an otherwise relatively stable cross-section, and causing fluvial change to occur. The distribution of the fluvial energy that drives this process is controlled by in-channel accumulations of woody debris. One conclusion from these data is that fluvial changes may only occur because vegetation locally controls the pattern of energy dissipation. If this is true then the channel planform would be a direct result of debris-instigated change, and would be quite chaotic. However, in reaches 12 to 19 the planform distinctly meanders (Fig. 3.12; photo 17), suggesting that the lateral migration described by Wolman and Leopold (1957) has occurred. This process is a direct result of distinct flow helices that in turn results from meandering planform with pools and point bars that has evolved since channelisation.

In-channel debris causes fluvial energy to be directed at small areas of the bank or bed, causing erosion and channel change over a small area. Stream power at this locus is increased, and assuming a finite source of fluvial energy, the energy lost to friction and sediment transport reduces that available for distribution elsewhere. Therefore, once the eroded sediment moves downstream out of the zone of high energy and beyond the influence of the debris, it will be deposited as a bar. This reduces channel capacity and potentially causes (lateral) bank scour, the material from which moves further downstream to another section of lower energy, where it is deposited to narrow the channel and instigate adjacent erosion (cf. Nelson and Smith, 1989). These disturbances to the hydraulics of channelised sections (where stream power is higher) therefore cause alternating bars to form downstream, which in turn could promote helical flow and the process of lateral accretion described by Wolman and Leopold (1957). Because stream power is higher in the channelised sections, and because flow is concentrated within a smaller cross-sectional area of channel, then once lateral change begins, it is likely to continue until the local bed slope (and therefore stream power) is reduced by the increasing thalweg length in the meander. This is a system of negative feedback that starts where (1) channelisation increases stream power, which (2) is then redistributed across the bed by woody debris, triggering (3) self-sustaining fluvial processes that lengthen the channel and disperse fluvial energy over a larger bed area, leading to a stable morphology that dissipates excess stream power.

This conceptual model, where direct and indirect changes to fluvial geomorphology are caused by debris, can also be applied to the natural reaches of the Highland Water but the suite of processes differs slightly. Two physical differences are important: firstly, the existing meandering planform provides a lower slope and stream power; and secondly, the river banks are lower, so that overbank flow is more likely to occur. The most active parts of the natural sections observed during this survey were: (1) where erosion instigated by in-channel debris occurred, leading to widening or deepening; or (2) where changes in channel planform (either meander cutoffs or avulsions) occurred. For the first type, cross-section enlargement around a debris dam could undermine that dam and lead to its breakup, and any eroded material will move downstream, reducing the area of the cross-section and causing concomitant channel change. Thus, widening or deepening caused by in-channel debris leads to a diverse planform and bed morphology. Secondly, an in-channel dam may block a meander loop, pond flow and cause overbank flow to occur across the meander neck (cf. Gay et al., 1998). Flow across a meander neck may also occur without the direct influence of an in-channel debris dam because roots and LWD frequently line the river, increasing roughness, decreasing channel capacity and increasing bank strength. During flooding, therefore, the neck of a meander provides the shortest, steepest route for the water to follow, causing scour and meander cutoff (photos 6, 7 and 22). The actual pathway of overbank flow across a meander neck is controlled by the distribution of trees, vegetation and woody debris on the floodplain surface (photo 22), and these influences of vegetation require further investigation. When a meander is cutoff, it will locally increase the bed slope and stream power. This increase in energy could then promote lateral migration processes, eventually leading to a reduction in bed slope: this forms a second negative feedback loop, triggered by fluvial or biotic factors, and then driven by fluvial processes towards a stable channel form.

Local avulsions around in-channel debris dams have been described in small, steep streams in California by Keller and Swanson (1979); and Harwood and Brown (1993) described how in-channel debris created flow avulsions in the Gearagh, a low-gradient, anastomosing channel with cohesive banks in Ireland. In-channel debris therefore appears to affect fluvial hydraulics across a range of environments.

3.3.5 Conclusion

This section aimed to investigate how significant lateral accretion was throughout the Highland Water, and concludes that it does occur and appears to be either driven or at least modified by biota. The exogenic and spatially heterogeneous addition of vegetation or woody debris to the river channel drives processes of lateral floodplain accretion. These processes have been accelerated by the impacts of management, especially increases in bed slopes following channelisation.

While the processes of lateral accretion described by Wolman and Leopold

(1957) occur on cleared floodplains at regular, quasi-period spatial intervals, the biotically driven geomorphic processes described for the Highland Water are spatially much more variable. Floodplains can therefore be divided into (1) those dominated by lateral and vertical accretion that is driven by hydraulic structures and regular morphology (the model of Wolman and Leopold, 1957), and (2) this model, where processes lateral (and vertical) accretion are spatially incoherent, reflecting the strong control of in-channel biota. The resulting alluvial architecture of a forest floodplain will therefore differ significantly from that of a cleared river. However, this survey implies that the floodplain stratigraphy is likely to be similar for either type of floodplain whether or not it has been affected by forests, because the ponding caused by in-channel debris is likely to ensure that bedload remains in the channel, whereas fine sediment may be deposited overbank. Indeed, bank exposures within the Highland Water show a layer of fine sediment around 1 m deep on top of a layer of coarse gravel. Finally, while this survey has identified that debris dams promote overbank flow, whether this results in the deposition of a thick mantle of fine-grained sediment remains an open question, and is the subject of the next chapter.

3.5 Summary and conclusion to the surveys

As a whole, this chapter aimed to characterize floodplain geomorphology and compare it with existing conceptual models of floodplain formation. The first half of the chapter described how the floodplain geomorphology of the Highland Water has a characteristic suite of features including some, such as ephemeral channels, that as yet have no clear origin. The Wolman and Leopold (1957) model of floodplain formation could not explain the formation of all these features. The second survey, undertaken to examine whether in-channel debris affected lateral migration, concluded that in an environment where the rates of lateral migration are generally very low, debris is a key element in the functioning of fluvial change, especially where the fluvial system has been modified by management such as channelisation and debris clearance.

The unusual combination of forest floodplain, low-gradient (0.0085) meandering stream and cohesive banks makes a uniquely valuable site to compare with cleared lowland floodplains elsewhere. Almost all research into the effect of woody debris on fluvial and floodplain processes has focused on upland environments (chapter 2), so there is virtually no knowledge about how woody debris affects lowland meandering rivers, nor about how to restore such environments. Yet meandering, low-gradient rivers with cohesive banks are characteristic features of many regions. The first conceptual model of laterally stable meandering rivers and forest floodplains is therefore provided by this study (Fig. 3.6), and underlines that process and morphological diversity is driven by biota. Many recent studies confirm that geomorphic diversity is generic to most forest floodplains, and that this physical variability results in high biodiversity (Smock et al., 1989; Hupp, 1992, Friedman et al., 1996; Piégay et al., 2000; Bendix and Hupp, 2000; Deiller et al., 2001; Gurnell et al., 2001; Hughes et al., 2001; Ward et al., 2001). The geomorphic baseline provided by this survey could be highly valuable not only for expanding scientific understanding but could also prove to be a useful reference for restoration.

The two halves of this chapter describe a new model of forest floodplain formation based on the heterogeneous spatial impacts of vegetation. The chapter has concentrated most explicitly on in-channel processes, only looking in a qualitative manner at overbank processes. Extensive overbank sedimentation was observed on the Highland Water around a large debris dam near Millyford Bridge. Large dams promoting flooding are now uncommon because many of them were cleared from the channel in 1990. The interaction of these overbank processes with vegetation are the subject of detailed experiments (chapter 4) that were undertaken for two reasons. Firstly, the larger number of dams that previously existed probably promoted more overbank flow, and so the process of vertical accretion could therefore have been historically more important than it is today. Because the processes of floodplain formation are slow – no significant fluvial or floodplain changes were observed between surveys – a process of rapid vertical accretion, such as that described above, would be important for long-term floodplain evolution. Secondly, a test needs to be made of whether overbank accretion as described by Wolman and Leopold (1957), and later by James (1985) or Pizzuto (1987), occurs on the floodplain of the Highland Water.

3.5.1 Choice of study sites

The two surveys provided an ideal dataset to locate an experimental site for the investigation of the effects of vegetation on overbank processes. In-channel debris accumulations appeared to play a very important role in determining the location and amount of overbank flow, and thereby overbank deposition. The frequency of debris dams on the Highland Water is currently much lower than it was before debris clearance in 1990 (Gregory et al., 1993). The only place the floodplain was still active was at the largest debris dam near Millyford Bridge. This dam was the largest contemporary example on the Highland Water and, as it is the most likely site to closely replicate the pre-disturbance conditions, the area around it was chosen for detailed process investigations.

Chapter 4
The control of woody biota on overbank deposition

4.1 Introduction

The experiments described in this chapter investigate the effects of woody vegetation on overbank flow and patterns of sediment deposition on the floodplain of the Highland Water. This complements the previous chapter by addressing the second half of the most widely-accepted conceptual model of floodplain evolution, that of Wolman and Leopold (1957). This chapter tests whether the patterns of overbank deposition observed on a wooded floodplain are similar to those predicted by numerical models of overbank deposition (James, 1985; and Pizzuto, 1987).

Two field campaigns were undertaken: a pilot study on a relatively small, low energy part of the catchment; and the principal study in a relatively energetic part of the main channel (Jeffries et al., in press). The pilot study provided information on the technique of using Astroturf ™ sediment traps to sample overbank deposits of sediment. Unfortunately, the pressure transducer failed to record stage properly, and algal growth on the turbidity probe prevented the estimation of suspended solids. Nevertheless, this initial testing of sediment traps gave useful information about the amount and pattern of sediment deposition.

During the second study, on the study site identified above on the main stem of the Highland Water, sediment traps were deployed, recovered and redeployed during nine intervals coinciding with one or more flood events. Stage-discharge and turbidity-suspended solids relationships were integrated to provide estimates of water and sediment flux for each sampling period, and these values were compared to the gross amounts of deposition observed on the floodplain (Jeffries et al., in press). A survey of the floodplain topography (including vegetation and woody debris) was undertaken, and the interpolated surface of this was visually compared with the patterns of sediment deposition. Thus, the relative influences of (1) hydrology (independent driving variable); and (2) geo/biomorphology upon sediment deposition were investigated. The relationships between these variables were also analysed using correlograms and statistical analyses.

4.2 Aims, objectives and methodology

By relating driving hydrology, surface topography and patterns of sediment deposition observed using sediment traps, the experiment aimed to assess how vegetation affected overbank sediment deposition. Two objectives were proposed:

(i) Investigate how biota (principally in-channel debris dams) modify channel and floodplain hydrology and thus affect gross amounts of floodplain sediment deposition.

(ii) Relate patterns of overbank deposition to the topography of the floodplain surface (including morphology, trees and woody debris).

To address these aims, firstly, river stage and suspended sediment load were recorded continuously at each site using a Druck PCDR-1730 pressure transducer (range 1.5m) and Partech IR40C turbidity probe linked to a Campbell CR10X datalogger. Secondly, post-event sampling provided information on the inter- and intra-event patterns of floodplain sediment deposition. Many authors have used a network of sediment traps across the floodplain to collect overbank sediment. No evidence suggests that these devices trap sediment significantly more than a natural grassy surface (Asselman and Middelkoop, 1998; Briggs, 1999; Middelkoop and Asselman, 1995; Mansikkaniemi, 1985; Lambert and Walling, 1987; Nicholas and Walling, 1997).

Briggs (1999) compared sediment accumulation rates between AstroTurf ™ mats, short cropped grass, long cropped grass, and bare soil, and found no significant difference between them in terms of sediment trapping. Mansikkaniemi (1985) also found no significant difference in sedimentation rates between artificial grass traps and rubber or plywood traps. Therefore, traps provide stable and precise samples, that permit comparisons to be made between this experiment and sedimentation rates observed elsewhere (e.g. Middelkoop and Asselman, 1995).

Most authors have previously used Astroturf™ mats with dimensions of around 0.5 m by 0.5 m. However, the baseline survey (Chapter 3) revealed that deposition on the floodplain of the Highland Water is highly variable across space; boundaries between zones of erosion and deposition are often less than 10 cm. Traps 0.5 m wide would therefore have been impractical to deploy: I considered the maximum practical size to be 0.2 m per side, and cut the traps accordingly. The traps were deployed within a stratified random sampling network: a grid was paced and the traps set down at intervals by throwing them onto the floodplain surface, thus providing a random element that prevented deliberate sampling bias. However, occasionally a trap fell onto an unsuitable area, such as a log, in which case it was moved to the nearest area of floodplain. The surface of the floodplain differed between study sites, and this is reflected by different layouts at each study site.

Selective deposition of suspended sediment (Lambert and Walling, 1987) can be caused by the hydraulic effect of vegetation (Tabacchi et al., 2000). The grain size of a deposit affects its resistance to erosion, changes soil chemistry (with implications for contaminant uptake or retention), and defines the environment for ecological colonisation (Bendix and Hupp, 2000). To assess the effect of vegetation on the type of deposit, therefore, size fraction analysis was undertaken for each sample. The fraction of organic matter was also analysed.

Laboratory analysis

After each flood the traps were removed carefully from the surface of the floodplain and sealed into plastic bags. New traps were deployed to replace those collected. During the pilot study, bagged traps were returned to the lab where sediment was washed off into a plastic container, the contents of which were then wet-sieved. Each sample was predominantly fine-grained and deposits were often dominantly composed of organic material. A 2mm (-1ø) sieve was used to segregate all coarse particles (this fraction was always organic). The second division (1.4mm or around -0.5ø) confirmed the presence of inorganic sediment between 1 and 1.5mm in diameter. The final division (0.063mm or 4ø) separated sands from silts and clays. These subsamples were dried at 105°C and weighed. The entire sample beneath 1.5mm was homogenized and a subsample of around 1g (if this quantity was available) was analysed for the organic fraction using Loss On Ignition (LOI).

To perform LOI, samples were placed in a weighed, dried crucible and the crucible was then rapidly reweighed (before any atmospheric moisture had been absorbed) to determine sample weight. This was placed in a furnace and slowly heated to 450°C for four hours. The crucible was cooled to room temperature in a desiccator and reweighed. This determines the loss on ignition (LOI) of organic matter. Changes in the structural water in clay minerals can occur above 500 °C, thus changing the characteristics of the sample and below 450°C there is a risk of incomplete combustion. After the mass and LOI analyses, there was usually insufficient material on each trap to perform particle size analysis (initial attempts were made to do this using an LS-100 laser particle size analyser, but the quantities were insufficient to provide output).

During the main study, traps were collected in the same manner as before. As found in the pilot study, a significant proportion of each deposit was found to be organic material such as leaves, twigs and seeds. However, the volumes of fine material were great enough to allow a laser particle-size analysis using a Coulter LS-100. The LS-100 analyses sediments up to 700 μm in diameter and the coarse fraction of the sample was therefore retained by passing the sample through a 700 μm sieve. There was no inorganic sediment coarser than this fraction. Both fractions were subsequently dried at 105 °C for at least 4 hours (or until dry) and weighed.

Three samples for laser particle size analysis were taken from each trap. This usually represented a small loss from the gross mass that was measured, but for some traps the volume retained here (to be later analysed and discarded via the LS-100) was quite significant, so this loss was quantified for all traps. The volume of sediment lost in each sample tube was visually estimated for transformation into the mass lost. A volume - mass relationship was estimated by filling sample vials with a range of dry masses of 125μm sand and these were filled with water, agitated and left to settle. The volume of sediment per vial was visually estimated and related to the known mass. The masses lost were added to totals per trap.

The analysis therefore quantified (1) the total mass of deposits (2) the mass and size distribution of the (inorganic) fraction below 700 μm and (3) the proportion of the sample composed of coarse (organic) material ($\geq$ 700 μm). Finally, to facilitate analysis of the spatial patterns of sediment deposition, the locations of the sediment traps were surveyed, in the same coordinate system and at the same time of the topographic surveys.

Topographic surveys

Two site surveys were undertaken to establish floodplain topography, and particular attention was paid to surveying the locations, sizes and characteristics of floodplain vegetation, both living and dead. The pilot study site was surveyed in January 1999. Two surveys were undertaken during the main study: the first (6th October) covered an area upstream of the dam, and around 600 points were surveyed across an area of around 719m^2. The second survey was undertaken across a larger area (around 1425m^2) and had more points (around 1300). In each case, triangulation with linear interpolation was used to produce an elevation model of the floodplain surface. This interpolation technique is very simple but has the advantage that it does not extend the calculations beyond the spatial boundary set by the points themselves. The very high spatial variation found on the floodplain means that interpolating beyond this boundary would have almost certainly produced incorrect data.

Interpolations were also undertaken on the amount of deposition and percent silt and clay recorded on the network of sediment traps per event, and these surfaces were analysed using correlograms to assess trends in the spatial pattern of the variables. The value at the centre of the grid was correlated with those at increasing distances along the vector **h**. This type of analysis is covered in more detail in Isaaks and Srivastava (1989). The correlation highlights the spatial orientation of major trends within the data (it describes a measure of the spatial anisotropy of the variable). This is perhaps best explained by a simple example. Consider a flat floodplain with a straight channel running along its centre. During flooding, the James (1985) and Pizzuto (1987) models will predict a linear reduction in sediment deposition away from the channel, and an interpolated surface of this deposition will illustrate a central zone of high deposition running parallel to the channel. There will therefore be a strong spatial correlation along the channel but a weaker relationship perpendicular to it. A correlogram is a plot of the spatial distribution of correlation from the centre of the grid, and will illustrate the trend as a narrow oval, oriented along the channel and decreasing more rapidly away from it than along it.

4.3 Process investigations 1: pilot study on Millyford tributary

4.3.1 Introduction

The baseline survey identified that the floodplain around the largest debris dam near Millyford Bridge was the most active and complex geomorphological site on the Highland Water, and this was chosen for detailed study. However, to test the techniques, and to provide information on a forest floodplain unaffected by in-channel woody debris, a pilot study was undertaken. For both studies the underlying methodology remained the same, although the setup was tailored to best suit each site.

Choice of pilot site

It was necessary to investigate how repeatable sampling with sediment traps on a forest floodplain was, but in an area that was more easily comprehensible than the area around the Millyford dam. The pilot study site therefore had to (i) be relatively unaffected by debris dams; and (ii) be less heterogeneous than the floodplain surface found on the main channel. Along the Highland Water, no surveyed sites existed that fulfilled these criteria: reaches one and two were largely independent of debris dams, but in these areas the width of inundation was often fairly narrow (up to around 5m either side of the channel) and locally controlled by valley topography (e.g. constricted by terraces). Sections of the river further downstream, around Millyford Bridge, were either affected by the bridge or by the large debris dam.

Close to the site of the debris dam (but not affected by it) lay a small tributary that experienced overbank flow but had a relatively simple floodplain topography with reaches that were unaffected by debris dams and with no other dominant controls such as terraces. This relatively simple environment therefore allowed a test to be made of the sampling characteristics of sediment traps and the technical logistics required to deploy them, and was therefore chosen for the pilot study.

Field deployment

Two events were monitored on the 17th and 28th of February 2000 respectively. Throughout the monitoring period, the pressure transducer was recording. However, these data display a diurnal signal that appears to be related to temperature rather than to stage. The equipment had kindly been loaned by the Oceanography Department and the cables were 80m long. When this length of cable was coiled up, the sensors probably responded to internal pressure changes caused by diurnal heating and cooling. Therefore, estimates of water discharge could not be reliably quantified.

In the field, the sediment traps were deployed approximately 5m apart at the nodes of a semi-regular grid. There were 48 traps in total (in rows of seven and nine), and the traps spanned the width of the floodplain (Fig 4.1). This achieved a stratified sample of floodplain surface, where the traps fell on wet, dry, flowing or still areas according to the position of each trap.

4.3.2 Results

The amount of sediment deposited per trap varied from zero to 0.92 kg m^{-2}, although the average, at around 0.1 kg m^{-2}, was considerably less than the maximum (Table 4.1). The two floods demonstrate a difference that appears to be consistent with a change in event magnitude: more sediment was deposited during the first event, and of this around one third was organic. Slightly less deposition occurred during the second flood, and a greater proportion of the deposition was inorganic (Table 4.1). The average proportion of silt and clay is also less during the first event, with deposition of fine material more common during the second event. Although no recurrence interval data area available for confirmation, these results indicate that out of the two events, the first was larger, with coarser sediments and more organic material; the second event was smaller, with deposition of more fines and fewer organics.

Table 4.1 Summary statistics for deposition during the two studied events

Event	Range in deposition (kg m^{-2})	Average deposition (kg m^{-2})	Inorganic fraction (mean % of total < 1.4 mm)	Silt and clay fraction (mean % of inorganic sediment < 0.063 mm)
1 (17/02/00)	0.005 – 0.920	0.123	69.9	38.4
2 (28/02/00)	0.000 – 0.670	0.088	75.6	72.3

The topographic variation across this forest floodplain was fairly gentle, and followed a down-valley gradient (Fig. 4.1). High areas often appeared to be associated with trees: individual specimens often occur on isolated topographic high areas, and the high area outlined in black in Fig. 4.2 is delineated along its north-west boundary by a line of trees (compare with Fig. 4.1). Overbank flow pathways, which were very shallow (often < 10 cm deep) and are therefore difficult to identify on the elevation model, are marked on the plots of deposition and percent silt and clay (Fig. 4.2). During flooding, these pathways transferred water along vectors defined by topography, trees and woody debris, and they appear to be related to the pattern of sediment deposition.

In order to qualitatively investigate the link between topography and overbank accretion, the elevation model of this floodplain surface was overlain onto interpolated surfaces of deposition amounts (Fig. 4.2). As with the average values, more accretion occurred during the first event, and although less occurred during event 2, it displayed a very similar pattern of overbank deposition (Fig. 4.2a and c). Most sediment accreted in four areas; three in the south-central part of the site; and one in the northeast; several of these ("X", "L", and "T") coincide with low areas of topography (Fig. 4a and c). Overbank flow pathways that follow these low areas also coincide with the three south-central deposition peaks. The north-east sediment peak, lying to one side of another overbank flow channel, appeared to be ponded by a topographic "high" (outlined in black). Though the pattern of deposition is similar for both events, a minor shift occurs from "X" during event 1 (Fig. 4.2a) to "Y" during event 2 (Fig. 4.2c). Field observations indicate that the shift was probably caused by mobile organic matter (leaves and twigs) forming a small dam that locally diverted the course of the channel. The longevity of such features is low compared with trees or existing topography, however, and such effects are local and temporary.

The amount of sediment recorded was frequently very low (often < 0.01 kg m^{-2}), and the determination of the fraction of fine sediment within small samples may be subject to error. Considering this factor, and although the pattern of deposition was consistent for both events, the distribution of fine inorganic sediment was contrastingly variable. During the first event, more fine sediments were deposited at the margins of the sediment sampling network than in its centre; a pattern that is broadly similar to the arrangement of deposition. However, following the second event, a highly variable pattern emerged that is not qualitatively associated either with deposition or with topography, and this is possibly due to measurement errors resulting from the very small masses of sediment involved.

Overall, therefore, while the distribution of fine material can be qualitatively linked to the pathways of water and sediment for event 1, a more variable pattern emerged after event 2. A consistent pattern of deposition emerges, and this is linked to (i) pathways of overbank flow (defined by topography) and (ii) areas of ponding associated with higher topography.

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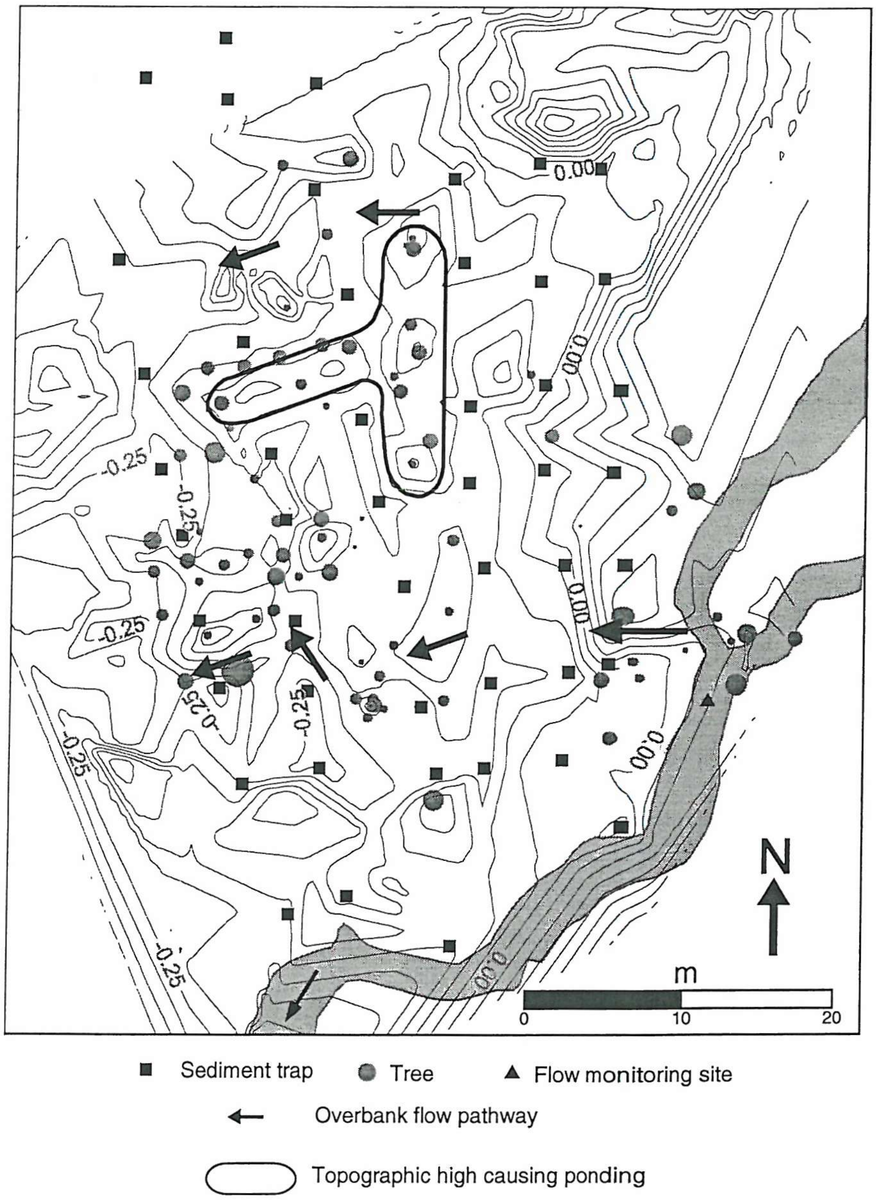


Figure 4.1 The topography, trees and location of sediment traps on the pilot study site, a tributary to the Highland Water near Reach 8. The 0.2 m contour interval is shown

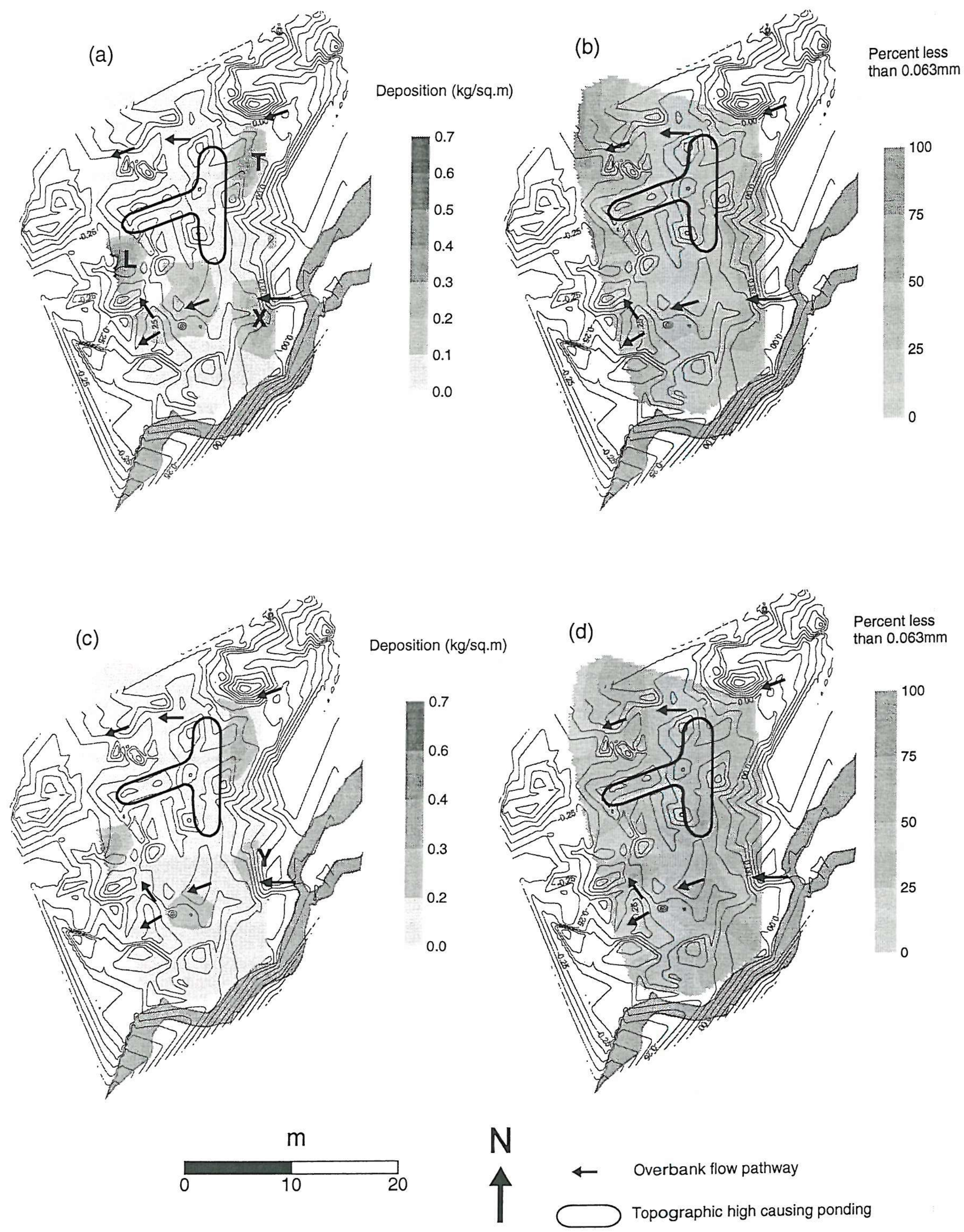


Figure 4.2 Interpolations of deposition and percent silt-clay at the pilot study site (a) Total deposition 17/02/00; (b) Grain size distribution 17/02/00; (c) Total deposition 28/02/00; (d) Grain size distribution 28/02/00.

A more abstract approach to analysing these data is to examine underlying anisotropic trends within the data using correlograms (Fig. 4.3) (Keckler 1997). The analyses of the **amount** of deposition demonstrate consistent NW-SE anisotropy between floods, indicating a cross- and down-valley trend that can be linked to overbank flow (Figs. 4.3a and c). While the anisotropic orientation underlying **type** of deposition shifts between floods, a strong linear pattern is observed within both (Figs. 4.3b and d). It is clear that sediment traps allow repeatable patterns to be observed that appear to be linked to floodplain orientation.

4.3.3 Discussion

After both floods, a zone of deposition spanned the southern part of the study area and this is contiguous with floodplain flow. Topography modified the pathways of overbank flow and in turn influenced the spatial arrangement of deposited sediment. Most accretion occurred in areas that were ponded, or low-lying or experienced flowing water. Overbank discharge at location X, during a flood on 7th February 2000, was 0.065 $m^3 s^{-1}$, with a velocity ~ 0.3 $m s^{-1}$. Although the discharge at this location is low compared to that of the main channel (where Q = 0.235 $m^3 s^{-1}$; velocity ~ 0.25 $m s^{-1}$), this overbank flow is theoretically sufficient to entrain grains between ~ 0.01 mm and 0.1 mm; and to transport grains smaller than 0.3 mm (Hjulström, 1935). However, in reality roots, vegetation (principally moss and grass) and woody debris increase the roughness of the floodplain and slow overbank flow to protect the surface. Therefore, deposited sediment probably did not originate from the floodplain surface within the study site, but originated instead either from the main channel (upstream debris dams cause overbank flow) or from erosion of the floodplain surface up-valley (although no evidence to support this was observed), and was transported by overbank flow.

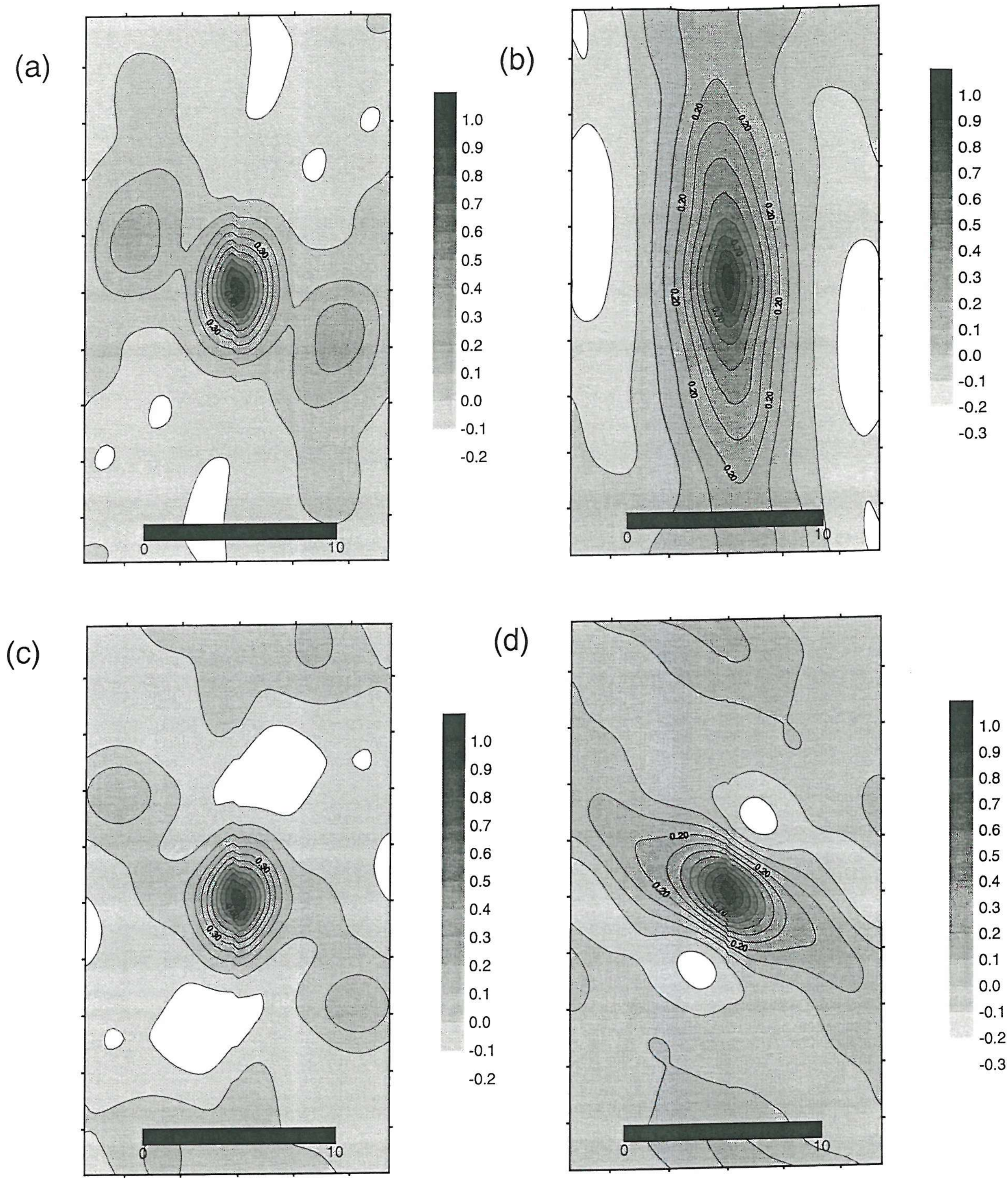


Figure 4.3 Correlograms of the trends in (a) Total deposition 17/02/00; (b) Grain size distribution 17/02/00; (c) Total deposition 28/02/00; (d) Grain size distribution 28/02/00. The correlation with increasing distance from the centre is shown to the right of each plot.

The effects of topography changed between events as a result of mobile micro-debris dams that either locally diverted water (and sediment) elsewhere or caused ponding in areas that were previously flowing. In either case, elements of both spatial and temporal change were observed in the amount of deposited sediment. Such dams will be temporary obstacles compared with existing topography, and their effect will therefore also be temporary, but they do create short-term spatial variations, and will depend on the input of wood to the floodplain, itself a function of the type, age and density of woody species growing there (Gregory et al., 1993).

The amounts of deposition quantified here were broadly similar to those observed for other lowland UK rivers with a maritime climate (e.g. Lambert and Walling, 1987; Nicholas and Walling, 1997; Table 2.2). However, the spatial pattern of deposition here was more variable than that on 'cleared' floodplains, with 'hotspots' that were related to overbank flow confined by topography, in turn controlled by woody vegetation (Fig. 4.2). As a result of this biotic control, the spatial distribution of overbank flow and resulting pattern of deposition observed here differed significantly from the environment of deposition predicted by the diffusion model proposed by James (1985) and Pizzuto (1987). Principally, lateral sediment diffusion did not occur because water and sediment instead advected across the floodplain surface. No lateral accretion was observed elsewhere on this tributary, so this variable deposition of overbank sediment was the dominant form of floodplain accretion. Due to instrument malfunction, neither the flood magnitude nor the recurrence interval for these events could be derived, and estimates of the amount of deposition per annum could not be made. Nevertheless, even after the large events examined in the main study, the extent of inundation appeared to have changed very little; therefore, underlying patterns of sediment deposition consistently seemed to occur between floods of different magnitudes.

These findings support the findings of Asselman and Middelkoop (1998), Briggs (1999), Lambert and Walling (1987), Middelkoop and Asselman (1995) and Mansikkaniemi (1985) that Astroturf™ sediment traps can be used successfully to sample floodplain deposits. This pilot study also demonstrates that consistent repeat sampling can be achieved with these traps.

However, sediment trapping is an event-based sampling technique and this, in addition to fairly heavy processing demands in the laboratory, makes for a cumbersome, logistically complex procedure. For successful event sampling to occur, the traps need to be deployed immediately prior to a flood and recovered as soon as possible thereafter, both of which can provide logistical problems within the vagaries of the U.K.'s climate. Once in the laboratory each trap requires around 40 minutes of sieving and weighing interspersed with ~ 8 hours of drying. Fewer than ten per day were processed. Processing all the traps between the end of one flood and the beginning of another during a wet period therefore depended on a lengthy dry period between floods; otherwise, extra sets of traps are required. For these reasons I decided that the main study should sacrifice some spatial resolution for the sake of temporal accuracy, and fewer traps should be deployed.

4.3.4 Conclusions

Two main conclusions can be drawn from the admittedly limited results of this pilot study:

(i) The floodplain topography was consistently (within two events) influenced by trees and topography, and this in turn affected the pathways of both water and sediment. Ephemeral channels and ponded areas thus incurred the greatest rates of deposition. Temporal and spatial changes in deposition were caused by micro-debris dams ponding or diverting overbank flow. These patterns differ significantly from the 'traditional' model of floodplain evolution described in chapter 2.

(ii) Sediment traps provide a repeatable and precise technique to trap sediment for analysis. If a high temporal response rate to flooding is desired, however, fewer sediment traps should be used on the main channel because of practical limits from processing time.

4.4 Process investigations 2: Main study

4.4.1 Introduction

On the Highland Water, the site of the most active floodplain process lies to the south of Millyford Bridge, west of Lyndhurst (SU 426990, 107690). At this location, a stable debris dam has for at least 9 years been promoting overbank discharges of water and sediment (Fig. 4.4). On this area of floodplain, patterns of overbank sediment deposition were recorded for nine flood events, and these coincided with the wettest period for over 100 years (U.K. Meterological Office data). The amount of sediment deposition appeared to be principally related to event hydrology. Although no correlation between accretion and depositional environment was proven via statistical analyses, correlogram analyses and visual interpretations of samples reveal underlying trends in deposition that cannot be explained by the diffusion model of overbank accretion (cf. James, 1985 and Pizzuto, 1987).

4.4.2 Methods

Flood monitoring took place between mid-September 2000 and mid-February 2001, after which time the monitoring programme had to be suspended due to Foot-and-Mouth disease restrictions. Stage was measured with a Druck PCDR1730 pressure transducer, and turbidity with a Partech IR40C sensor. The turbidity probe was initially calibrated using Formazin solution to estimate any deviation from a linear relationship between turbidity of the sample solution and voltage output. It was then calibrated for the Highland Water turbidity by suspending it in samples of river water across a range of concentrations (Fig. 4.5). The mV output could then be linearly converted to an estimate of suspended sediment concentration in mg/l (Fig. 4.5). Readings from both sensors were taken every five minutes and logged on a Campbell CR10X datalogger from which data were downloaded every two weeks.

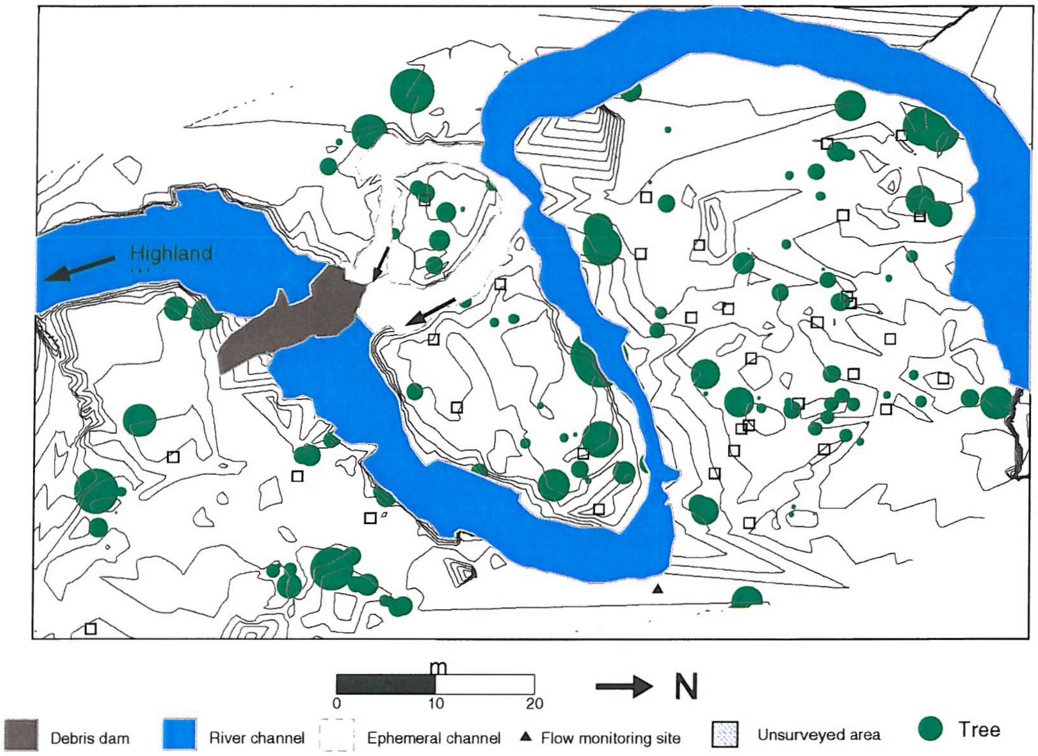


Figure 4.4 The topography, trees and location of sediment traps on the main study site

As might be expected, the dam gauging section had an unstable cross-section that did not permit a simple linear relationship to be derived between flow stage and Q (Fig. 4.6). Additionally, due to accumulated leaf litter, the debris dam itself had an increasing backwater effect through the flood season, and this further decreased the reliability of any derived relationship. However, by correlating low flow discharges between the debris dam and a gauging station located around 100m downstream, it was possible to remove the ponding effect of the dam from the record. The stage-discharge relationship changed as overbank flow commenced, and two rating relationships were drawn up and these separated the in-channel part of the flow from the overbank part. Consequently, an estimate of discharge upstream of the debris dam could be derived. The degree of error associated with these data is constant and it is valid to directly compare observations.

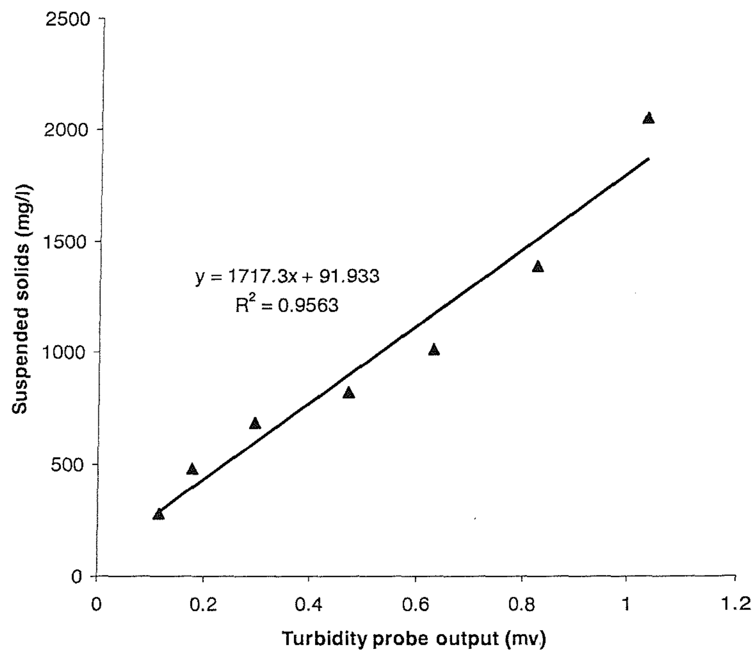


Figure 4.5 The response of the Partech IR40C probe to progressive increases in turbidity

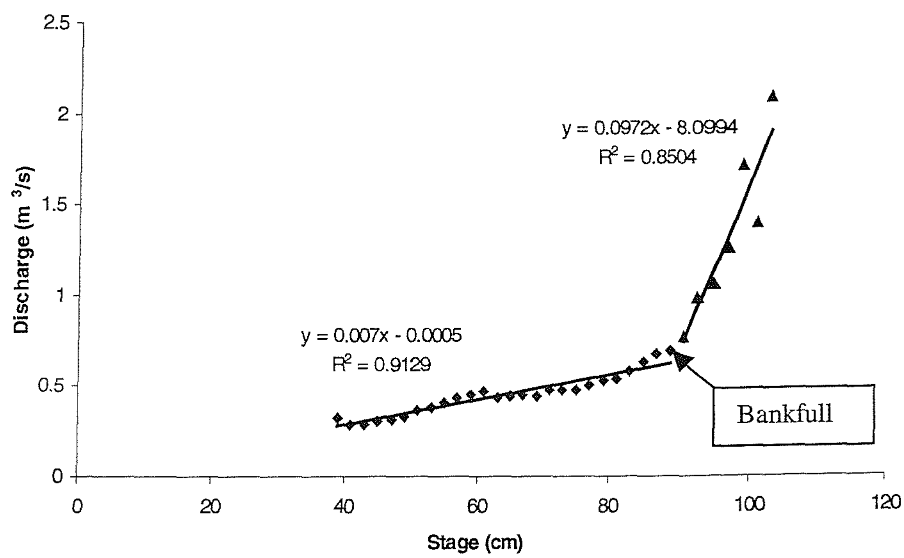


Figure 4.6 Stage and discharge at the debris dam near Millyford Bridge

Based on results from the pilot study, it was clear that, in order to achieve a rapid response to a series of floods, around 30 sediment traps was a realistic number to deploy, collect, process and redeploy. Therefore, 28 traps (0.2m by 0.2m) were initially deployed over an area upstream of the debris dam; during the larger events this network was increased to 38 and extended over a greater area.

4.4.3 Overbank deposition after a series of floods

Weather and flood hydrographs

The field experiments were undertaken during the wettest autumn since UK Meteorological Office records began in 1766. A sequential series of cyclonic weather fronts provided around 200 % more rain than the autumn average, and most of this fell between the end of October 2000 and mid December 2000; the following dry period was twice broken by runoff-generating precipitation in early and late January 2001 (Fig. 4.7). During this unusually wet winter, overbank deposits of sediment were sampled after nine periods of floodplain flow (Fig. 4.8). The flood hydrographs (Figs. 4.7 and 4.8; Table 4.2) ranged from the relatively short (9.3 h; event 2) to the relatively long (92.2 h; event 7). Peak discharges followed a similar pattern, with Q_{max} ranging from 1.63 m^3/s (event 1) to 2.26 m^3/s (event 7). Although the total amount of water discharged per event (Q_{total}) also changed in line with event magnitude, the peak (Qs_{max}) and total (Qs_{total}) loads of suspended material were more variable (Table 4.2). The lowest peak in suspended load occurred during event 6; the highest during event 9, which provides another level of flood classification, secondary to water discharge.

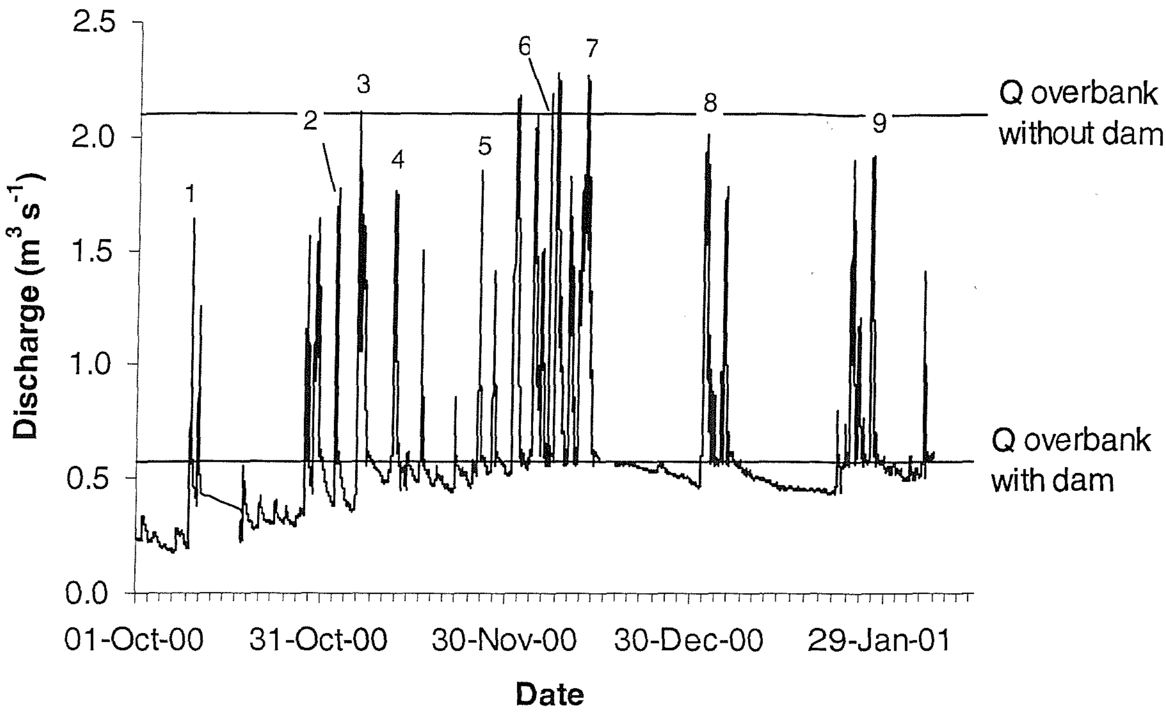


Figure 4.7 Flow discharge for the period of study with events when sediment traps were deployed

Table 4.2 Hydrological and sedimentological characteristics for sampled events. Q_{max} is the maximum discharge; Q_{total} is total discharge integrated over the duration of overbank flow; Qs_{max} is peak in suspended sediment; Qs_{total} is total sediment discharge for the duration of overbank flow

Event no.	Duration overbank (hours)	No. of flood peaks	Q_{max} (m^3/s)	Q_{total} (m^3/flood)	Qs_{max} (mg/l)	Qs_{total} (tonnes/ flood)	Mean % < 0.063mm	Mean % organic	Mean deposition (g/trap)
1	9.7	1	1.63	14,457	1,681	15.48	44.0	12.9	106
2	9.3	1	1.77	19,508	1,106	8.10	36.1	12.7	128
3	45.7	1	2.10	104,073	1,207	39.37	42.6	2.1	65
4	23.0	1	1.76	48,196	1,098	29.41	45.2	6.8	208
5	12.5	1	1.85	24,923	1,446	17.71	59.6	7.5	137
6	56.2	1	2.09	113,618	711	28.83	47.3	2.7	155
7	92.2	2	2.26	222,855	1,718	176.01	46.5	6.7	322
8	67.0	2	2.01	167,671	1,670	97.36	44.2	7.0	246
9	40.4	3	1.92	138,570	2,520	69.67	39.8	10.2	268

Therefore, three categories emerge:

(i) low magnitude events 1, 2, 4, and 5: short, single peak, low to moderate Q_{total}; and low Qs_{total}

(ii) medium magnitude events 3, 6, 8, and 9.

(a) events 3 and 6: moderate duration, pseudo, multipeak events, medium Q_{total}, low or moderate Qs_{total}

(b) events 8 and 9: moderate duration, multipeak events; medium or moderate Q_{total}, moderate or high Qs_{total}

(iii) high magnitude event 7: long, multipeak event, very high Q_{total} and Qs_{total}

Within a single period of overbank flow, secondary or tertiary flood peaks are not always paralleled by peaks in suspended solids. During event 6, for example, a second flood peak occurs that is associated with virtually no change in suspended solids. This implies that sediment sources can be exhausted following a single flood peak.

The study period did not allow the collection of extended hydrological records, and the calculation of the return period for each flood cannot be made. Therefore, the 'low', 'medium', and 'high' flood categories are relative. Nevertheless, these nine events occur across a wide range of magnitudes and are therefore likely to encompass a considerable range of different return periods. Hence, the 'low-magnitude' events perhaps reflect the more frequent (1-2 year) flows normally associated with overbank flooding, while the high-magnitude event 7 represents an extreme event resulting from the wettest of the unusual weather experienced during the monitoring period.

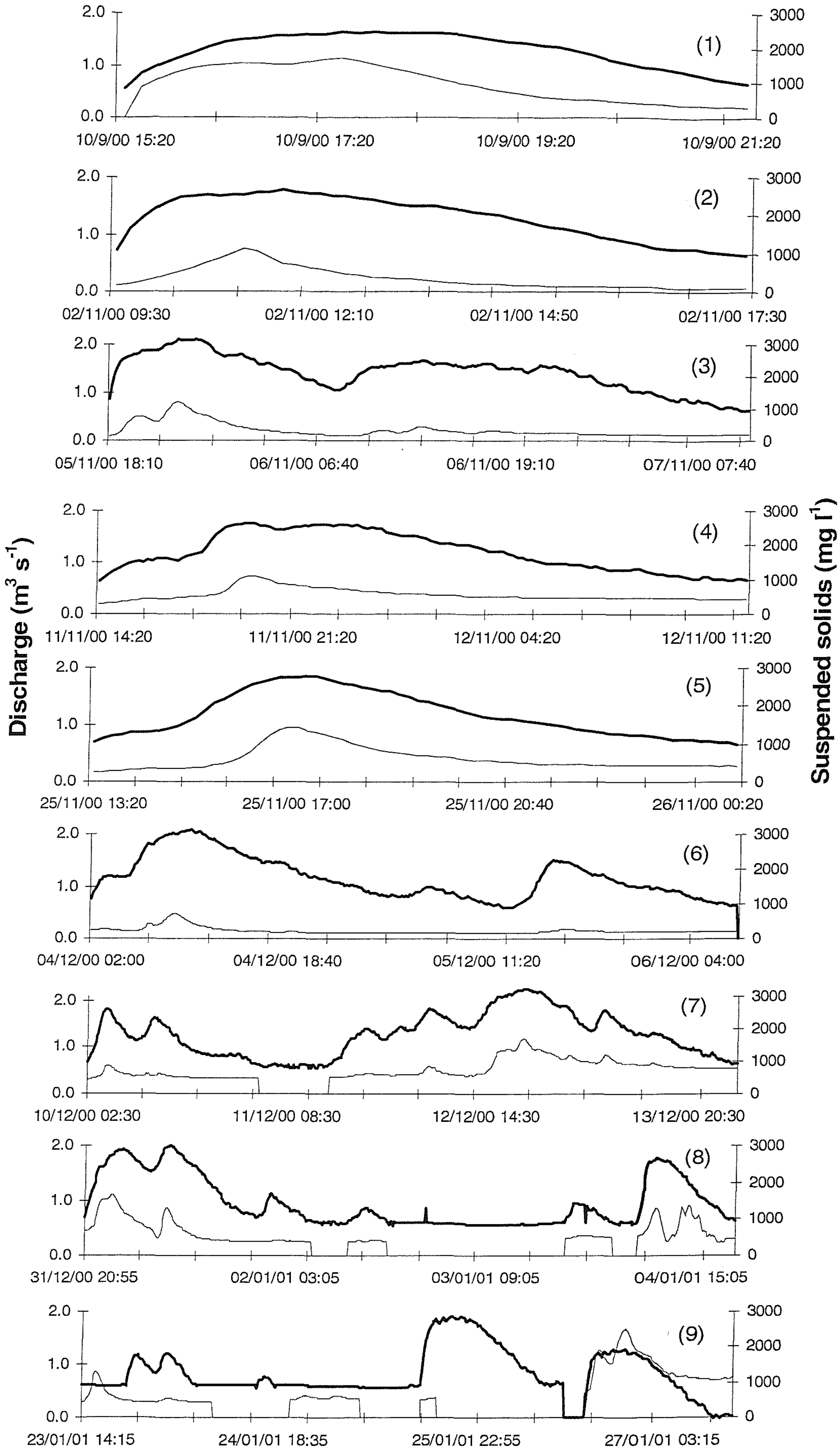


Figure 4.8 Discharge (heavy line) and suspended sediment load (thin line) for flow above bankfull for each event (troughs in turbidity indicate cessation of overbank flow during multipeak events)

Floodplain hydrology and overbank sediment deposition

By decreasing the bankfull capacity of the channel, the debris dam significantly increased the proportion of time during which overbank flow occurred. Bankfull discharge at the dam occurred at around 0.55 m^3/s, but 100m downstream, where no dam exists, it was 2.2 m^3/s (Sear et al., 2000). Therefore, floodplain flow occurred for 41.5 % of the study period at the dam site, but only for 0.22 % of the same period 100 m downstream (Fig. 4.9; see also Fig. 4.7). It could be argued that these data are not representative because the study took place during an exceptionally wet period when intense and prolonged rainfall led to increased flood frequency, duration and magnitude, which allowed the dam to control the connection between the channel and the floodplain to an unusally high degree. Nonetheless, even during small floods, such as events 1 and 2, this in-channel accumulation of LWD increased the occurrence of overbank flooding, and its effect will therefore persist even within a drier winter.

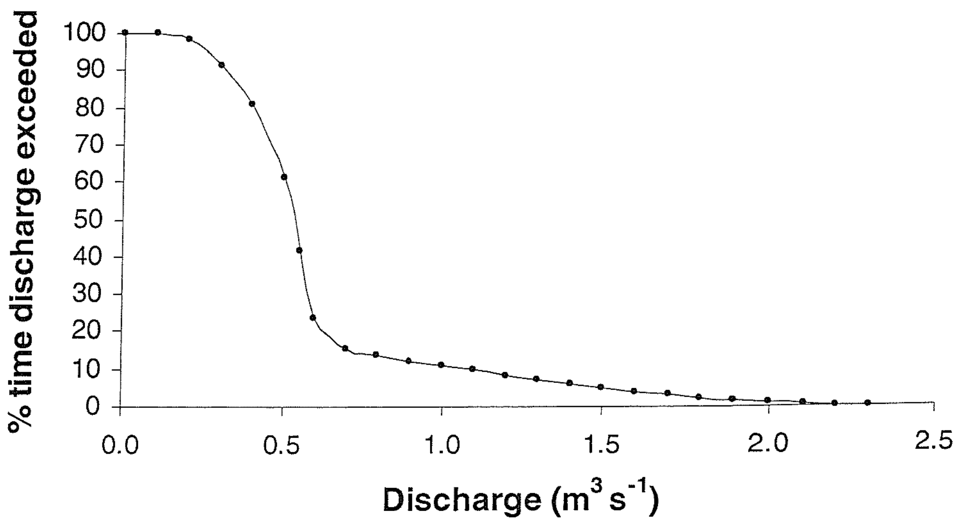


Figure 4.9 Flow duration curve for the study site

A strong correlation exists between the average amount of overbank deposition and total discharge (Q_{total}): R^2 = 0.99 for monopeak events and 0.94 for multipeak events (Fig. 4.10). The average amounts of overbank deposition are therefore dominated by flood magnitude, although sediment supply effects are also important, as is evident from the correlation that also exists between the total discharge of suspended material (Qs_{total}) and mean floodplain deposition (R^2 = 0.91 for monopeak events and 0.78 for multipeak events). A positive visual correlation also exists between event hydrology (as expressed by the flow discharge and suspended load transported) and accumulated deposition on the floodplain surface (Fig. 4.11). Thus, the smaller, shorter floods (category 1) resulted in the least overbank sediment deposition (e.g. event 1, with 106 g per trap), and the larger events concurrently had more (e.g. event 7, with 322 g per trap). The gross amount of floodplain deposition in the study site was therefore a function of the overbank discharges of (i) water and (ii) sediment. No parallel relationship existed between increases in discharges of water and sediment and the fraction of organic material that was deposited (Fig. 4.12), nor between increases in discharges of water and sediment and the fraction of silt/clay deposited (Fig. 4.13).

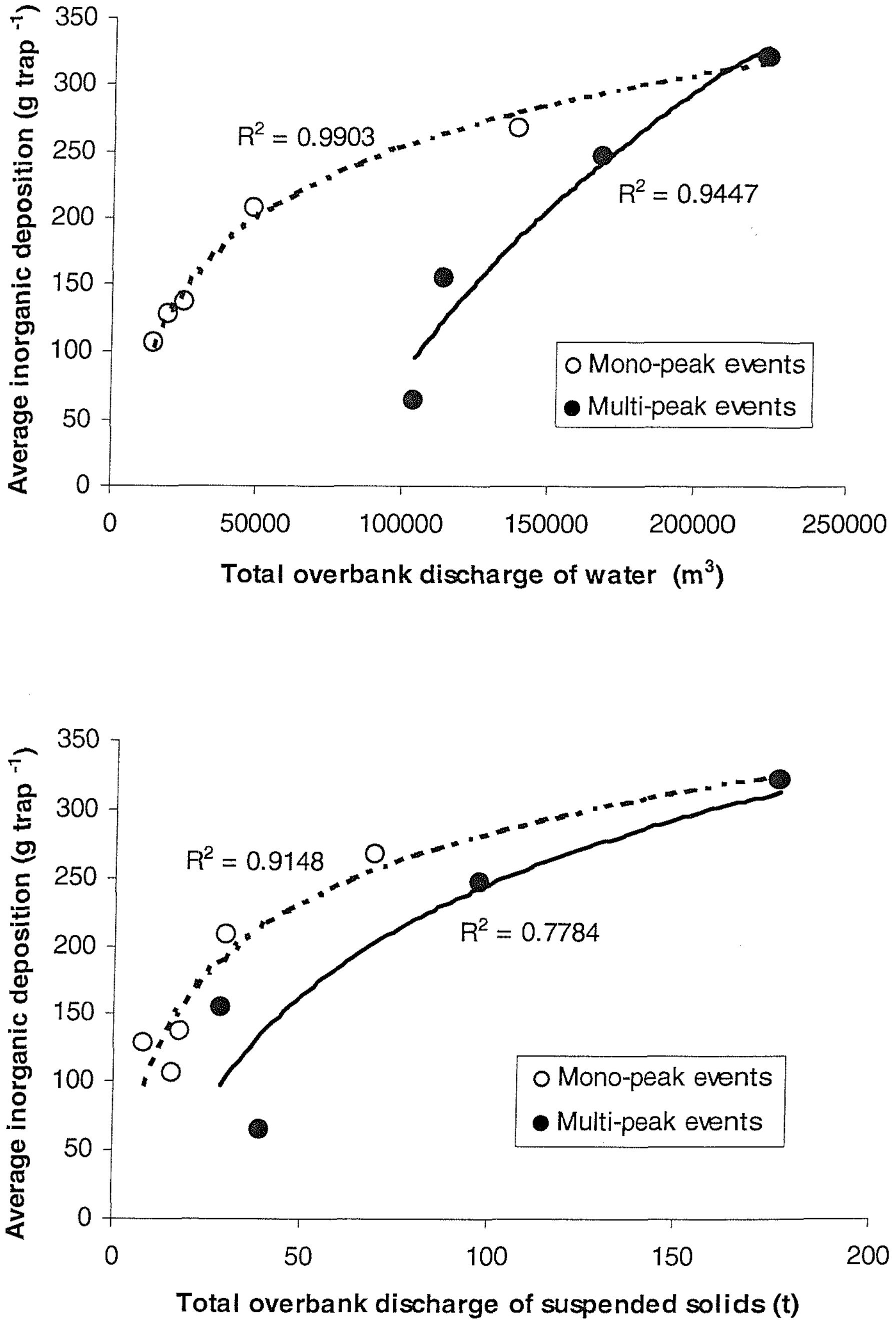


Figure 4.10 Average amount of inorganic material retained on the sediment traps as a function of (a) total overbank water discharge; and (b) total overbank discharge of suspended solids for monopeak (open circles) and multipeak (closed circles) events.

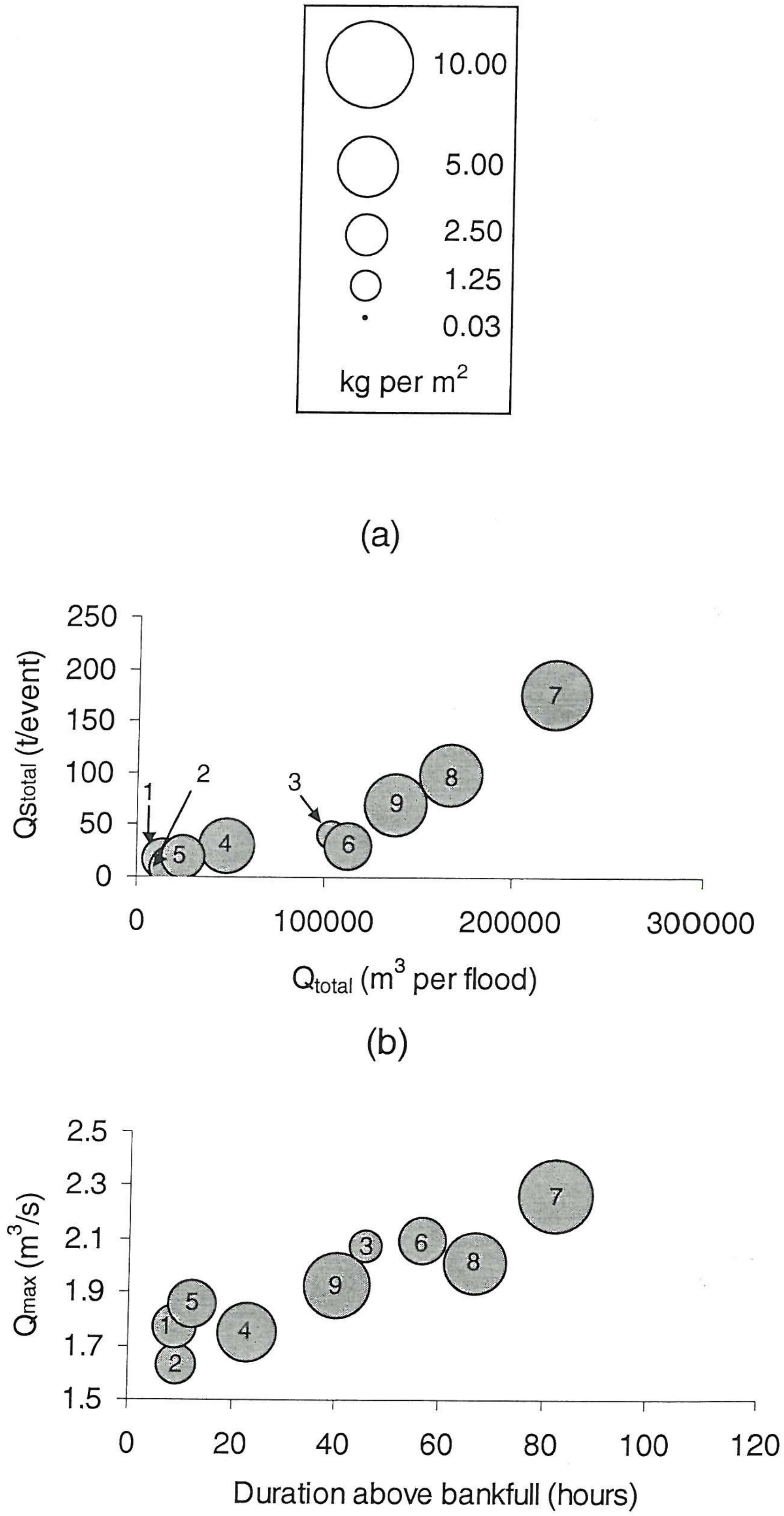


Figure 4.11 Average amounts of inorganic deposition per flood compared to (a) overbank discharges of water and sediment and (b) duration above bankfull and peak discharge.

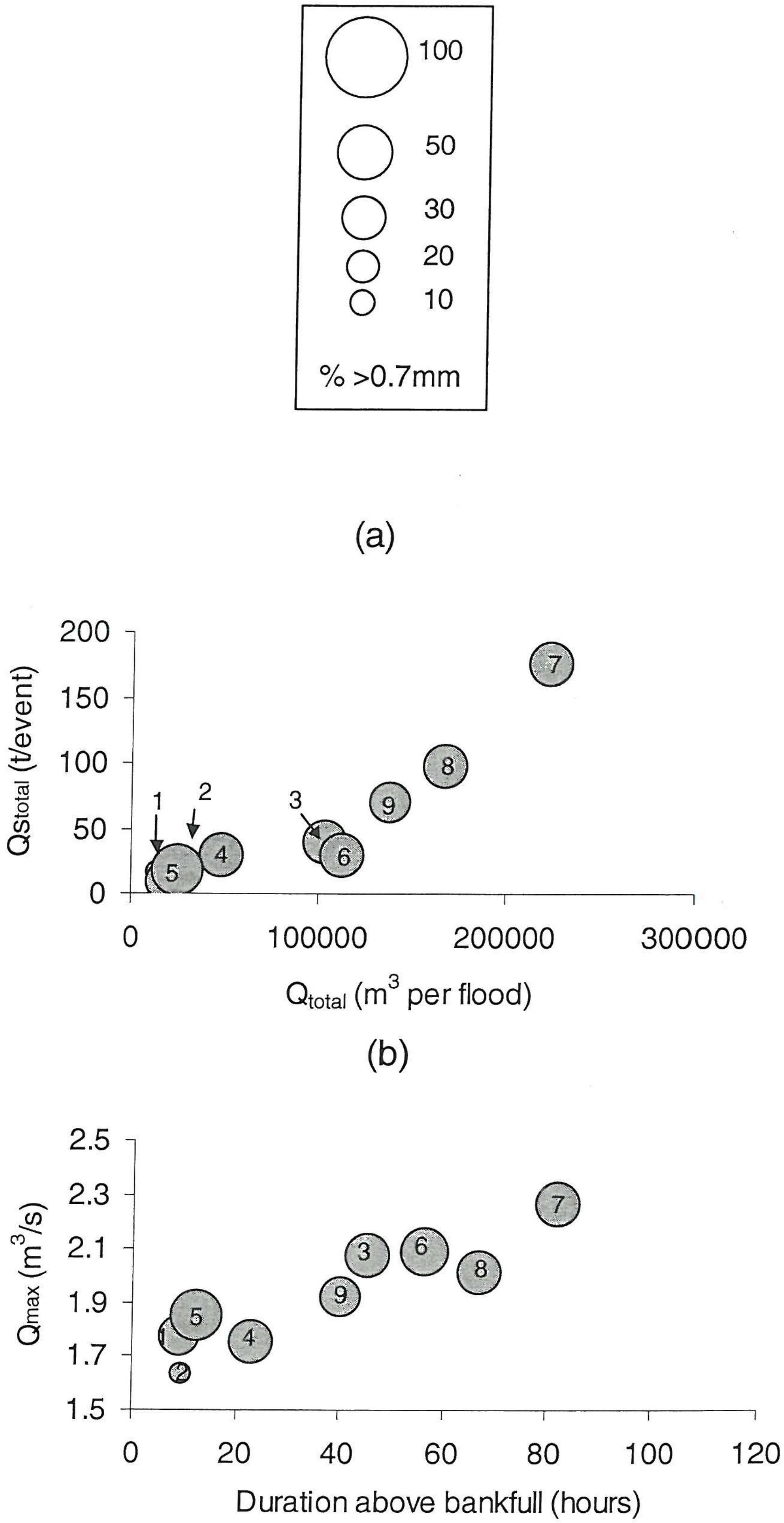


Figure 4.12 Mean percent organic for all traps compared to (a) overbank discharges of water and sediment and (b) duration above bankfull and peak discharge.

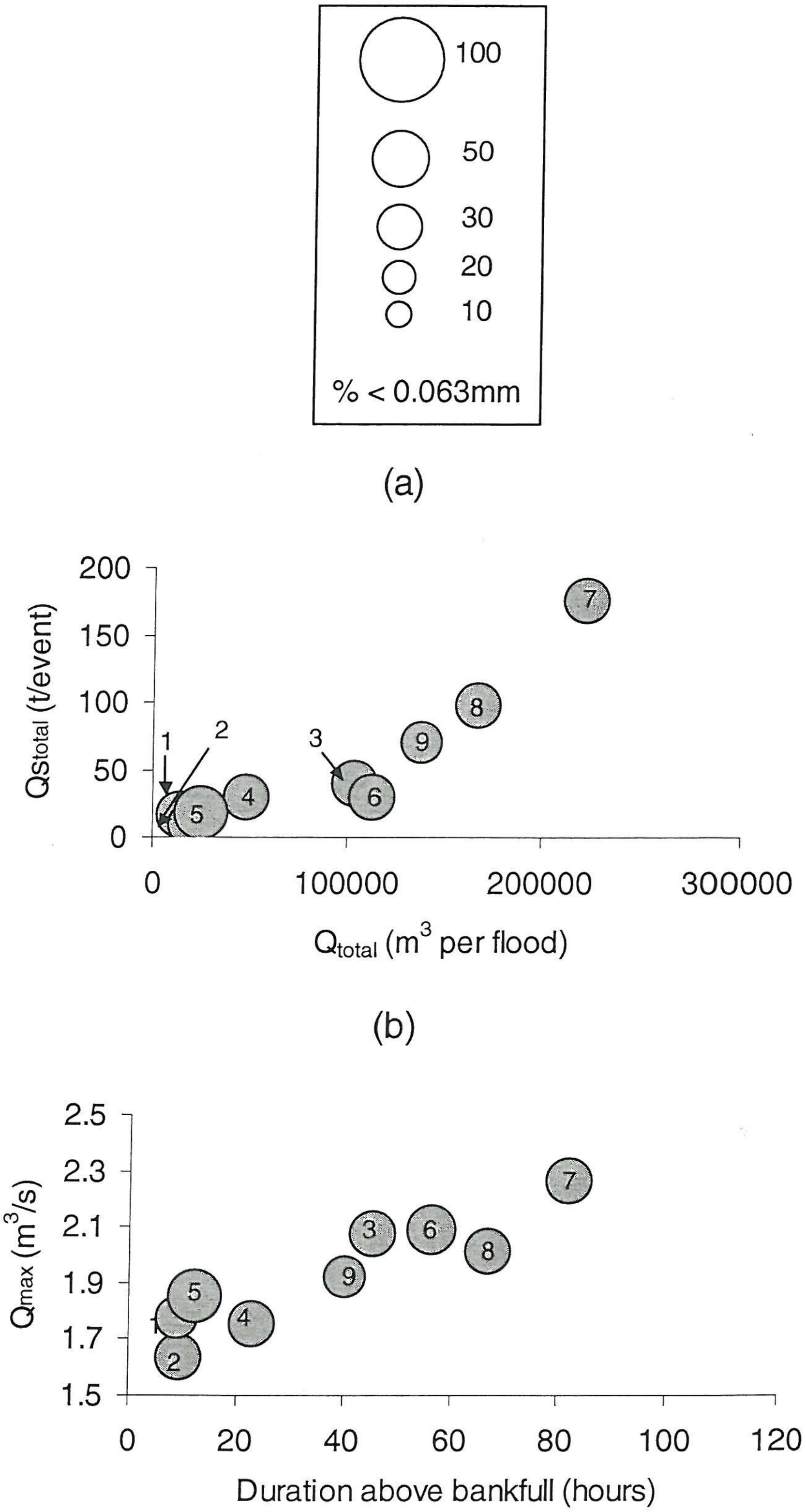


Figure 4.13 Percent of deposit below 0.063mm for all traps compared to (a) overbank discharges of water and sediment and (b) duration above bankfull and peak discharge.

Influences of floodplain vegetation and LWD on overbank sedimentation

While the amount of deposition per flood was primarily dependent upon flood hydrology and sediment delivery, the pathways of overbank flow and patterns of deposition were related to two distinct hydraulic regions formed by vegetation, LWD, and topography: ponded and flowing (Fig. 4.14). Ponded areas had no appreciable advection and occurred where water was backed up behind the in-channel dam, or where floodplain vegetation, LWD, or topography provided areas of shelter (Fig. 4.14). Flowing areas were characterised by advective currents, occasionally > 1 m s^{-1}, although with an average velocity closer to 0.3 m s^{-1}, and these tended to occur more frequently further away from the dam as the water drained down valley. Although these two areas are clearly different (discussed below), their distribution did not closely relate to the complex pattern of deposition. In fact, although ponded areas usually trapped more sediment than flowing areas, three floods (3, 5, and 9) had more deposition in flowing areas than in ponded areas, and the difference between hydraulic regions was fairly small (Fig. 4.15).

The qualitative difference in deposition between flowing and ponded areas was not matched by changes in the fraction of fine sediment (Fig. 4.16), but ponded areas did experience slightly more coarse (organic) deposition than flowing areas (Fig. 4.17). Thus, all types of sediment (whether inorganic or organic) were transported into ponded and flowing areas alike. The organic fraction of each deposit was less dense than water, and field observations confirm that it was transported at the interface of water and air along dominant flow vectors. In contrast, the inorganic fraction was denser than water and would therefore have been transported near the bed-water interface (Richards, 1982) and may therefore provide some understanding of internal flow structures. Thus the following results concentrate only on the inorganic fraction.

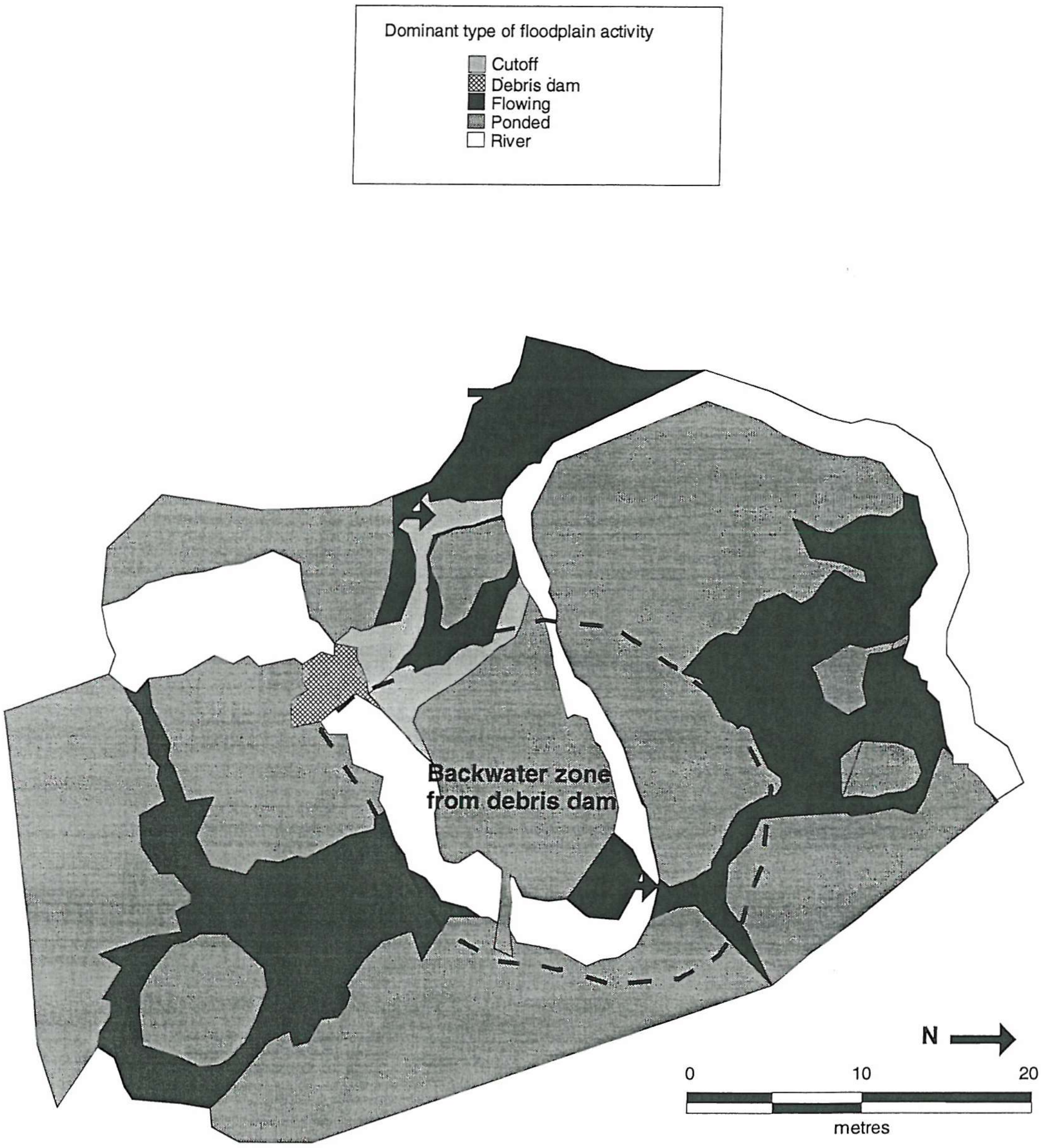


Figure 4.14 Thematic map indicating ponded (medium grey) and flowing (black) areas of the study site; see text for definitions of these areas.

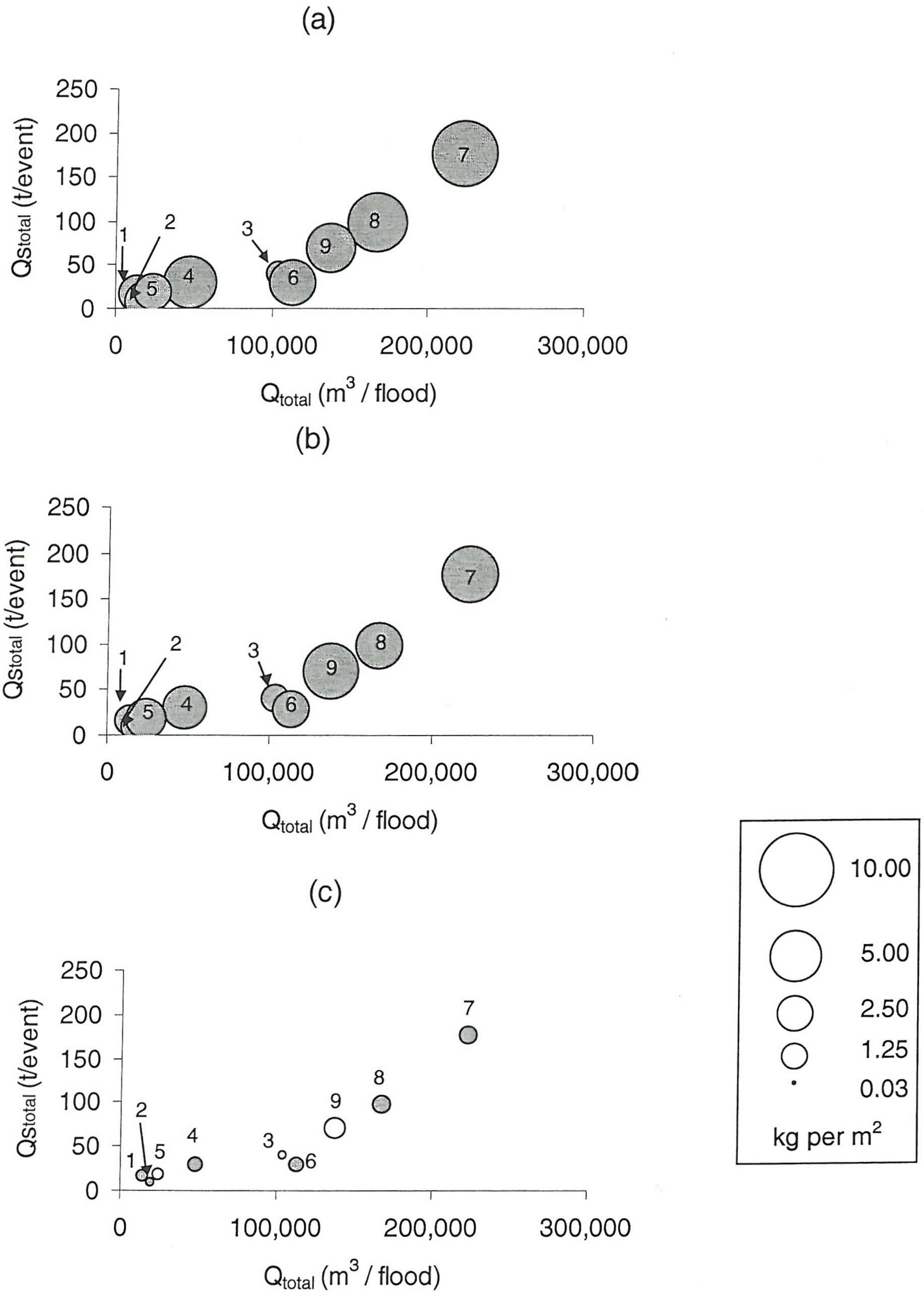


Figure 4.15 Mean floodplain deposition rates as a function of event hydrology for (a) 'ponded' and (b) 'flowing' areas of the floodplain. Differences (c) in deposition rates between 'ponded' and 'flowing' areas are also highlighted with shaded values indicating more deposition in ponded areas than in flowing areas.

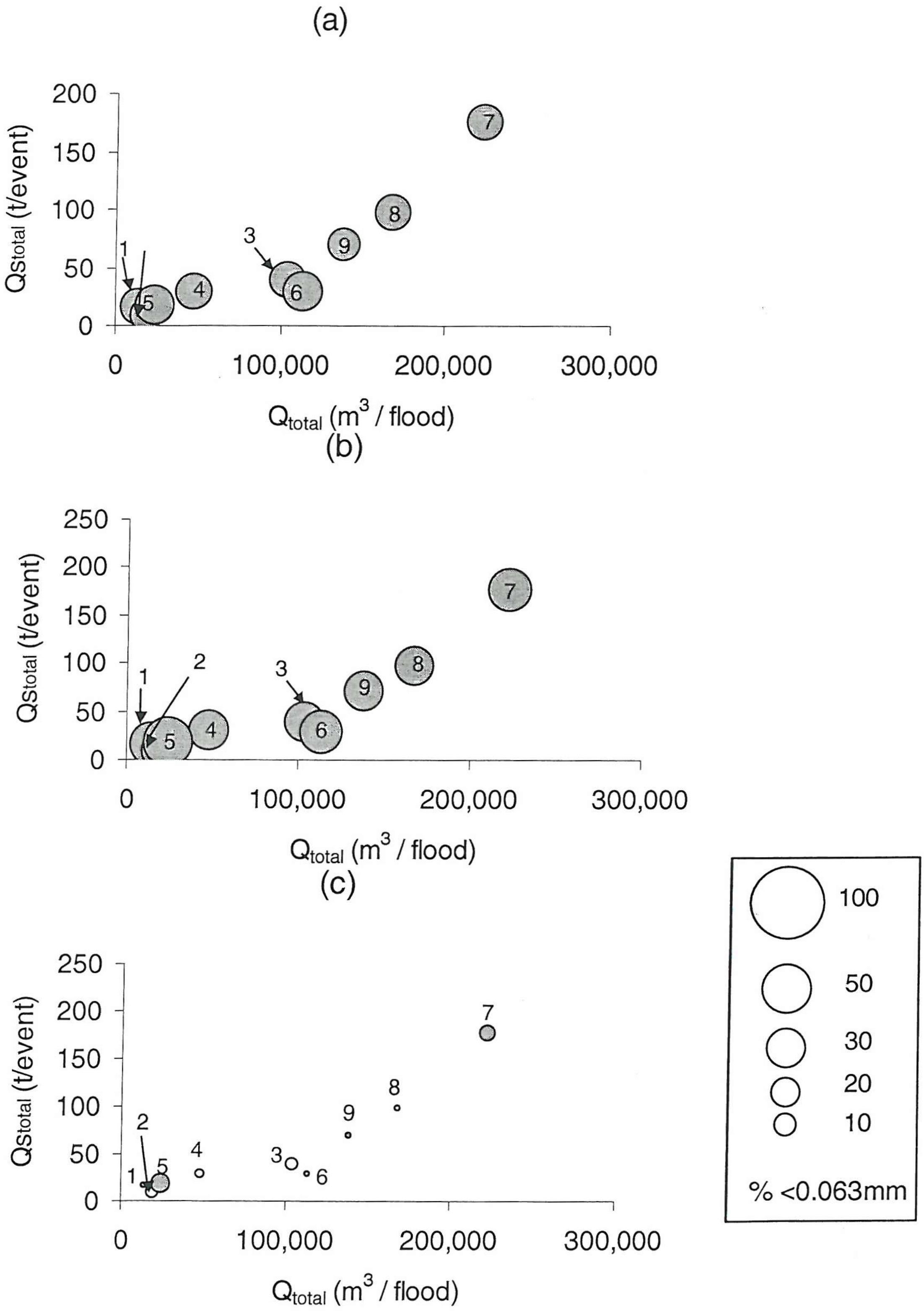


Figure 4.16 Mean percent silt and clay as a function of event hydrology for (a) 'ponded' and (b) 'flowing' areas of the floodplain. Differences (c) in deposition rates between 'ponded' and 'flowing' areas are also highlighted with shaded values indicating more deposition in ponded areas than in flowing areas.

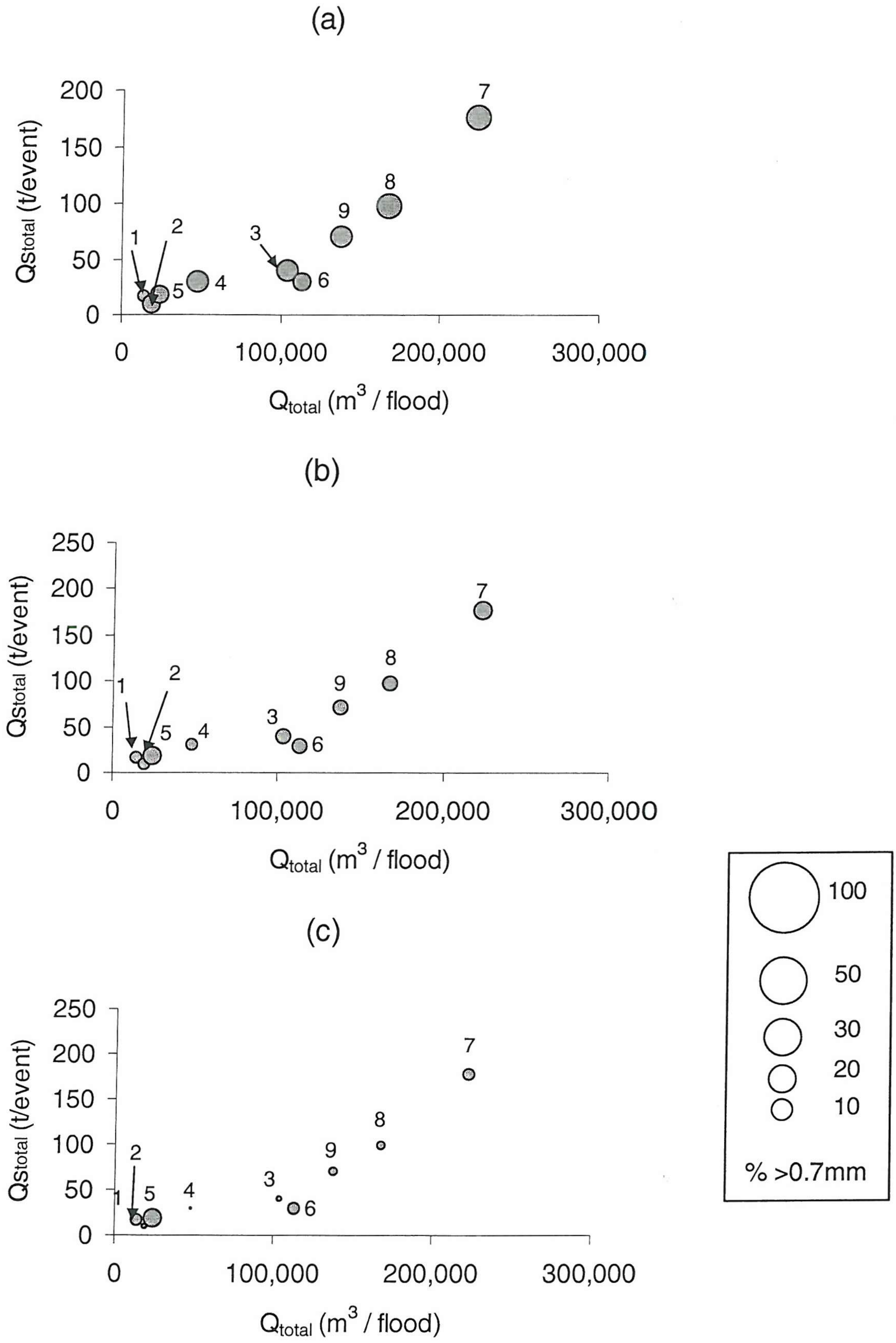


Figure 4.17 Mean fraction of samples composed of organic material (>0.7mm)as a function of event hydrology for (a) 'ponded' and (b) 'flowing' areas of the floodplain. Differences (c) in deposition rates between 'ponded' and 'flowing' areas are also highlighted with shaded values indicating more deposition in ponded areas than in flowing areas.

Statistical tests were carried out to discern if flowing and ponded areas caused significant differences between floods in (i) the amount of deposition and (ii) the pattern of silt-clay deposition on the floodplain. The student t-test compares two sample means to see if they are drawn from the same overall population (Shaw and Wheeler, 1985). This was used to compare flowing and ponded areas. These tests revealed that no significant differences (at 95% confidence) existed between flowing and ponded areas for any of the events either in the amount or type of sediment deposited (Table 4.3).

Table 4.3 Students t-tests on (a) the amount of sediment deposited in flowing and ponded areas - H0: There were no significant differences in the amounts of sediment between flowing areas and ponded areas. *H1: There were significant differences in the amounts of sediment* between flowing areas and ponded areas. (b) the type of sediment deposited in flowing and ponded areas - H0: There were no significant differences in the proportions of silt and clay in flowing areas and ponded areas. H1: There were significant differences in the proportions of silt and clay in flowing and ponded areas.

Event	F-statistic from data	F-critical (95 %)	Accept H0?	Second test t-statistic	Second test t-critical 95 %	Accept H0?
H0: The amount of deposition is the same between flowing and ponded areas						
1	1.338	3.00	Yes			
2	4.649	3.30	No	1.73	0.492	Yes
3	0.284	3.15	Yes			
4	0.838	2.91	Yes			
5	0.903	4.03	Yes			
6	0.699	3.07	Yes			
7	0.640	2.43	Yes			
8	0.731	2.50	Yes			
9	0.550	2.50	Yes			
(b) H0: The type of deposit is the same between flowing and ponded areas						
1	1.316	3.35	No	1.73	0.544	Yes
2	1.820	3.35	No	1.73	0.514	Yes
3	0.847	3.10	Yes			
4	1.157	19.33	Yes			
5	1.899	2.79	Yes			
6	0.793	3.06	Yes			
7	0.874	2.45	Yes			
8	0.832	2.59	Yes			
9	1.246	2.57	Yes			

The anticipated pattern of deposition in flowing and ponded areas was possibly masked by additional surface complexity. Specifically, the in-channel LWD at the Millyford debris dam causes ponding across a restricted and discrete area, whereas the floodplain surface was covered by a variety of living trees and dead organic matter that created a complex hydraulic environment at small spatial scales. To evaluate the possible effects of small-scale floodplain LWD on overbank sedimentation, a high-resolution topographic survey of the floodplain surface, including all features such as LWD, vegetation and trees, was used to generate a simple digital elevation model (DEM) of the study site. Survey points that corresponded to LWD or vegetation were subsequently removed from the original data to create a second DEM representing the "bare" floodplain surface. This surface was subtracted from the original surface to highlight fine-scale elevation changes associated with floodplain LWD and vegetation (Fig. 4.18). Floodplain LWD and vegetation affect micro-topographic diversity by introducing local elevation variations at scales < 1 m (Fig. 4.18). The effects of organic material highlighted by the DEM were closely associated with ponded and flowing areas, and especially with parallel flood channels 10-20 cm deep, where overbank flow moved down the valley and across the neck of the upstream meander loop. These channels are also evident on Figure 4.4, and, as noted above, are common throughout the Highland Water catchment.

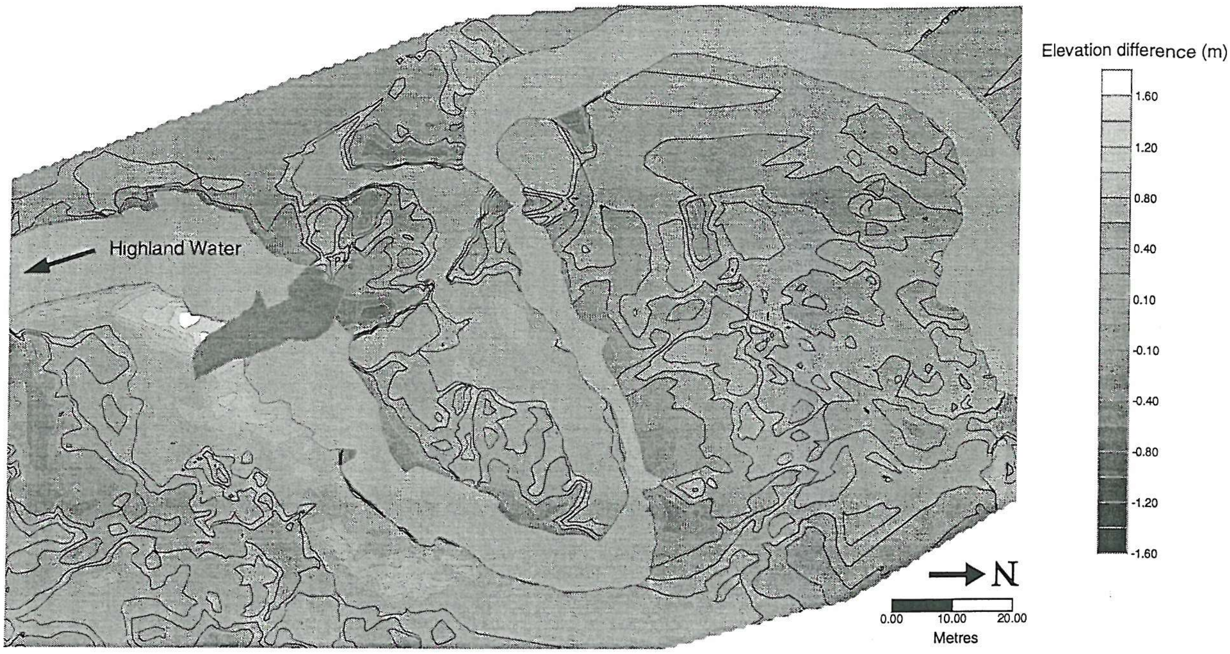


Figure 4.18 Relief map illustrating local change in floodplain elevation due to the presence of woody debris.

Secondly, to evaluate whether observed floodplain micro-topographic diversity (Fig. 4.4) had an impact on observed patterns of floodplain deposition, data from the sediment traps were interpolated to produce deposition surfaces. The mapped pattern of (i) floodplain deposition and (ii) type of deposit were then compared with the micro-topographic features on the floodplain surface for all events. The patterns of floodplain deposition observed were broadly consistent for events of a given type (Fig. 4.19). For low-magnitude events, the amounts of deposition were relatively low (up to 8.0 kg m^{-2}). During event 1 a roughly linear deposition feature occurred that stretched approximately NW away from site "A" (Fig. 4.19a). A small floodplain debris dam was located at the far end of this arm, but this was later removed by overbank flow. Site "A" was also the main focus of deposition during the other low-magnitude events, and while the northern half of the meander loop usually experienced little or no accretion, there was a gentle decrease in deposition towards the southwest, and relatively little deposition was observed close to the in-channel debris dam. More sediment was deposited during medium-magnitude events (up to ~20.0 kg m^{-2}), and patterns of deposition were also more variable (Fig. 4.19b). As with the low-magnitude events, maximum amounts of deposition were concentrated around site "A", but deposition around the in-channel debris dam was also significant (up to ~10.0 kg m^{-2}), exceeding any amount deposited during the low-magnitude events. Trap 25 (marked with a "T") was washed away during event 8 (Fig. 4.19b), so the low values of deposition mapped in this area must be treated with caution. For the highest magnitude event 7 (Fig. 4.19c), spatial patterns were consistent with those observed during the medium-magnitude events, although there was notably greater sediment accrual around the in-channel debris dam (~20.0 kg m^{-2}), including on the downstream part of the floodplain, and again at site "A" (~28.0 kg m^{-2}). A significant amount of sediment also amassed on the point bar of the central meander loop, opposite the gauging section, providing evidence that lateral accretion (if not erosion) occurs even in an area heavily influenced by LWD.

The spatial changes in the percent silt and clay content of the deposited material displayed inconsistent trends when compared with the pattern of deposition (Fig. 4.20). All events exhibited a wide spatial variation in Xthe amount of silt and clay (usually from near zero to most of the fraction) but these patterns were not temporally consistent between events. A tentative correlogram analysis of the complex signal presented by these data is described later in this chapter.

A high degree of micro-scale control by vegetation, LWD and topography on overbank depositional environments is reflected by the fact that some areas demonstrated a consistent pattern of overbank deposition, even after the extreme event 7. Although the average amount of overbank deposition per event varied widely (from 1.6 to 8.1 kg m^{-2}), and the pattern of deposition did not display a close visual link to flowing and ponded areas, most sediment consistently accreted in site "A" (Fig. 4.19). Site "A" is located on a boundary between 'ponded' and 'flowing' areas and trees also shelter this area, reducing overbank flow velocity and promoting deposition. The combination of location and shelter therefore resulted in large amounts of deposition at this site. Other areas of consistently high deposition occurred around the in-channel dam, particularly during the medium (Fig. 4.19b) and large (Fig. 4.19c) events. This area lies in another zone of transfer for water and sediment that exists between the main channel and the floodplain. Therefore, although the general patterns of overbank deposition are not closely related either to surface topography or to the effect of organic material, consistent patterns occurred that appeared to be controlled by the hydraulic effect of trees and in-channel debris.

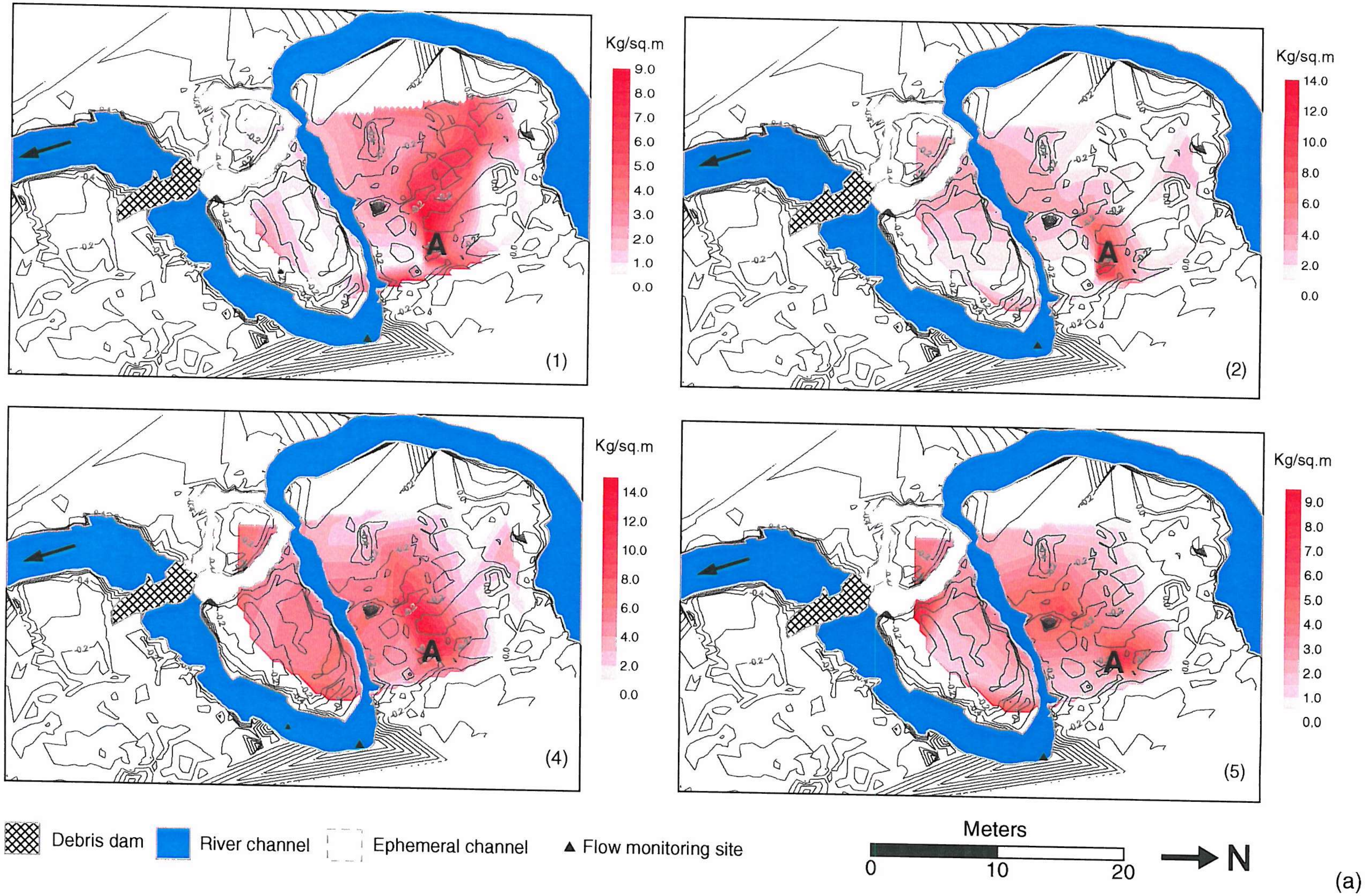
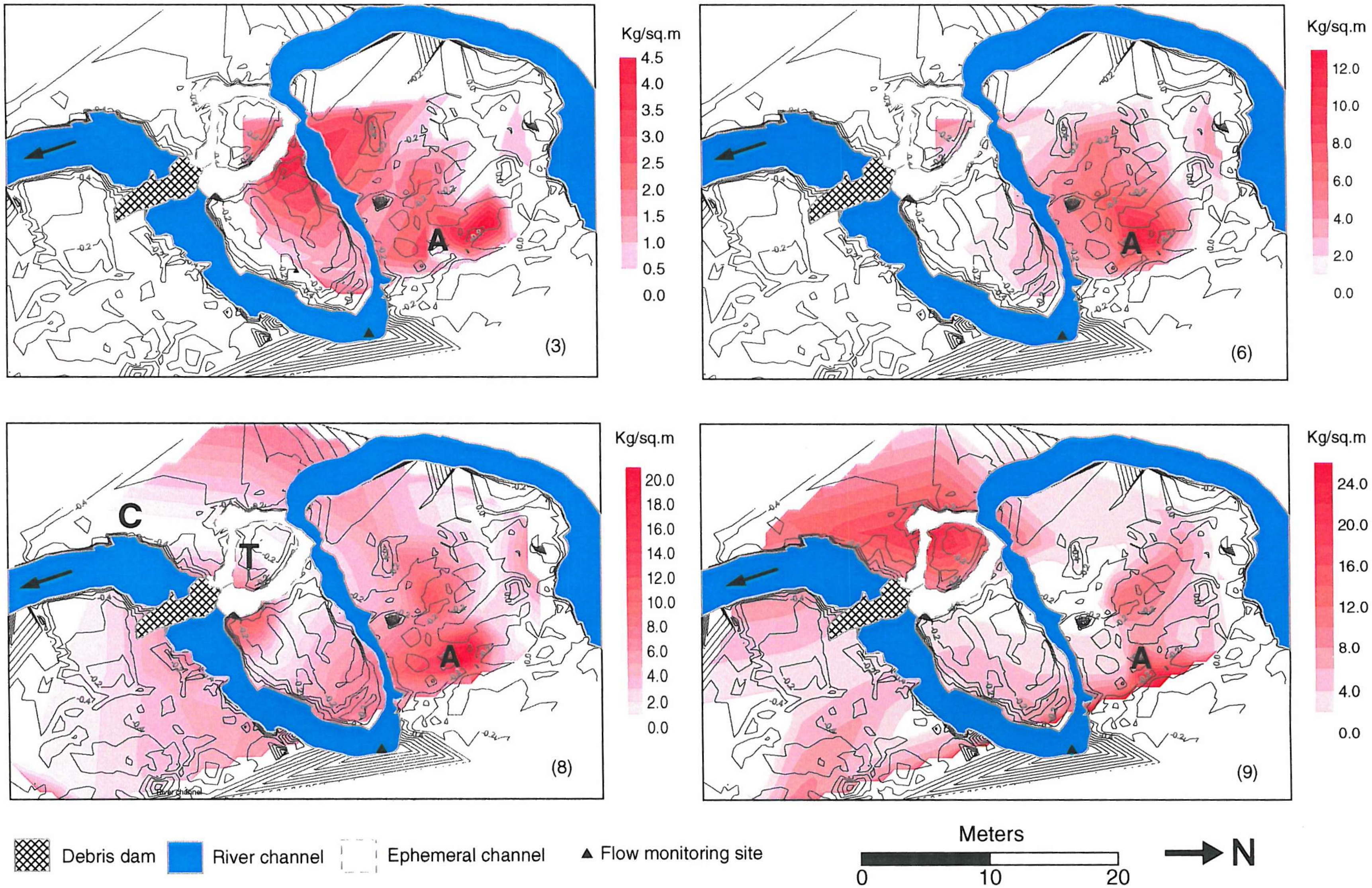
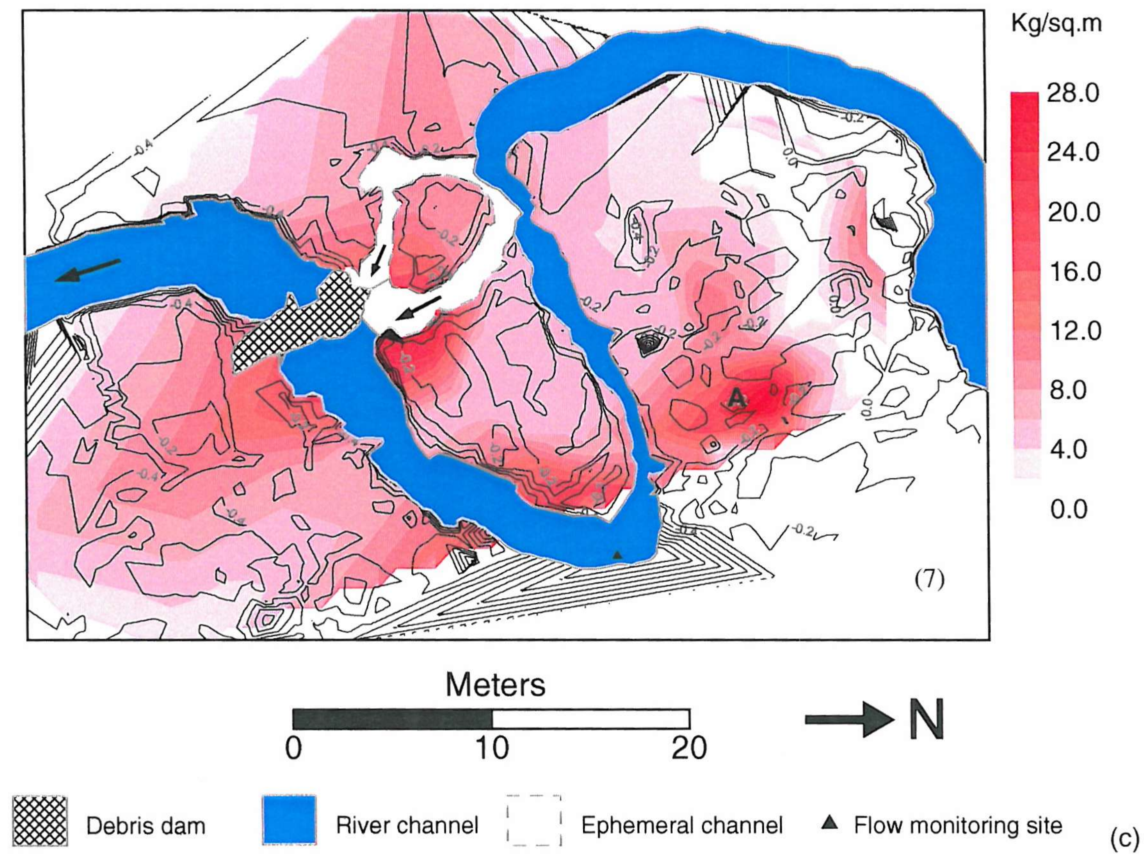


Figure 4.19 Interpolated patterns of overbank deposition for (a) low magnitude, (b) medium magnitude and (c) high magnitude events as defined in the text. The topography of the floodplain surface (0.2m contour interval) is also shown. Diagrams (b) and (c) are on the following pages.


Kg/sq.m
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
A
(3)
Kg/sq.m
12.0
10.0
8.0
6.0
4.0
2.0
0.0
A
(6)
Kg/sq.m
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
C
T
A
(8)
Kg/sq.m
24.0
20.0
16.0
12.0
8.0
4.0
0.0
A
(9)
Debris dam
River channel
Ephemeral channel
▲ Flow monitoring site
Meters
0
10
20
N

(b)


Kg/sq.m
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0
A
(7)
Meters
0
10
20
N
Debris dam
River channel
Ephemeral channel
Flow monitoring site
(c)

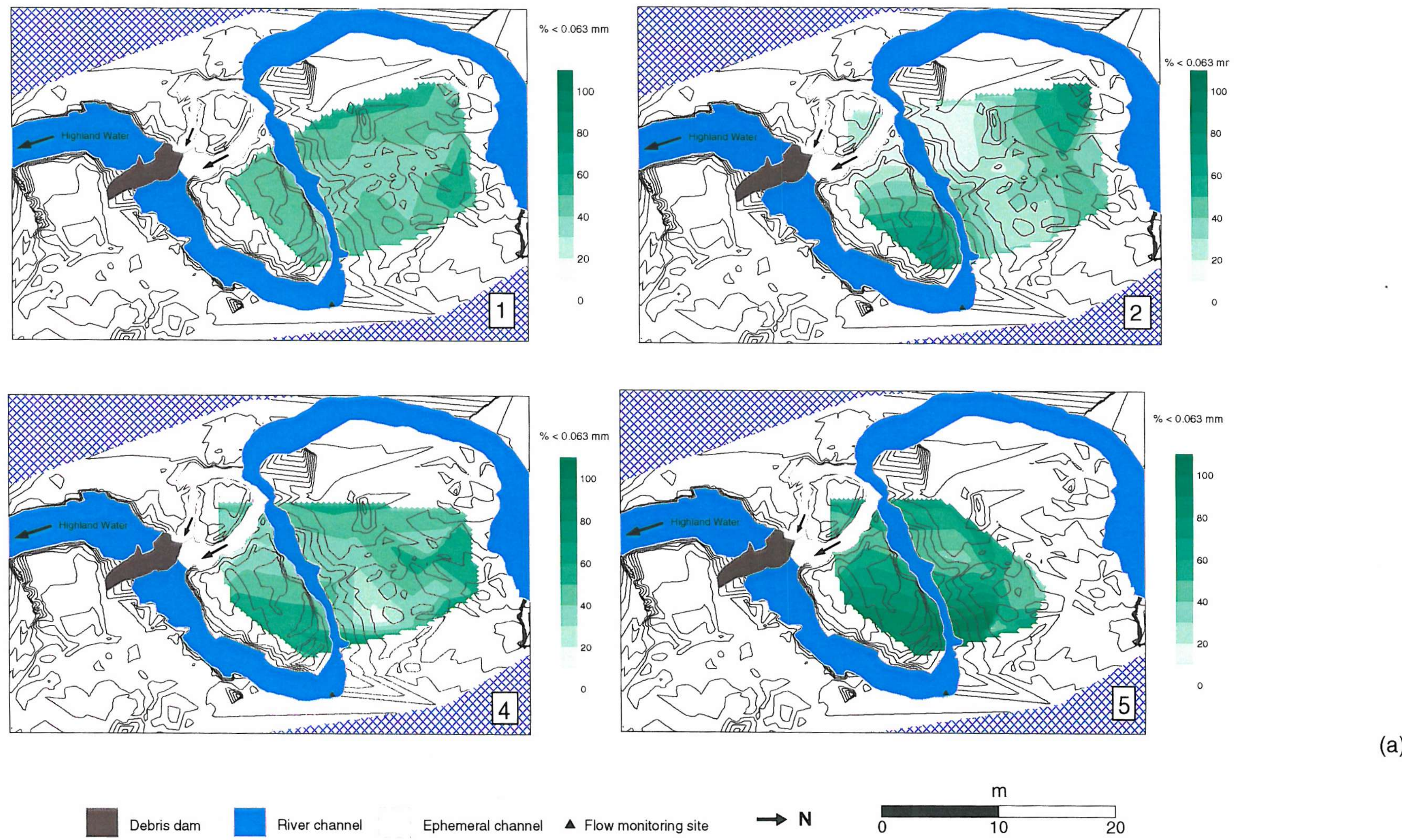
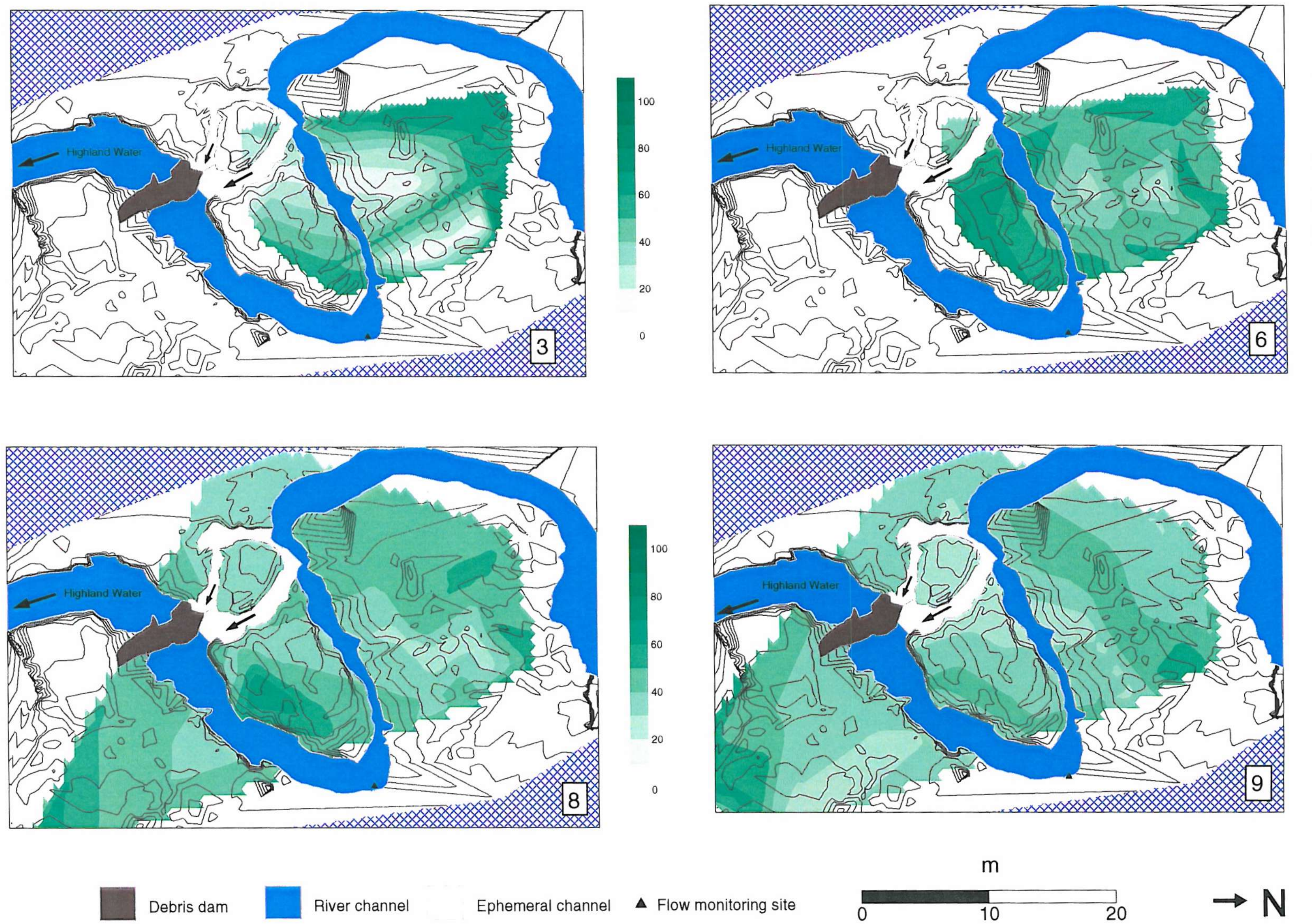
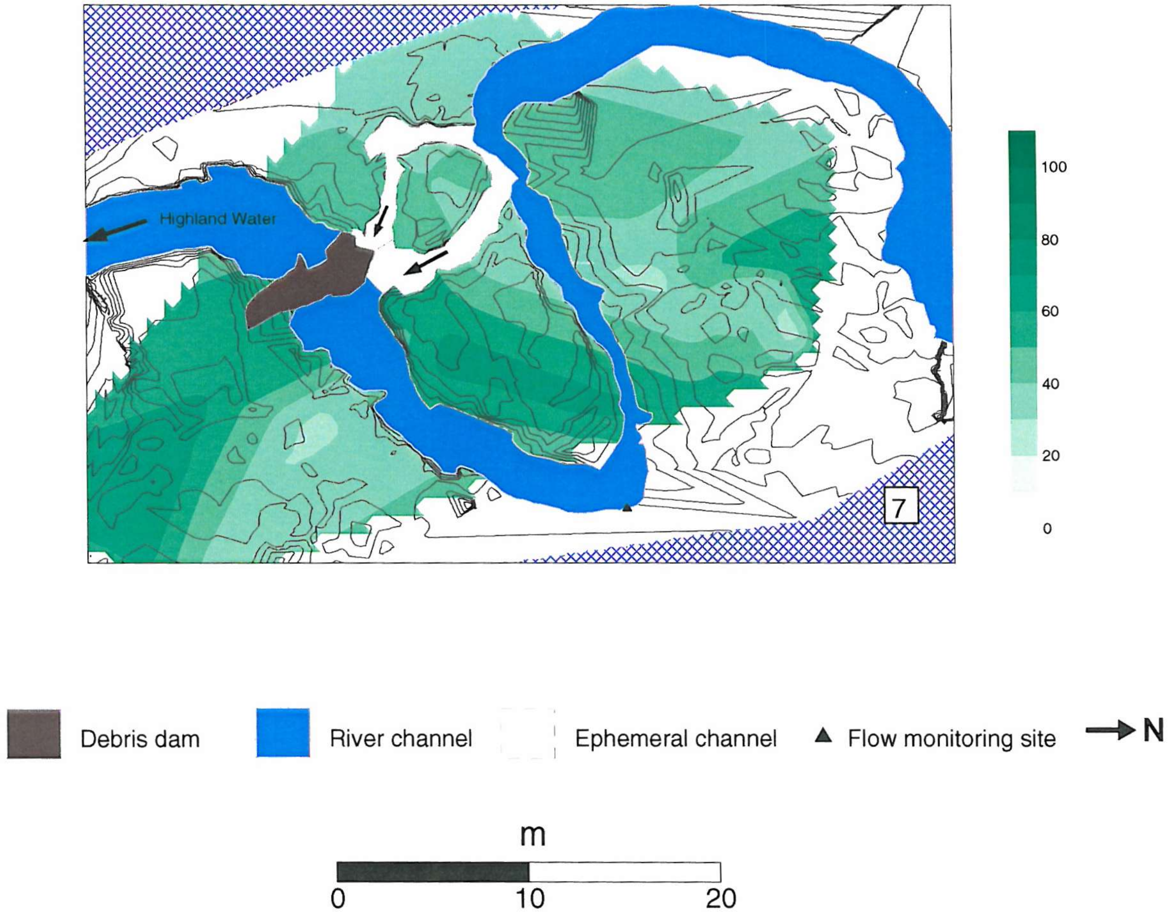


Figure 4.20 Interpolated patterns in the change in fraction of silt and clay for (a) low magnitude, (b) medium magnitude and (c) high magnitude events as defined in the text. The topography of the floodplain surface (0.2m contour interval) is also shown. Diagrams (b) and (c) are on the following pages.


Highland Water
100
80
60
40
20
0
3
6
8
9
Debris dam
River channel
Ephemeral channel
Flow monitoring site
m
0
10
20
N

(b)


Highland Water
7
100
80
60
40
20
0
Debris dam
River channel
Ephemeral channel
Flow monitoring site
N
m
0
10
20

(c)

Trend analyses of overbank deposition

Correlograms of complex surfaces reveal the underlying orientation of spatial changes – they partly describe the spatial anisotropy of a given variable (Isaaks and Srivastava 1989; Keckler, 1997). The technique was used here to assess the general orientation of two overbank variables (amount and type of sediment) for each flow event (Fig. 4.21). The original trap sampling interval affects both the interpolation and the derived correlogram – this is demonstrated by the markedly different correlograms for events 7-9 – but the technique is nevertheless precise because the error or effect is consistent for events 1-6 and 7-9. Further, similar trends are exhibited between events with different sampling patterns, indicating that this technique is fairly accurate.

Areas within approximately 2m of each other display the closest correlations (Fig. 4.21). The strong anisotropic orientation varies consistently between floods and between variables. Deposition distinctly trends *across* the valley. Six deposition correlograms (1, 2, 4, 5, 8 and 9) are anisotropic along a WSW-ENE gradient, and the remaining three (3, 6 and 7) approximately mirror this with a WNW-ESE trend. Contrastingly, silt-clay trends are oriented *down* valley (Fig. 4.21b). All but flood 9 (which is similar to the deposition correlograms), follow a SSW-NNE orientation.

Complex correlograms such as these do not indicate what *vector* the trends follow, only their general orientation. However, the elongation within each plot gives some indication of the general *shape* of the pattern – whether it is linear or clustered. The linearity of most correlograms in Fig. 4.21 implies that the variables are elongate: deposits are unevenly spread along the valley (deposition is greatest upstream of the dam), but the plots for 3, 6-8 and 9 are rounded (indicating a concentration of deposition around the dam). Correlograms of the percent < 0.063 mm are elongate, so the type of deposit varies as a function of distance from the river.

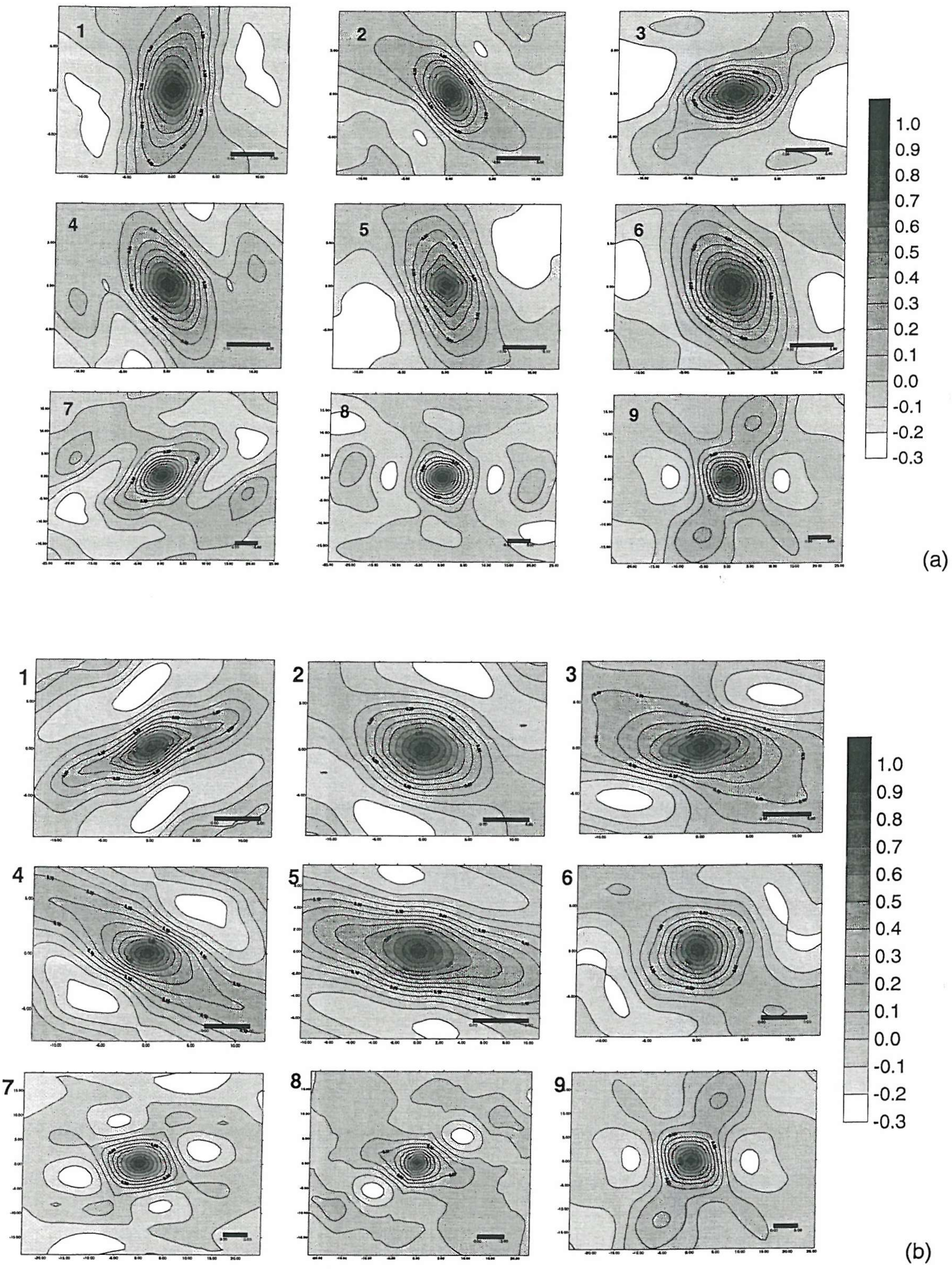


Figure 4.21 Correlograms of (a) deposition indicate trends perpendicular to the valley; more complex correlograms of silt-clay fraction (b) indicate trends parallel to the valley. Plots are oriented the same as in Figs. 4.19 and 4.20. Event numbers are indicated on the top left of each plot and correlation coefficients (R^2) on right. Plots are oriented the same as in Figs. 4.19 and 4.20 (ie. north is to the right of the page), and black bars are 1m long.

4.4.4 Implications of the main study

At the reach scale, and in a fairly small meandering river, in-channel LWD significantly increased the overbank ejection of water and sediment. The hydrological connection between the channel and the floodplain was strengthened so much that overbank flow occurred for 41.5% of the study period at the LWD jam, but only for 0.2% of the study period in an adjacent dam-free section. This hydraulic and hydrologic control was, however, highly localised around an accumulation of LWD that entirely blocked the channel and therefore, overbank processes were highly active only over 5% of this section of floodplain. Usually, LWD only forms complete blockages in small channels < 5 m wide (Robison and Beschta, 1990; Gregory et al., 1993; Wallerstein et al., 1997), so the relationships observed here (also reported in Jeffries et al., in press) are most likely to occur in headwaters and small rivers. The hydraulic effect of an accumulation of LWD will also vary with its size, ranging from a complete blockage that increases overbank discharges (Jeffries et al., in press), to small accumulations with only a minor influence (Gregory et al., 1993; Wallerstein et al., 1997). Channel roughness concomitantly varies as a function of the type of accumulation and degree of channel blockage (Gippel, 1995). Finally, the control of in-channel accumulations on overbank discharges of water and sediment not only changes downstream, but also in time (Gurnell and Sweet, 1998). Therefore, LWD increases the spatial and temporal diversity of areas of activity in small, lowland floodplains.

The pattern of overbank sediment deposition observed here is far more complex than that described within existing models of overbank accretion (e.g. James, 1985; Pizzuto, 1987; Nicholas and Walling, 1997). Most deposition occurred in zones of water and sediment transfer; e.g. at site A, the junction of the ponded and flowing areas; and around the LWD dam itself. On 'cleared' floodplains, other researchers have documented that a similar, though larger, zone of sediment transfer exists in the form of a free shear layer between the main channel and the floodplain surface (Knight and Shiono, 1996; Nicholas and McLelland, 1999). The juxtaposition of fast and slow flow appears to foster sediment deposition below this shear layer, and on floodplains without LWD most sediment is therefore deposited close to the channel (e.g. Nicholas and Walling, 1997). The areas of highest deposition on this forest floodplain occurred where small free shear layers were created by woody debris, vegetation and topography. These free shear layers were, however, much smaller and frequent than those described by Nicholas and Walling (1997), and the fluxes of turbulence they are associated with probably extend to adjacent flowing and ponded areas, delivering both coarse and fine sediment to most parts of the floodplain. This may explain why the fraction of silt and clay in each sample was not statistically, quantitatively or qualitatively related to any other variable. The driver of these hydraulic features was the spatial arrangement of organic material on the floodplain: this was related to surface topography (compare Figs. 4.1 and 4.15), and therefore to patterns of overbank flow and deposition at the microscale (10^{-1}-10^{0} m); meanwhile, the in-channel dam provided the dominant control on the observed patterns of sedimentation at the mesoscale (10^{1} m). Thus, overbank patterns of sediment deposition are a function of local ponding (10^{1} m), overlain onto a complex hydraulic environment provided by a micromosaic (10^{-1}-10^{0} m) of LWD and vegetation.

4.4.5 Conclusions from the main study

Two specific conclusions can be drawn: (i) LWD jams significantly affect the hydrology and hydraulics of the channel and flood-plain; (ii) complex patterns of overbank sediment deposition occured, which may be related to free shear layers caused by LWD and vegetation at fine spatial scales $< 10^{-1}$ m.

4.5 Discussion

Both studies described in this chapter underline the importance of woody debris on floodplain deposition. A large, stable in-channel accumulation of debris significantly increased the hydrological connection between the main channel and the floodplain. During both studies, the pattern of overbank flow was controlled by topography, vegetation and LWD. While the amount of deposition observed during the pilot study was broadly in line with the amounts observed on 'cleared' floodplains, during the main study, and on a much more dynamic floodplain, there was more deposition and its distribution was more variable. Most deposition appeared to be associated with free shear layers associated with floodplain debris, vegetation and topography.

The effects of LWD on overbank deposition observed here begin to describe a new genetic sequence for small, lowland floodplains that significantly differs from the model of Wolman and Leopold (1957) and Leopold et al., (1964). Intuitively, the hydraulic effects of in-channel LWD are likely to heavily influence the secondary flow pathways that drive processes of lateral accretion (Bathurst et al., 1977; Thorne et al., 1985). This study demonstrates that LWD significantly increases the frequency and duration of overbank flow, and increases the spatial distribution and amount of overbank deposition. James (1985) and Pizzuto (1987) both modeled overbank flow and demonstrated (i) sediment diffusion, with a decrease in sediment deposition as the distance from the channel increases, and (ii) vectors of overbank flow and sediment moving parallel to the channel. The patterns of lateral diffusion that were modeled and observed on the 'cleared' floodplain of the R. Culm, Devon, by Nicholas and Walling (1997) were partly modified by floodplain topography. In contrast, this study describes how LWD, vegetation and topography on the floodplain surface cause significant diversification in the pattern of overbank flow and sedimentation. No gradient of lateral diffusion is apparent; instead, a complex pattern of deposition occurs, controlled by (i) the hydraulic affect of the dam in the channel extending to the floodplain, and (ii) the hydrological and hydraulic affect of woody debris, vegetation and topography on the floodplain surface. The resulting deposition is spatially variable, and can be concentrated to create levels that are much higher than those found elsewhere (Table 2.2). The patterns of deposition observed implies that the hydraulic affect of woody debris creates a new type of environment for overbank accretion. These results also pose significant challenges for numerical simulations of long-term floodplain evolution because the distribution of LWD is highly variable between regions, within a catchment, and over time. Further, physically based numerical simulations will require a full definition of these complex microscale processes of sediment deposition.

4.6 Conclusions

The two experiments recorded the pattern and type of sediment deposited after a total of eleven floods in two environments. The patterns of deposition were usually consistent between events, and were strongly related to vegetation and woody debris both in the channel and on the floodplain. The type of deposit was not related to any observed variables, which is probably because overbank flow hydraulics are complicated in the presence of vegetation and woody debris. Three main conclusions can be drawn:

1. In-channel accumulations of woody debris:
   - (i) locally strengthen the connection between the floodplain and the channel;
   - (ii) locally pond overbank flow and, thereby, control meso-scale floodplain hydraulics.
2. Amounts of overbank deposition are greatest:
   - (i) on forested floodplains, compared with 'cleared' floodplains;

(ii) on forested floodplains associated with debris dams;

(iii) in zones of sediment transfer associated with free shear layers where organic material interacts with overbank flow.

3. The pattern of overbank deposition is a function of:

   (i) the interaction of overbank flow with topography, woody debris and living vegetation;

   (ii) zones of sediment transfer associated with free shear layers where organic material interacts with overbank flow.

Chapter 5

Conclusion: The effects of vegetation on cohesive lowland floodplains

5.1 Summary

This chapter summarises the thesis and synthesises the findings from the two preceding results chapters. The first objective, to define a research agenda, was achieved by reviewing literature concerned with floodplains and the impact of biota (living and dead vegetation) upon fluvial, hydraulic, hydrologic and geomorphic processes. The most widely-held process model of floodplain formation was outlined by Wolman and Leopold in 1957, who described how lateral and vertical accretion could both operate to create a floodplain. Each accretion process is driven by hydraulic structures that can be modified by vegetation. The research agenda therefore was to focus firstly on forest floodplain geomorphology; and secondly on whether lateral or vertical accretion processes as described by Wolman and Leopold (1957) and by many researchers since (e.g. Allen, 1967; 1970; James, 1985; Pizzuto, 1987) occurred on a forest floodplain. The second objective, to test this agenda, was addressed with three field campaigns: two catchment-scale floodplain surveys; and a reach-scale experiment into floodplain deposition.

One of the largest areas of primeval floodplain woodland in England lies around the Highland Water in the New Forest. Using this as a study area, a reconnaissance survey was undertaken (described at the beginning of chapter 3), which defined an inventory of forest floodplain geomorphic features. The survey highlighted that in-channel debris and floodplain biota (principally trees or woody debris) appeared to play a key role in determining the extent and location of lateral and vertical floodplain processes. The second survey (the second part of chapter 3) concluded that lateral accretion was in fact triggered by in-channel accumulations of woody debris, and that these could also activate overbank processes, where the pathways of overbank flow were controlled by floodplain biota.

Detailed experiments into the distribution of overbank sediment deposition following 11 floods demonstrated that vertical accretion did occur but the amount and spatial distribution of deposited sediment was highly variable (chapter 4). This heterogeneiety was a result of micro-scale variations in flow hydraulics caused by obstructions such as trees. Hence, floodplain biota controlled the micro-scale processes of vertical accretion. Debris dams act as foci for the lateral accretion of the channel and the vertical accretion of the floodplain. Vegetation and debris on the floodplain surface subsequently modify the water and sediment ejected at these foci to create a spatially and temporally dynamic and heterogeneous surface.

The third objective was to synthesise the conceptual models generated from the literature and the previous chapters, and to assess their relevance for floodplain research, and these issues are addressed in the present chapter. A modified model of lateral and vertical accretion can be presented for lowland floodplains. Lateral accretion is controlled by in-channel accumulations of woody debris. The general location of overbank accretion is also controlled by these accumulations, but the patchiness and distribution of overbank deposition is a function of floodplain biota. Thus, processes of floodplain formation are locally controlled by wood. Finally, some options for future research directions are outlined.

Floodplains are frequently subject to a variety of management practices. The catchment surveys highlighted that the processes described were so sensitive to modification such as channelisation that fluvial changes are still occurring decades later. In addition to their scientific worth, the findings from this research could be applied to define management practices that will maintain and improve forest floodplains. A variety of management options, focused on the aims of the Forestry Commission, whose funding partly supported this research, is therefore presented in Appendix B.

5.2 Synthesis and discussion

The original research aim was to investigate the morphological diversity of a lowland floodplain and to investigate how this is influenced by vegetation. The most popular model describes how lateral and vertical accretion create and erode floodplains (Wolman and Leopold, 1957). Both types of accretion are a direct result of the hydraulic structures that are generated from the morphology of the river itself. These structures are (1) in-channel flow helices (secondary flow circulations), which occur in meanders and result in distinct outer bank erosion and incipient inner bank deposition at meander apices (Allen, 1970); and (2) a decline in turbulence and sediment deposition with increasing distance from the main channel, causing successive layers of overbank sediment to be deposited (James, 1985; Pizzuto, 1987). However, both hydraulic structures can theoretically be significantly modified by biota (e.g. Thorne and Furbish, 1995; Tabacchi et al., 2001). The impact of this modification on processes of floodplain formation was the subject of this research, and it was postulated at the end of chapter 2 that, of the four types of forest floodplain identified (Fig. 2.11), least was understood about small, lowland forest floodplains. This type of floodplain was therefore specifically investigated.

The next step was to test whether either of the processes of accretion actually occurred on a forest floodplain, but this posed a problem: there were no literature-based descriptions of lowland, forested floodplain geomorphology – were processes of lateral or vertical accretion important? Did they even exist? A reconnaissance survey was carried out that not only investigated the existence of lateral and vertical accretion, but also identified the geomorphic features of a lowland forest floodplain. Assessments were made of channel geomorphology (including debris dams), reach morphology (bank height and local management such as channelisation or debris clearance), and downstream changes through the catchment. From the survey, a list of forest floodplain features was created, many of which were associated with vegetation and some of which had not previously been documented. An especially interesting floodplain feature was the ephemeral flood channel, which could have been formed either from erosion of or deposition on the floodplain surface. Whichever process was responsible, trees and other biota were frequently associated with the channels. This evidence suggested that significantly different overbank processes occurred to those numerically simulated by James (1985) and Pizzuto (1987). The survey also identified that lateral accretion did occur, and that lateral channel change was associated with in-channel debris dams. Thus, vegetation and woody debris appear to modify processes of lateral and vertical floodplain formation.

More research was required to verify these conclusions, however, because they were the result of qualitative observation. Experiments were therefore designed to investigate lateral and vertical accretion in more detail. Vertical accretion was most complex and in any case occurred over a relatively small area. A site-specific experiment was therefore undertaken to observe detailed patterns of overbank deposition (chapter 4). In comparison, lateral accretion was more widespread, and this was therefore investigated within a second catchment-scale survey. The survey identified that channel changes were irregular and appeared to be more closely linked to in-channel debris, which disrupted secondary flow helices and caused other types of bank scour. These processes were accelerated by a steeper slope within the channelised sections, where the rates of lateral movement since modification were quantified. Seven out of nine reaches had experienced lateral movement greater than the 2.1 m survey error, and the average rate of movement for these reaches varied from 1.2 to 4.3 cm yr^{-1}. In considering that channelisation accelerated lateral accretion because of a higher slope, it is likely that the lower gradient and stream power in the natural sections would militate against lateral movement, except where in-channel debris could focus fluvial energy to cause local changes.

Factors driving reach scale processes

Three types of lateral channel change associated with debris were conceptualised (chapter 3), and some of these involved negative feedback loops. The first type occurs where an in-channel debris dam forms, ponding flow upstream and causing highly localised energy dispersal, which enlarges the cross section due to erosion of the banks at the sides of the dam (Fig. 5.1). However, overbank flow does not occur in this submodel either because the dam is too small, or because the banks are too high. This mechanism is most common within the channelised sections, where banks are highest. The bank scour promoted by the debris undermines the dam and causes its collapse. The post-process signature of this process is a short section of wider channel where this erosion occurred, with the scoured sediment deposited in bars downstream.

In the second model, which occurred in several of the natural reaches, a meander cutoff is instigated by an in-channel debris dam (Fig. 5.1). The dam ponds water above the banks and floodplain flow occurs across the meander neck, scouring the surface and eventually promoting a meander cutoff. This leaves the old channel relict with the debris dam inside it, and thereby negates the direct hydrological impact of the dam. The new, shorter section of channel has a greater slope that provides in-channel secondary flow helices with sufficient energy to cause lateral scour, causing lateral erosion and meander migration until the slope is reduced to a level similar to that before the disturbance. This fluvial process takes the outcome of the impact of the dam (a shorter channel with a locally greater slope) and effectively negates its impact (a longer meandering channel with a lower slope).

The third model, which does not necessarily involve negative feedback, occurs when a dam blocks the channel and causes localised overbank flow across a wider area of floodplain (Fig. 5.1). The dam may undermine itself through erosion at its margins (a negative feedback) or it may be biologically or physically broken up (evolution). In either case, the local overbank discharges of water and sediment that occur around the dam during its life exceed in duration and magnitude those occurring elsewhere on the river network. The floodplain flow is forced into coherent pathways by the pattern of floodplain vegetation and debris, and this results in patchy sediment deposition. This model of overbank deposition represents vertical accretion (cf. James, 1985 and Pizzuto, 1987) on a forest floodplain, and was specifically investigated in chapter 4.

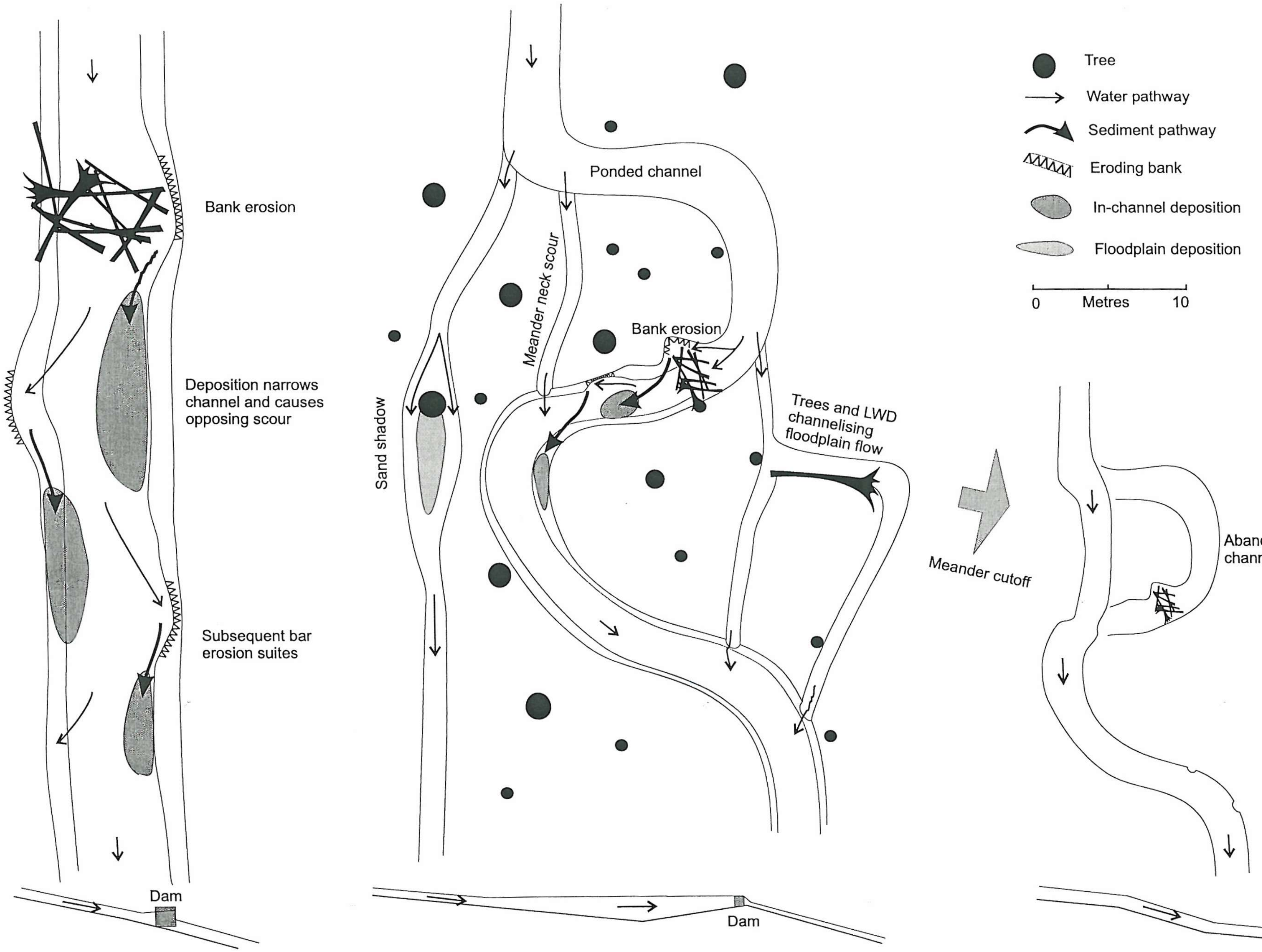


Figure 5.1 Types of geomorphic change associated with in-channel debris

The reconnaissance survey identified that the site where in-channel debris was most active in causing overbank discharges of water and sediment around 100 m downstream of Millyford Bridge (SU 426990, 107690). The dam caused an increase in overbank discharge from 0.2% to 42% of the study period, although note that this time included the wettest autumn since UK Meteorological Office records began. The dam itself directly caused ponding and deposition on the floodplain surface, and the resulting floodplain deposition reached levels that were much higher than those recorded elsewhere. The pattern of deposition was also much more spatially variable than on cleared floodplains, ranging from zero to 26 kg m^{-2} per flood over a distance of less than one metre. The rapid spatial shift from a zone of sediment transport (or scour) to an area of intense deposition was a result of the influence of the surface elements of the floodplain (notably trees but also woody debris and the topography itself), upon overbank flow hydraulics. Trees in particular led to the creation of free shear layers and flow vortices, and it was within the transfer zone between fast and slow flow that the highest rates of sediment deposition occurred. Because these free shear layers were clearly associated with vegetation, it can be hypothesized that different patterns of biota will result in different patterns of sediment deposition and vertical accretion. This variable environment promoted sediment deposits that were unsorted and did not differ significantly over space or between floods (at a 95% confidence level). The response of overbank deposition to a range of types of floodplain cover was not quantified in this study; but, when compared to non-forested floodplains, the very high rates of deposition observed provide strong evidence for the sediment-trapping potential of wood and trees. Note that the observed spatially incoherent and highly variable patterns of overbank accretion do not conform to the predictions of the existing numerical models of overbank sedimentation (James, 1985; Pizzuto, 1987). Instead, floodplain deposition occurred in a highly variable pattern that was related to the pattern of vegetation. The complexity of micro-scale (10^{-2}cm) processes was not explicitly investigated in this study, and more research to address processes operating at these scales is necessary before they can be incorporated within numerical models of overbank sedimentation.

Floodplain formation in this low-energy system with cohesive banks is driven by the concentration of energy, water and sediment by debris dams in discrete sections of the river. Dams pond water in the channel and this helps to increase the frequency and extent of overbank flow, which itself is further modified by floodplain vegetation. Hence, energy is dissipated at 'hotspots' within a longitudinal river-floodplain unit. This sporadic focusing of energy is quite different to the more regular dissipation at meander apices inherent within the Wolman-Leopold model (1957), which occurs where helical flow focuses energy at the outer apices of each meander bend, causing outer bank erosion and deposition at the inner bank to create new floodplain.

The clear impact of biota on lateral and vertical accretion at the local and sub-local scale raises the question of whether systematic variations in floodplain process occur at the catchment scale. To address this, it is necessary to consider both the downstream change in fluvial character, and the spatial distribution of LWD, which was the most dominant feature to affect floodplain processes.

Catchment scale changes in a lowland forested floodplain.

In the headwaters, debris can fall across or over small streams and is therefore less likely to cause in-channel dams (Gregory et al., 1993; Nakamura and Swanson, 1993; Piégay and Gurnell, 1997). Channel processes also appear to be unimportant, and a floodplain cannot be readily identified (chapter 3). In these very small streams, therefore, woody debris has little impact.

As the channel width increases, debris has a greater chance of blocking the channel (Gregory et al., 1993), so the number of debris dams increases (in the Highland Water the number of debris dams reaches a peak around 2 km downstream from the upper limit of the headwaters; Gregory et al., 1993). Fluvial processes also become more active and a discernible floodplain becomes evident. Where dams block the channel, they refocus fluvial energy at the riverbank causing erosion, lateral movement and floodplain creation. Where dams block meander loops they may cause cutoffs and consequent increases in slope, stream power and the ability of a short section of the river to erode. Larger dams that completely block the channel may also cause overbank flow, injecting water and sediment onto a small area of floodplain, where floodplain vegetation creates a highly diverse micro-topography (Chapter 4). Debris therefore has the ability to directly control and indirectly instigate processes of lateral migration and vertical accretion, leading to a new sequence of sediment deposition and floodplain evolution that is additional to the model of lateral and vertical accretion (Wolman and Leopold, 1957). This intermediate scale is that at which the field research described in chapters 3 and 4 was aimed.

As the size of the river increases, the character of debris dams changes. Accumulations that fully block the channel become less frequent - though over longer periods of time snags may block even very large rivers (Wallerstein et al., 1997); instead, logs pile up on the outer banks of meanders (e.g. Hickin, 1984; Piégay et al., 1998), protecting them and dissipating fluvial energy (similar to that described by Thorne and Furbish, 1995, but in a larger channel). Any vegetation or woody debris that lies in the channel has the potential to modify the flow field, usually making it more complex (Newell, pers.comm., 2001), and often dissipating fluvial energy (e.g. Thorne and Furbish, 1995). In very large rivers, where the channel is significantly wider than debris at the margins, the additional roughness provided by woody debris is likely to be confined to the banks, and the flow field in the centre of the channel could therefore remain mostly unaffected. The scale of fluvial processes in very large rivers therefore has a theoretical potential to subsume some of they hydraulic effects of in-channel debris. The effect of woody debris is therefore less important in these large streams than it is in small and medium channels.

It can therefore be argued that the geomorphic influence of woody debris is felt most strongly in small and medium size rivers (but not the headwaters) where (1) stream power is not quite always sufficient to cause fluvial scour within the existing cross section unless the flow hydraulics are modified by vegetation and where (2) the channel is narrow enough for debris to frequently and completely block it. In other words, the scale at which debris has the greatest geomorphic influence approximates to the channel scale. This concept makes the Highland Water a useful research site for the purposes of this research, especially the section studied where average channel width varied from 0.5 to around 5 m, which is a broadly similar length to many wind-thrown debris. The fact that the Highland Water has relatively few dams is a result of management practices such as debris clearance, and possibly lack of new growth. It is fortunate, therefore, that a dam of theoretically maximum impact existed on the Highland Water because this demonstrated that dams have a significant impact on the spatial distribution of overbank flow. Further research could be usefully undertaken at the micro scale (to determine the physical principles behind extreme rates and patterns of sediment deposition and floodplain creation), and at the scale of larger rivers (to determine the impacts of wood on the geomorphology of large, lowland floodplains).

In fact, the impact of management practices on the Highland Water was starkly demonstrated by the facts that half of the surveyed length of river has been channelised, that even after 191 years the river channel has not resumed an original course, and that the number of debris dams has been significantly reduced following debris clearance. Other streams, in the New Forest and elsewhere, have been subject to similar management practices. The low stream power and reliance on forest processes that may take decennia to reach maturity means that this type of low-gradient forest stream and floodplain is highly sensitive.

The findings from this research could be applied to improve the geomorphic functioning of floodplain forests, and the possible management options to achieve this are outlined in Appendix B. This uses the Highland Water as a case study with a specific focus on the aims of the Forestry Commission who partly funded this work (via Forest Research), and who manage riparian land throughout the New Forest and in other parts of the UK.

5.3 Conclusions and recommendations for further research

This research has found that the Wolman-Leopold (1957) model of floodplain accretion cannot, in its original form, be applied to the forested floodplain of the Highland Water, and instead proposes a modified model where fluvial processes are controlled by vegetation. Firstly, the highest rate of lateral migration was low compared with other rivers (only detectable over meso-time scales of 10^1-10^2 years). Instead of being evenly distributed at each meander bend apex, lateral erosion occurred where the stream power was focused upon the river bank by in-channel debris. Despite a meandering planform, there was little evidence of active lateral movement except where in-channel dams caused bank scour or meander cutoff. To summarize: the spatial distribution of fluvial energy and lateral accretion was controlled by woody debris, which acted as a trigger to instigate short reaches of change. The distribution of fluvial change at the catchment scale was associated primarily with the occurrence of debris dams, which are systematically distributed through a channel network. Thus, lateral migration in a forest floodplain is more spatially variable and less predictable than on cleared floodplains.

Secondly, it was only at specific locations where large debris dams blocked the channel that significant fractions of the floodplain were inundated. The observed uneven pattern of accretion did not conform to that predicted by the models of James (1985) or Pizzuto (1987). Instead, a highly variable pattern of overbank deposition depended upon the existence of small shear layers where floodplain vegetation influenced the hydraulics of overbank flow, leading to wake deposits (sand shadows). The most significant changes in floodplain evolution therefore occurred where instigated by accumulations of in-channel woody debris; and these were modified by living vegetation on the floodplain surface.

The model presented here is specific to meandering rivers, but other studies underline that wood has significant geomorphological effects in many systems. The floodplain of the Highland Water was naturally less geomorphically active than higher-energy systems such as the Fiume Tagliamento, Italy (Gurnell et al., 2001), or the Ain, France (Piégay et al., 1998). A common thread to each of these, however, is that biota promotes diverse spatial pattern of hydraulics and sedimentation. For example, in the higher energy systems, biota promotes island development (e.g. Gurnell et al., 2001), or channelises overbank flow (e.g. Piégay et al., 1998).

This study has by necessity been concentrated across a fairly small spatial area and on one river only. These conclusions are therefore tentative and need to be tested more rigorously. Future studies should concentrate on establishing a similar baseline on an intact low-gradient forest floodplain but in a larger system. More detailed investigations of how vegetation affects overbank hydraulics on this floodplain are also necessary: experiments are necessary that investigate event-scale patterns of erosion and deposition after each event and that examine flow lines through the injection of dye or other visual tracers. In the Highland Water, it is also necessary to co-ordinate investigations of (1) the palaeohydrological and stratigraphical and (2) palaeoecological history of the floodplain during the Holocene. A synthesis of such findings will address the vital question of whether the floodplain aggraded, through the Holocene, and, if so, what role vegetation may have had. Such a study could be combined with similar palaeoenvironmental reconstructions on a larger but formerly forested river in a similar environment to provide a regional perspective.

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Appendix A - Photographs of floodplain features

Photo 1a. The maximum extent of flooding is illustrated by a lack of leaf litter on the floodplain surface (near the A31).

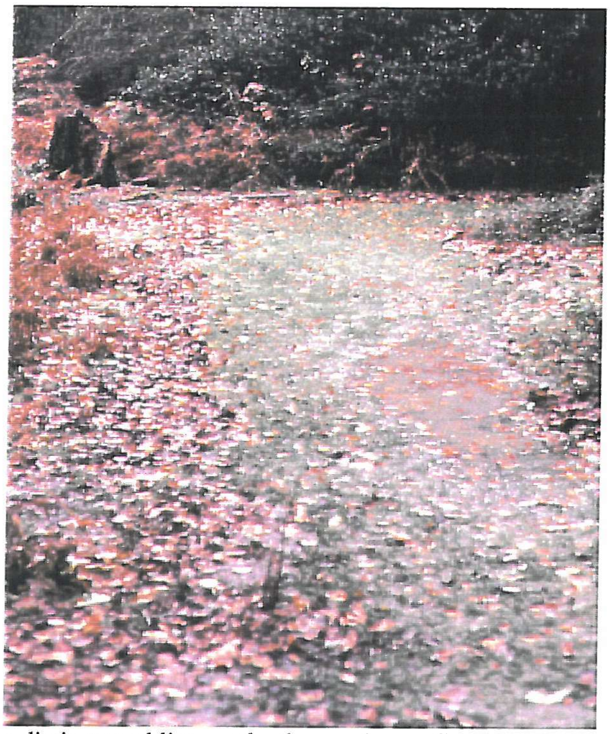

Photo 1b. Elsewhere, a distinct trashline marks the maximum flood extent (near Millyford Bridge).

Photo 2. An active debris dam downstream of the A31.

Photo 3. Ephemeral channel (right) running parallel to the channel.

Photo 4. Ephemeral channel running across a meander loop.

Photo 5. Around 2km from the drainage divide, the floodplain is fairly narrow (the trees on the right mark the maximum flooding extent).

Photo 6. A meander neck cutoff, probably aided by the stabilizing influence of the tree on what is now a veegetated mid-channel bar.

Photo 7. The entrance to an abandoned meander loop that is reactivated during flooding.

Photo 8. Complex floodplain microtopography and trees.

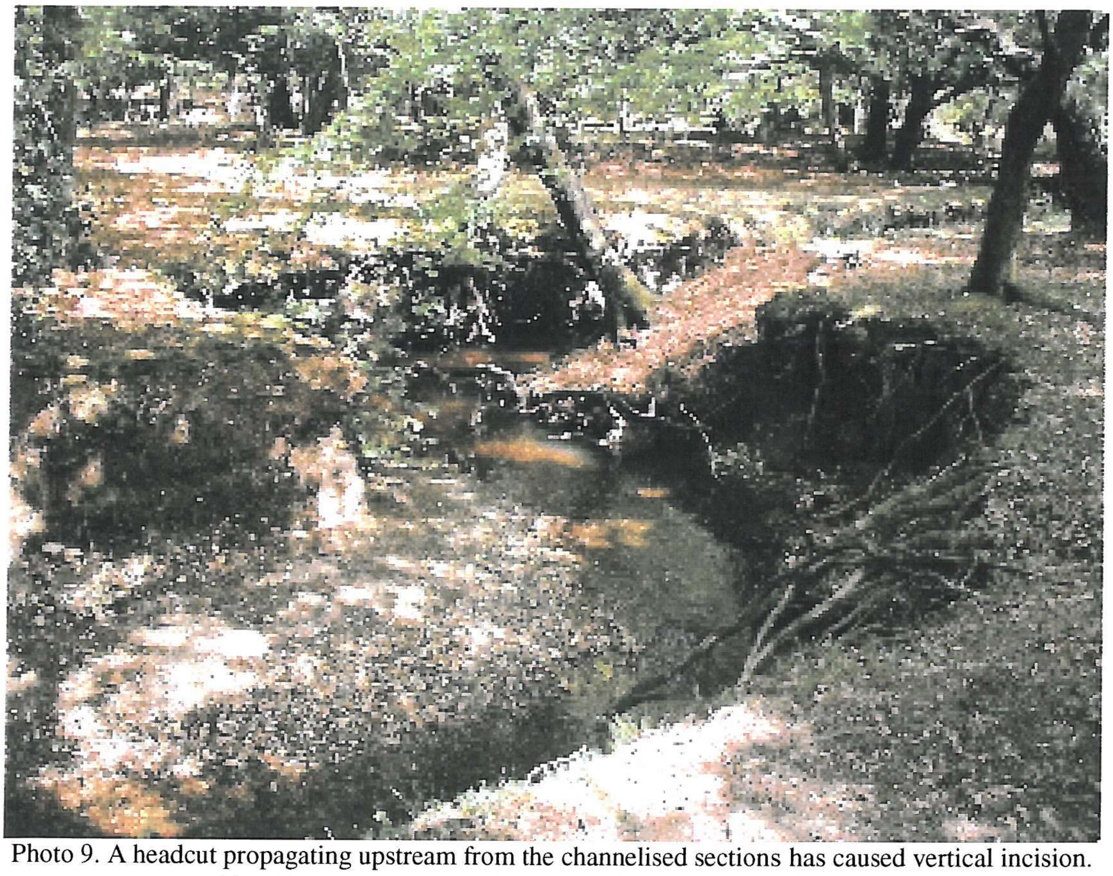

Photo 9. A headcut propagating upstream from the channelised sections has caused vertical incision. Note the geotechnical collapse picked out by the leaning tree.


Photo 10. The incision has cut down onto clay plugs embedded in the floodplain. These cohesive units cause steps in the water surface profile.


Photo 11. Densely vegetated floodplain abandoned due to channelisation in 1967. The channel runs behind the dredging spoil to the right.

Photo 12. The channelised reaches in the upper part of the Highland Water plantation have steep, high banks.

Photo 13. Adjacent to the channelised reach lies the old channel, now a pond under dense conifer cover, filled with logging spoil and litter.

Photo 14. Dense surface vegetation on floodplain abandoned in 1810 prevents the old channel, which runs through the right of the photo, from eroding.

Photo 15. Short section of incipient new floodplain (left centre) have been created in the upper part of the Holmhill Plantation.

Photo 16. Another short section of new floodplain in the upper part of the Holmhill plantation. The bank to the right marks the lcoation of the channel in 1810.

Photo 17. Lateral movementof 13m in 190 years has occurred in the middle of the Holmhill plantation. The former bank line is parallel to the left boundary of the photo.

Photo 18. Floodplain deposition of fine sediment. This was following overbank flow caused by a large dam near Millyford Bridge.

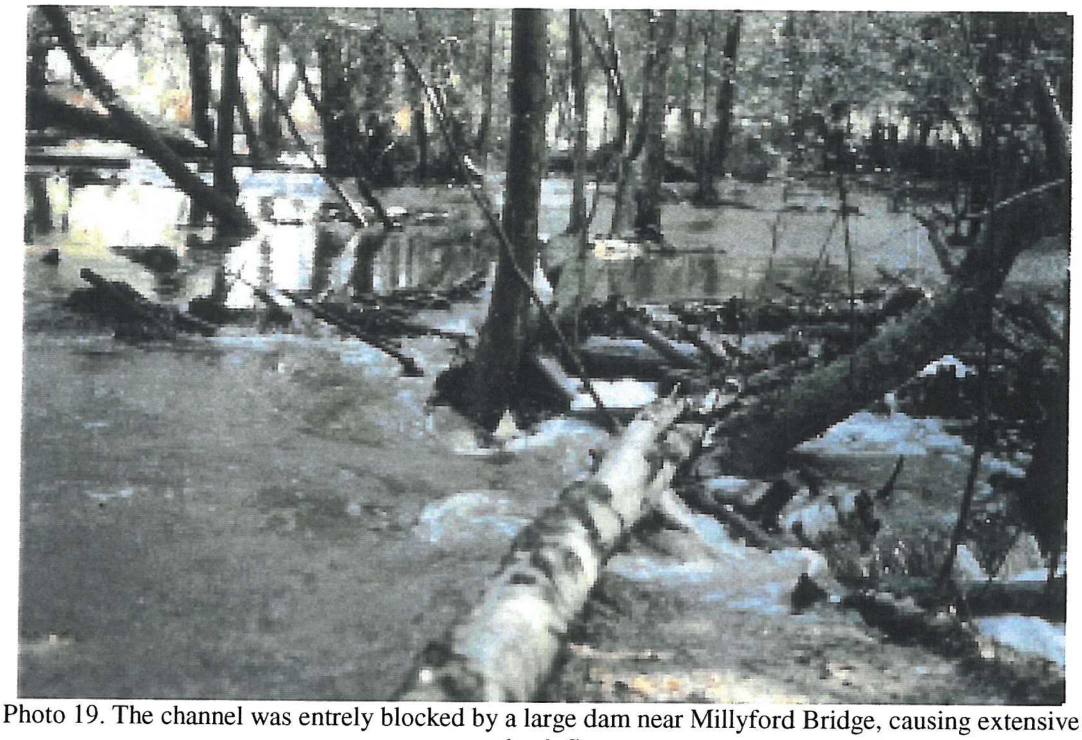

Photo 19. The channel was entrely blocked by a large dam near Millyford Bridge, causing extensive overbank flow.


Photo 20. Overbank flow controlled by trees (adjacent to the debris dam near Millyford Bridge).


Photo 21. A shallow-rooted coniferous tree, fallen into a section channelised in 1810.

Photo 22. Trees can directly control floodplain dynamics.

Photo 23. 'Minor' fluvial scour in the headwaters - small patches of vegetation have been removed.

Photo 24. 'Moderate' fluvial scour, where the bank is free from vegetation but is not rapidly retreating.

Photo 25. 'Severe' fluvial scour, leading to slumping. This erosion was cuased by incision after the bed downstream was lowered during channelisation.

Appendix B - River and floodplain management and restoration

1 Management context

One of the largest owners of forested land adjacent to streams in the UK is the Forestry Commission (FC). In the last decade, the FC has diversified its focus from principally economic aims towards a more holistic approach that considers environmental aims, the maintenance of biodiversity, and the public perception of FC woodlands. Lowland floodplain forests are one of the oldest and most fundamental landscape features, and it would therefore be appropriate if the aims of the FC accounted for them. A core concept of the following section is that the range of floodplain processes described elsewhere in this thesis can be managed to efficiently address several of the aims of the FC. This research was specifically focused on a lowland floodplain in the New Forest, and it is this type of river and floodplain in which the following discussion can be most readily applied.

This section provides advice for the FC to use in its efforts 'to improve understanding of the value of the environmental benefits of trees, woodlands and forests, and the environmental processes that they perform,' and to 'use the biodiversity action plan to guide nature conservation' (Forestry Commission, 2001). The Highland Water, a small stream in the New Forest, has provided an ideal opportunity to investigate the functioning of a forested lowland floodplain. This document now describes how the findings of this study could be used to guide management that aims to increase geomorphological and ecological diversity, as well as providing suggestions for where future research may be directed. The FC also aims to 'engage with the public to promote the benefits of trees, woods and forests.' The New Forest is a favourite tourist destination, annually attracting millions of visitors, and therefore provides a prime site to address the aim of the FC to promote a 'greater appreciation of the broad environmental benefits of trees and woods to practicioners, decision makers and the public' (Forestry Commission, 2001). Furthermore, restoration of forest floodplains could provide a valuable demonstration project to further increase understanding for science and sustainable management.

The general aims of the Forestry Commission (FC) are: the 'sustainable management of existing woods and forests; and expansion of woodland area to provide more benefits for society and the environment' (Forestry Commission, 2001). The action of the FC for the environment and conservation includes the following: 'Woodlands perform an important role in respect of a range of more general enviornmental processes. They influence the water cycle. Alongside watercourses, they act as a buffer, helping to intercept pollutants from adjacent land. They can increase river-bank stability and reduce erosion... They also help to form and protect soil resources,' (Forestry Commission, 2001).

Forest floodplains influence the water cycle while flood water is stored on the floodplain, where flow dynamics are affected by trees and other vegetation to create a heterogeneous environment. The time taken for the water to reach downstream sections is increased by this temporary storage, and flooding can therefore potentially be reduced. Water-borne sediments (and associated pollutants) can be stored on the floodplain by the same process. The deposited sediment is usually fine-grained (approximately two-thirds sand, one-third silt and clay, with variable amounts of organic material; see chapter 4) and is a spatially variable, fertile medium for propagule germination. All of these benefits are naturally promoted by debris dams, which block the channel and cause overbank flow. Indeed, the dam studied in this thesis increased the duration of overbank flow from 0.2% to 42%; and sediment deposition occurred that was significantly in excess of the amounts quantified for non-forested floodplains. In many streams these dams have been removed to increase the downstream passage of flood water and improve drainage, and this has not only reduced the connection between the floodplain and the channel, but has also removed the associated positive benefits.

Forest floodplains have frequently been accredited with being biologically very diverse (e.g. Bendix, 1998; Gurnell et al. 2001; Power et al. 1995). Habitat and species diversity result from a combination of physical factors: disturbance (flood water, new sediment, variable duration of inundation (Bayley, 1995; Bendix and Hupp, 2000; Brown, 1997; Brown et al. 1997; Gurnell, 1997; Tockner et al. 2000; Ward et al. 1999)); process heterogeneiety (caused at the scale of metres by the interaction of trees, vegetation and flood water; and variability about where flooding occurs is caused by the random distribution of debris dams (see chapters 3 and 4)), and nutrient dispersal (which is likely to be controlled by the same factors that influence the location of flood water).

Whether trees and forests improve channel stability and prevent bank erosion appears to depend on the channel itself, especially the degree to which it has been modified: this work has documented that very little bank erosion occurred within undisturbed reaches of a forested stream; but within channelised reaches of the same river running through coniferous plantations of varying ages, significant erosion took place. The channel within plantation woodland had been straightened and deepened to drain the surrounding floodplain, and was prone to instability because the straighter channel was also steeper, which increases stream power (Bagnold, 1966) and the propensity for fluvial erosion.

The fragmentation of woodland threatens its continued ecological viability (Forestry Commission, 2001). A priority of the FC is to work towards reversing this fragmentation by encouraging the creation of new native woodlands. This could be achieved by reforesting river corridors. The riparian zone ('the land immediately adjoining the aquatic zone and immediately influenced by it,' where the aquatic zone is 'the ground frequently or permanently under water, forming streams, rivers, ponds and lakes' (Forestry Commission, 1993)) includes damp forest floodplains. Its management 'must aim to protect and encourage the diversity of these rich habitats for the benefit of the whole forest' (Forestry Commission, 1993). Re-foresting such areas provides an opportunity to achieve many of these aims because rivers are diverse linear features that could be used to rejoin previously fragmented woodlands.

2 Maintaining and improving forested river channels: a case study

This research has demonstrated that floodplain processes, although influenced by vegetation, are essentially driven by energy derived from the river channel itself. Therefore, floodplain forest management must also address river management, and the following section provides a context for the case study by considering stream management in the New forest.

2.1 River channel management in the New Forest

Most New Forest streams are fairly small (less than 10 m wide) with a low gradient and cohesive banks, which makes them fairly stable. A broad classification of three types of riparian zone that surround these channels can be made: lawn (not addressed); channelised sections through coniferous plantations (inclosures); and semi-natural sections; and both of the latter have been studied in some detail in this thesis.

The semi-natural sections are, and have been, affected by historical management from commoners (local people with legal rights to forest resources) and Verderers (managers of the commoners' animals and the open forest). Verderers have a responsibility to prevent flooding of the forest floor by ensuring that water flows freely through the river channels, and they therefore remove in-channel accumulations of debris. The FC has also undertaken debris clearance with the aim of improving fish passage (in 1990; cf. Gregory, 1992; Gregory and Davis, 1993). Within the open forest (ie. those areas not within inclosures), commoners have the right to graze livestock, and new seedlings are usually consumed by ponies or deer before reaching maturity. In the late 1800s a deer cull reduced the grazing pressure for several years, and until deer populations recovered, seedlings and saplings were able to reach an age at which they could withstand the grazing pressure. Many of the trees surrounding the natural sections of the Highland Water appear to date from this time and seem to be over-mature: new saplings were rarely observed during the course of this study; new shoots were grazed almost immediately. (The effect of these apparently aged trees on the input of dead wood to the floodplain has not, to the author's knowledge, previously been quantified, and therefore presents an opportunity for future research.) This dead wood is significant because it can enter and then block the channel, causing channel changes and overbank flow as described above and in chapters 3 and 4. A greater input of wood, especially to the river channel, is likely to promote the formation of more debris dams, therefore increasing the storage of water and sediment on the floodplain. These areas of semi-natural forest floodplain form the best examples of such environments in England, yet are still fragmented by the effects of channelisation to improve drainage.

Many areas of the forest have been inclosed for coniferous plantation woodland: the Holmhill inclosure was set up around 1810; the Highland Water plantation in the early 20th Century (Stagg, 1990). Within inclosures, the channel was straightened, widened and the bed lowered by up to 1 m to improve drainage on the adjacent land. This intervention reduced the connection between the floodplain and the river channel, lowering the water table and disabling floodplain processes. The floodplain in many areas is nevertheless wet due to ponding, but because no flushing mechanism operates, pools undergo redox conditions. No other geomorphic process has since modified the floodplain surface; and in many areas the old channel line, though overgrown, is still identifiable (see chapter 3 for a more detailed description of channelised sections). Inclosures are fenced, and, although deer are able to jump the fences, commoner's livestock is unable to enter. The surface of what was the former floodplain within inclosures is therefore subject to a lower grazing pressure, and is covered either with dense grassy vegetation and bracken; or, if the plantation is dense and little light is able to penetrate to the ground, by a layer of dead wood and coniferous litter.

These two types of channels are repeated throughout the forest: areas of grazed, semi-natural floodplain that are fragmented by channelised sections. Compared with channelised reaches, the semi-natural sections have greater hydrological connectivity to the floodplain, leading to diverse geomorphic processes that could drive and ecological diversity, and management options therefore differ markedly for the two. The next subsection examines the potential for maintaining and improving both of these typse of forested river channels, using the Highland Water as a case study.

2.2 Opportunities for improving natural reaches of the river and floodplain

The unmodified (natural) sections of the Highland Water have highly variable channel-floodplain connections: much of the channel experiences overbank flow rarely (approximately 0.2% of the time or less); but short sections are flooded regularly and for long periods, which is a direct result of the effects of in-channel debris dams. Debris clearance in 1990 has reduced in-channel debris loadings and the number of debris dams remained very low, even after eight years. Increasing the number of dams could result in a better connection between the channel and the floodplain, and could store water and sediment out of the channel.

A range of techniques can be suggested to achieve such an increase (Table 5.1). Firstly, it is possible to deliberately add wood with the intention of it forming debris dams. This inexpensive procedure is likely to produce immediate results, but its main disadvantage is that there is no guarantee of the location or type of resulting debris accumulation, and they may form in undesirable locations such as around a bridge, causing undesirable outcomes, such as scour. Secondly, wood can be strategically emplaced to build a dam, but this requires definition of where the dam should be built, as well as ensuring a stable structure. Thirdly, there is the option of not removing wood from the river in the future and thereby letting the amount of in-channel wood naturally increase. This has two disadvantages: firstly, the existing tree stock is old and, once it has degraded, new trees are unlikely to establish themselves due to grazing pressure; and under this present circumstance, as discussed in chapter 3, natural replenishment to pre-disturbance levels of woody debris could take a very long time (up to 157 years). Finally, restocking of the floodplain forest could be undertaken, which should ensure a long-term input of woody debris to the channel. However, the benefits from this are likely to take decades to emerge.

The choice of options will vary according to the final aim, but assuming that it is to create a permanent increase in overbank flooding and sedimentation, then the best option would be to strategically emplace wood (to provide short term results) and restock the floodplain at the same time (to ensure viable long-term floodplain connectivity).

Table 5.1 Management options to improve natural reaches of the Highland Water

Option	Advantages	Disadvantages
Add wood to the channel and allow it to form debris dams	Simple, inexpensive in the short term	Continued addition of wood could prove an expensive long term operation Dams may form in undesirable locations (e.g. under a road bridge) May cause conflict with those with the responsibility to ensure that channels flow freely
Strategic emplacement of wood	Inexpensive	Necessity of knowing where best to place the wood May cause conflict with those with the responsibility to ensure that channels flow freely
Do not remove wood from the river channel	Free	May cause conflict with those with the responsibility to ensure that channels flow freely
Use forest management to increase the natural input of wood to the channel (plant broadleaved woodland and allow it to mature)	Provides a constant long-term supply of wood to the river	Saplings need to be protected until they can withstand grazing pressure; no short term gain

2.3 Opportunities for improving channelised reaches of the river

The channelised (modified) sections of the Highland Water have, in comparison to the unmodified reaches, a poor river-floodplain connection. Although some sections have undergone limited lateral movement, the new sections of floodplain are much smaller than those that existed before modification. A variety of management options to improve the geomorphological and ecological value of this channel are presented in Table 5.2.

Table 6.2 Management options to improve channelised sections of the river

Option	Advantages	Disadvantages
Do nothing	No cost	Fluvial recovery could take centuries, and the final river form is less diverse than the original
Introduce debris dams	Could locally focus fluvial energy to create new floodplain	Loss of adjacent land to erosion May cause conflict with those with the responsibility to ensure that channels flow freely
Raise the bed of the river	By increasing the height of the water table in the floodplain, better channel-floodplain connectivity could occur and more active processes triggered	Overbank flow relies on the formation of in-channel dams, and these are less likely to form within wider channels. Cost
Raise the bed and narrow the channel	Improve floodplain connection and will increase the likelihood of debris dam formation The higher slope but smaller cross section would promote (1) dam formation and lateral change and (2) fluvial scour and floodplain formation	Unpredictability of channel change Cost May cause conflict with those with the responsibility to ensure that channels flow freely
Remeander the channel and actively restore the floodplain	The most 'natural' and potentially the most stable option Unique demonstration site of forest floodplain restoration	Cost Technical expertise required Time taken for this low energy system to recover

The first (and current) option is to do nothing. This could lead to a very slow recovery to a stable channel that has poor connection (compared to the natural sections) to the original floodplain but does have small areas of new floodplain, although the river channel may never recover to its original form. Secondly, in-channel debris could be deliberately introduced to increase the river-floodplain connection by focusing fluvial energy and causing lateral channel change. However, the over-deep cross section would still leave the former floodplain disconnected from fluvial processes.

The three remaining options involve reversing some or all of the effects of channelisation through direct channel modification. A variety of advantages and disadvantages result from each option, but all are likely to be initially disruptive and costly. The first physical intervention could be to raise the bed of the river to its original level. This will increase the height of the water table in the adjacent floodplain and thereby potentially promote channel-floodplain connections. However, overbank flow relies so heavily on the formation of in-channel debris dams, but these are less likely to form in wider channels. Secondly, the bed could be raised and the channel narrowed, which is an option is likely to improve floodplain connection and will also increase the likelihood of debris dam formation. The planform will, however, remain essentially straight and the slope will therefore be greater than natural sections. This increased slope leads to a higher stream power (Bagnold, 1966) that is now focused within a small channel. The resulting channel instability could be useful if it creates new functional floodplain; but the actual location of channel change could be difficult to predict, and erosion may occur in undesirable areas. The final intervention aims to fully restore a floodplain woodland. It involves remeandering the channel along its original course (where apparent) or along a suitable course (using the most similar channel elsewhere as a guide). Planting broadleaved woodland ensures variability in floodplain surface hydraulics; and could provide a steady input of woody debris to the channel. Restoration is often complicated by the fact that the original course and character of the river have been irretrievably lost after many years of modification. Here, a major advantage in comparison to restoration elsewhere (e.g., Sear et al., 1998) is that the original form of the river is still evident in many areas, and only needs clearing, not re-engineering. The resulting system would not only create a significant increase in the amount of natural forest floodplain along the Highland Water, but if the inclosure fences are maintained could provide a less-heavily grazed (and more natural) forest floodplain. This would provide a uniquely natural forest floodplain site for demonstration to improve public awareness and for further research. The obvious disadvantages of this approach are that it is the most intrusive, the most costly and initially time-consuming.

The choice of a given option depends on the desired outcome and available resources. From a research perspective the complete restoration of a forested floodplain could provide the most opportunities to test hypotheses such as whether trees disrupt flow to cause deposition alone, or whether they also cause scour. Resulting from this would be an elevated level of scientific understanding that could help inform what role woodlands play in river and floodplain evolution. It could also increase the physical habitat diversity of what are presently rather homogenous grassy areas or forest floors (photos 11 and 13), and thereby indirectly address the FC's aim of protecting and encouraging the diversity of the riparian zone. The other methods to improve the floodplain functionality are less likely to address these aims, but are also likely to be less expensive.

3 Conclusion

For a relatively low cost, adding wood to a river could cause flood water and sediment attenuation on the floodplain and reduce the level of downstream flooding. It could also improve the geomophological and ecological diversity and biodiversity of forest floodplains in the Highland Water. The potential for restoring a fully functional forest floodplain within channelised sections of the Highland Water is great: the original planform of the river channel is evident; the adjacent unmodified sections provide a template to compare restoration to; and an inclosed forest floodplain could provide an even more natural floodplain for future research and to increase public and managerial awareness of forest floodplains.

Parallelling these opportunities are several threat from adding wood to a river. In-channel debris could cause local flooding at uncertain locations, depending on the type of intervention. Wood can also cause channel change, and because this is not always predictable, it may occur in undesirable locations.