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The geomorphological dynamics of a restored forested floodplain

by

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ABSTRACT

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River restoration has emerged as a method to alleviate some of the widespread damage caused to rivers through anthropogenic modifications. Due to increasing recognition of the importance of the floodplain to the functioning of the whole river system, particularly in relation to flows of energy and material, river restoration projects are increasingly including restoration of the floodplain wherever possible. However, in order to restore river and floodplain systems a good understanding of how the geomorphological processes operate on floodplains is needed. Much research has been conducted into the geomorphological processes operating on unforested floodplains (e.g. Walling and He, 1998; Nicholas and Walling, 1997a and b) but comparatively little has been done on forested floodplains, where geomorphological processes are complicated by interactions with woody vegetation. Our limited understanding of how these systems function hinders our ability to effectively restore them.

This thesis investigates geomorphological processes within the forested floodplain of the Highland Water, a small, lowland river in the New Forest, southern England. Geomorphological processes were monitored (a) before restoration, in order to define reference conditions, and (b) after restoration, in order to monitor the performance of the restoration against the reference conditions.

The results demonstrate that the restoration was successful at moving the restored system towards target reference conditions by re-connecting the channel and floodplain, and consequently floodplain geomorphological dynamics were increased after restoration. However, the restored floodplain was considerably more connected and more dynamic than an upstream semi-natural reference reach, indicating that the restored channel was perhaps undersized.

Floodplain channels were an important geomorphological feature observed on semi-natural floodplains, particularly in association with hydraulically effective wood jams. Experiments into sedimentation and erosion showed that overbank flow scoured the surface and distributed sediment, and rates of erosion and deposition were higher within floodplain channels than elsewhere on the floodplain surface. These channels were therefore a major control over the spatial distribution of energy and materials on the floodplain at the patch, feature and reach scale (10^{-1} to 10^{2} m).

The formation of in-channel wood jams, which force flow overbank, relies on the accumulation of wood. Experiments to investigate transport of small wood recorded travel distances ranging from 0 to over 1000 m. Shorter travel distances were associated with higher in-channel geomorphological diversity, particularly the presence of in-channel wood jams.

This thesis therefore provides a greater understanding of the geomorphological processes operating on a forested floodplain in conjunction with monitoring the performance of a river restoration project that incorporated a forested floodplain.

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Chapter 1. Introduction and thesis strategy

1.1 Introduction

Ongoing fluvial research is providing a good understanding of how rivers and their floodplains function, but work so far has also highlighted how degraded many of our river systems have become. As a result, river restoration has emerged as a way to try to improve degraded river systems. Early river restoration attempts tended to be very localised, species specific (usually focusing on fish), and only concentrated on the channel, ignoring the surrounding floodplain. More recently, however, there has been a move towards more holistic, large scale river restoration. There is also increasing recognition of the importance of the floodplain to the functioning of the whole river system, particularly in relation to flows of energy and material. Consequently, river restoration projects are increasingly including restoration of the floodplain wherever possible.

In order to restore river and floodplain systems it is necessary to have a good understanding of how the geomorphological processes operate on floodplains. Much research has been conducted into the geomorphological processes operating on unforested floodplains (e.g. Walling and He, 1998; Nicholas and Walling, 1997a and b) but comparatively little has been done on forested floodplains; our understanding of how they function is relatively limited, which hinders our ability to effectively restore them. Many forested floodplains have been destroyed for purposes such as agriculture and power production. Therefore it is important to protect those that remain, and to restore them whenever possible. A difficulty in restoring forested floodplains lies in the lack of scientific understanding about how they function naturally (due to few studies and few remaining natural examples). This limits our ability to specify restoration targets and objectives for floodplain forests.

The LIFE 3 wetland restoration project in the New Forest (2002-2006, http://www.newforestlife.org.uk) provided an opportunity to study forested floodplain geomorphological processes (a) before restoration, in order to define reference conditions, and (b) after restoration, in order to monitor the performance of the restoration against the predefined reference conditions. Therefore a greater understanding of the geomorphological processes operating on a forested floodplain was gained in conjunction with monitoring the performance of the restoration, and a contribution is subsequently made towards the identified research gap.

1.2 Thesis strategy

The thesis is introduced in this chapter (**Chapter 1**), and the thesis strategy and aims and objectives, which are primarily to assess the restoration and learn more about the forested floodplain geomorphological processes whilst doing so, are discussed. **Chapter 2** reviews the restoration literature, discussing restoration philosophies and approaches, and particular focus is placed on restoration of forested floodplains. The main difficulty associated with restoring forested floodplains is the lack of reference or target conditions against which to assess restoration. This leads on to **Chapter 3** in which general reference conditions and targets for floodplain forest restoration are discussed based on a literature review of floodplain processes.

The overall research methodology and details of the study sites and the LIFE 3 restoration project are described in **Chapter 4. Chapter 5** builds on the general reference conditions and targets discussed in Chapter 3, by defining specific reference conditions and targets for New Forest floodplains from field observations and surveys of geomorphological features present on New Forest floodplains. Floodplain channels were identified as being particularly important geomorphological features, and their catchment and reach-scale distributions were analysed in order to gain a greater understanding of the processes leading to their development. Relevant processes to monitor in order to assess the impacts of the restoration on floodplain geomorphology were then identified on the basis of the reference conditions and targets defined.

Chapters 6, 7 and **8** report on the results from the pre- and post-restoration process monitoring: **Chapter 6** focuses on fine sediment loads and overbank deposition; **Chapter 7** focuses on floodplain erosion processes; and wood mobility and retention are discussed in **Chapter 8.**

Chapter 9 provides an evaluation of the restoration and floodplain processes, and discusses lessons learned for restoration monitoring and design. Finally, conclusions and recommendations for further work are presented in **Chapter 10.**

1.3 Research aims and objectives

The research aimed to monitor floodplain dynamics before and after the restoration of a small, temperate, lowland, forested floodplain, and in doing so, to increase current understanding of the geomorphological processes operating on forested floodplains.

Objectives

1. Identify general reference conditions and targets for floodplain forest restoration based on available scientific literature.
2. Identify specific reference conditions for New Forest floodplains through field based investigations of semi-natural forested floodplains within the New Forest, and use them to identify relevant processes to monitor before and after the restoration.
3. Design and implement monitoring at a restored reach, at semi-natural analogue reaches, and at a control reach before and after the restoration.
4. Use the results from the process monitoring, firstly to identify the effects of the restoration on the dynamics of the floodplain geomorphology; secondly to improve our understanding of processes operating in forested floodplains (including restored floodplains); and thirdly to evaluate the restoration design and process monitoring and so discuss lessons learned for future restoration projects.

Chapter 2. Restoration

2.1 Overview

The literature review is divided into Chapters 2 and 3. Chapter 2 covers the basic notions, techniques and processes of river restoration, and is illustrated with examples of restoration projects from around the world. It goes on to discuss the inclusion of floodplains in restoration projects, with an emphasis on *forested* floodplains, addressing why it is necessary to restore forested floodplains and highlighting some of the difficulties involved, particularly the lack of scientific understanding about how the geomorphological processes operate in these systems.

Most restoration projects attempt to restore degraded river systems to predefined target or reference conditions. A sound understanding of how physical and ecological processes operate under the target or reference conditions is a prelude to successful restoration (Kondolf, 1998). The focus of this thesis is restoration of a forested floodplain; therefore an initial understanding of the geomorphological processes operating in semi-natural forested floodplains (reference conditions) is gained from the literature and discussed in Chapter 3. Emphasis is placed on interactions between the water, sediments and vegetation, as these interactions are important in forested floodplains (Hughes, 1997). From the reviews, the lack of scientific literature addressing such interactions in low order, temperate, lowland forested floodplains becomes apparent, and it is this type of system that is the focus of this study.

2.2 Restoration philosophies and approaches

2.2.1 Introduction

River restoration projects have substantially increased in number since the 1980s due to the combination of a dawning realisation that large-scale habitat degradation of riverine environments through human exploitation is undesirable, and as a response to legislation enforcing protection and restoration of riverine environments (for example the 1972 Clean Water Act in the USA, the 1988 Wildlife and Countryside Act in the UK, and the European wide Water Framework Directive in 2000 (Sear and Arnell, 2006)). However, most river restoration in the UK and northwest Europe has focused on channel and channel-edge environments, with little attention paid to floodplain restoration (Brookes *et al.,* 1996a;

Adams and Perrow, 1999). This section starts with a brief overview of restoration practice, including definitions, notions, scales and techniques of restoration; and is followed by a discussion of floodplain forest restoration, with a focus on why it is necessary, the difficulties involved, and examples of floodplain forest restoration projects.

2.2.2 Definitions of restoration

The term 'restoration' is frequently used loosely to describe any improvement to damaged land, although strictly speaking restoration is defined as the complete structural and functional return to a pre-disturbance state (Cairns, 1991). However, this 'pre-disturbance' or 'natural' state is difficult to define (Graf, 1996; Sterba *et al.,* 1997), and complete restoration to a 'natural' state is effectively impossible for a number of reasons. Firstly, catchment and climatic conditions may have altered so much that such a state would no longer be sustainable even if it could be re-created (Sear, 1994; Brown, 2002). Secondly, some geomorphological and ecological changes, for example related to floodplain conditions (Brookes, 1996; Brown, 2002) and the construction of dams (Graf, 1996), may be irreversible; and thirdly, we do not always know what natural functions of river ecosystems have been altered (Sterba *et al.,* 1997). Furthermore, due to the fact that most European and North American rivers were highly modified before the science of river ecology developed (Petts *et al.,* 1989), false perceptions of 'natural' conditions may exist (Ward *et al.,* 2001). Therefore, true 'restoration', by its definition, is impossible, and most 'restoration' is in fact 'enhancement' (any improvement of a structural or functional attribute (National Research Council, 1992)) or 'rehabilitation' (the partial structural and functional return to a pre-disturbance state (Cairns, 1982)). However, having acknowledged difficulties with the use of the term 'restoration' in its true sense, for simplicity the term is used in this thesis as a blanket term to describe any improvement to a river system (as advocated by Bradshaw, 2002, and Brookes and Sear, 1996).

2.2.3 Notions of restoration

The concept of river restoration is based on beliefs or notions about how a particular river system should function. Therefore, the style of restoration deemed necessary depends on how the system is functioning compared with common beliefs of how it should function (Sear and Arnell, 2006). In the past, a static notion of 'nature in equilibrium' dominated, resulting in restoration efforts focused on form-mimicry. Increasingly, however, a more dynamic view of 'nature in flux' is taken, whereby change is expected (Hughes *et al.,* 2001; Sear and Arnell, 2006). This has resulted in restoration projects allowing "*change* to be part of their design and anticipated outcomes, restoring processes so that systems can be self-managing in the future" (Hughes *et al.,* 2001 p327).

Form-mimicry involves engineering a specific morphological feature such as a meander, pool-riffle sequence, or mid-channel bar or island "to look like what you want it to look like in the hope that this will create the processes necessary to maintain it" (McDonald *et al.,* 2004 p261). Early restoration projects were mainly form-mimicry and used the 'cook-book' approach (Kondolf, 1998), whereby restoration designs were based on classification systems, for example by Rosgen (1994), specifying bed and bank structures suitable for each 'stream type' (Kondolf, 1998). This assumes that rivers are in equilibrium, adjusting morphology to sediment and water delivery, and that for the outcomes of restoration to be sustainable, the correct type of stream needs to be identified (McDonald *et al.,* 2004). Restoration projects based on form-mimicry tend to focus on organisms, particularly fish (Gore *et al.,* 1998; Ward *et al.,* 2001) and aim to re-create key habitats or in-channel features for a specific species, for example riffles for fish spawning. The targets of this type of restoration are often unsustainable as physical and ecological processes which underlie the causes of a degraded system are not restored (Kondolf, 1998; Clarke *et al.,* 2003); in short, it treats the symptoms of a problem rather than its cause (Sear *et al.,* 1995).

Various examples of unsustainable outcomes of form-mimicry restoration projects have been reported. For example, Newson *et al.* (2002) argue that it seems inevitable that riffles created for fish spawning in the River Waveney, East Anglia, UK, will need regular maintenance in the form of desilting due to excess accumulation of fine sediment, as there are large concentrations of fines nearby in the channel, and large amounts enter the channel near the riffles. Similarly, although artificial riffles constructed on the Holly Fork River, west Tennessee, USA, initially increased habitat availability for macroinvertebrates, their sustainability is questionable and they are also likely to silt up as the catchment drains agricultural areas from which high fine sediment supply is expected (Gore *et al.,* 1998).

A further example of potentially unsustainable form-mimicry restoration is the construction of a diversion on the Evan Water, Scotland, to allow widening of the A74. The diversion was based on mimicking the form of abandoned, natural sections of the river (Gilvear and Bradley, 1997). After two floods of recurrence intervals between 1.5 and 2 years, substantial geomorphological adjustments of the river occurred, including channel-bank erosion, point-bar formation, scour on the outside of meander bends, and re-distribution of fine gravels intended for fish spawning (Gilvear and Bradley, 1997). The sustainability of this project is doubtful as, according to Gilvear and Bradley (1997), in an attempt to create a stable channel, the channel was designed to be in equilibrium with current sediment transport processes, without considering that sediment input and transport processes may change in the future.

The addition of wood jams to re-create instream habitat diversity for fish and invertebrates is another example of potentially unsustainable form-mimicry restoration. For example, although construction of wood jams on reaches of the Douglas River, Co. Cork, Ireland, appeared to increase trout density and biomass through improved habitat, the restoration will only be sustainable if diverse riparian vegetation is also established to provide natural inputs of wood (Lehane *et al.,* 2002).

As the above examples demonstrate, form-mimicry often results in features that are "designed in isolation from the catchment or channel network" (Sear, 1994 p169) and that are based on current geomorphological relationships between channel parameters and fluvial landforms; thus assuming a static fluvial system in equilibrium (Sear, 1994). Most river systems, however, are in a state of constant change or instability, adjusting to alterations in boundary conditions, rendering this form of restoration prone to failure, for example through siltation due to increased sediment supply from landuse changes (Sear, 1994).

For restoration measures to be successful, the whole range of biota and important functional processes need to be considered, rather than just a single organism such as fish. Although fish are often regarded as reflecting the ecological integrity of a river-floodplain system, they provide little information on many important processes such as organic matter spiralling and ground water - surface water interactions (Tockner and Schiemer, 1997). If the dynamic notion of 'nature in flux' is held, then it becomes apparent that, in order for restoration to be sustainable, it is important to restore the hydrogeomorphological and ecological processes that create and maintain channel form and diverse habitats through dynamic change and evolution, as has been done on the Kissimmee River in Florida, USA (Jungwirth *et al.,* 2002) (Table 2.1), rather than trying to control channel form and create features or habitats for specific species (Brookes and Shields, 1996a; Kondolf, 1998; Hughes *et al.,* 2001; Clarke *et al.,* 2003). For example, Ward *et al.,* (2001 p321) suggest that it is less effective to construct features, such as islands, than to "reconstruct ecological processes that enable the river to construct its own islands"; and Collins and Montgomery (2002) argue that building wood jams in channels is not sustainable, and they emphasise the need for trees to be planted on the floodplain so that in the future wood can be recruited into the channel as wood jams through wind-throw and dynamic channel processes of bank erosion and avulsion. Although this appears to be a sensible ultimate goal for restoration, in some circumstances, such as low-energy streams, recovery would take too long and it may be necessary initially to build wood jams due to their importance for floodplain processes and hence vegetation composition. Furthermore, restoration is constrained by socio-economic factors, and some areas simply cannot be allowed to flood. Thus river restoration should aim to reconstruct the functional integrity that characterises intact river corridors (Ward *et al.,* 2001), sustaining, rather than suppressing environmental heterogeneity (Ward, 1998) within the time and socio-economic constraints imposed upon it.

2.2.4 Scale of restoration

Most restoration is focused at the reach-scale, although river degradation has led to geomorphological and ecological alterations which often need catchment-scale information to rectify. For example, a river's hydrological regime, flooding processes and the supply of sediment and water quality are affected by activities across the whole catchment (Sear, 1994; Brown, 2002; FLOBAR, 2003). Furthermore, due to the longitudinal, transverse and vertical connectivity of the river in terms of morphological change and fluxes of water, sediment and energy (Ward and Stanford, 1995), reach-scale changes caused by restoration may impact the whole catchment (Clarke *et al.,* 2003). Therefore, for the output of river restoration to be sustainable, it needs to be based within a catchment-scale context (Sear, 1994; Stanford *et al.,* 1996; Brookes and Shields, 1996b; Harper *et al.,* 1999; Clarke *et al.,* 2003), anticipating future channel dynamics brought about by water management, landuse and climate changes (Newson *et al.,* 2002).

Although it is increasingly recognised within the restoration community that catchment-scale approaches to restoration are desirable, in practice most restoration projects are still small-scale, focusing on a single reach of a river. For example, in the online International River Restoration Survey, 52% of eligible respondents thought that most restoration projects were designed and constructed within the reach-scale (Wheaton *et al.,* 2004), highlighting the predominance of small-scale restoration projects, despite widespread advocation for them to be based within the catchment-scale.

Possible reasons for this disparity are that catchment-scale restoration is more costly, it requires consensus among many stake-holders (Brookes and Shields, 1996a; Clarke *et al.,* 2003; FLOBAR, 2003), and, as reach-scale processes are easier to study, our understanding of processes at the reach-scale is much greater than it is at the catchment-scale (Sterba *et al.,* 1997; Hughes *et al.,* 2001). Therefore, although river restoration projects may aim to be carried out at the catchment-scale, they are often based on an understanding of the linkages between processes, form and management history at smaller scales such as site or reach (Hughes *et al.,* 2001). However, for the outputs of river restoration to be sustainable, it needs to be based on a sound understanding of functional processes operating within the fluvial environment at the micro, reach, and catchment scales (Harper and Everard, 1998).

2.2.5 Techniques and processes of restoration

The restoration process involves a number of key stages which are outlined in Figure 2.1 (for a more detailed discussion on the different stages see Brookes and Shields, 1996a). Omission of any of these essential stages may result in a lack of clear targets against which to assess performance of the project (Jungwirth *et al.,* 2002), undesirable outcomes that potentially could have been avoided had the system been modelled prior to construction, and repeated mistakes from lack of or inadequate monitoring (Kondolf, 1998; Downs and Kondolf, 2002; Clarke *et al.,* 2003). Selected restoration projects are described in Table 2.1 to demonstrate examples of what these steps may involve.

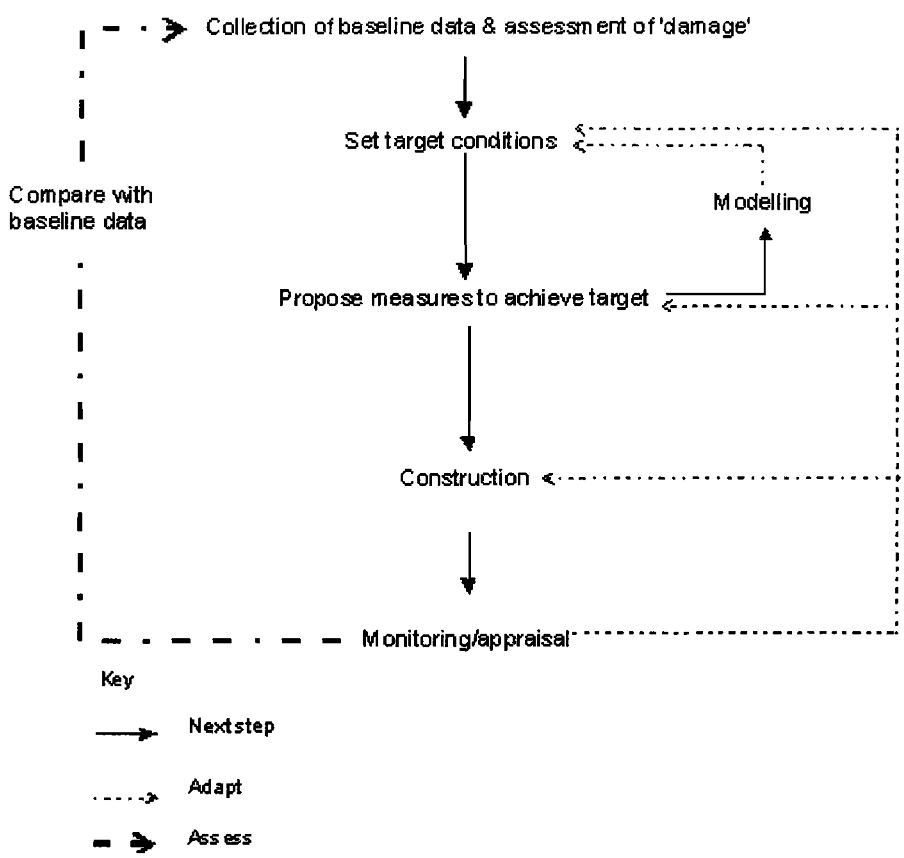

Figure 2.1 Stages in restoration, adapted from Brookes (1996) and Holl and Caims (2002).

Table 2.1 Examples of restoration projects demonstrating some of the stages involved.

River	Damage	Target	Proposed measures to achieve target	Testing the plans/modelling	Reference
The Cosumnes River in Sacramento County, California	Modification of the river corridor, e.g. clearing of large stands of riparian forest for agriculture and levee construction to reduce flood risk. Development in the area had lead to a decline in the ground water table which may have been responsible for a reduction or elimination of summer and/or autumn flows. Diversions for irrigation further reduced flows, and catchment changes altered the timing and magnitude of runoff peaks.	Re-establish physical processes that will lead to the creation of cottonwood forest, and ultimately regeneration of riparian oak woodland, whilst at the same time preserving or reducing off-site flood risk.	Levee setback to the edge of the 5 year floodplain and raising channel bed levels.	Hydraulic analyses were performed with these changes, and resulted in attenuation of the flood peak, hence reduced upstream stage; a 50% reduction in shear stresses, resulting in lower sediment transport capacity; increased frequency and extent of floodplain inundation which is expected to improve floodplain habitat and biodiversity, and increase groundwater recharge.	Andrews, 1999.
The River Rhine in the Netherlands	The channel was straightened, and groynes and minor dykes were built to prevent inundation of parts of the floodplain during minor floods.	Enhance fluvial dynamics within the floodplain area, restore riverine ecosystem and habitat types, e.g. river forests, snag wood, side channels, marshes and natural shores, and increase discharge capacity of high-water floodway to reduce flood risk.	Construction of side channels through the floodplain, lowering the floodplain surface by a few decimetres, removing minor dykes, and reintroducing floodplain forest.	The potential effects of such measures are assessed by comparing overbank sedimentation rates and patterns at eleven floodplain sections characterised by different topography. Results suggest that removal of minor dykes and lowering the floodplain surface will significantly increase overbank sedimentation, however the impact of changing vegetation cover from grass to grass with clusters of trees will be small.	Asselman, 1999.

Table 2.1 Continued

River	Damage	Target	Proposed measures to achieve target	Testing the plans/modelling	Reference
Muddy Creek, near Vaughn, Montana, USA	Channel incision of up to 6.7m from an 8-fold increased in annual flow volume caused by irrigation of 32,375 ha of farmlands since the 1930s. Incision has led to channel banks becoming sheer cliffs, disconnecting the channel from its floodplain. Furthermore, incision has been accompanied by high sediment transport rates (200,000 tonnes per year), degrading downstream water quality.	"Stabilize the stream gradient and reduce erosion and sedimentation" (Wittler et al., 1998 p83).	Install chevron weir rock ramps (hydraulic structures that dissipates excess energy in the stream-wise direction and maintains the elevation of the stream bed) for grade control and barbs (hydraulic structures that deflect current away from eroding banks) for planform control and the creation of riparian areas through trapping bedload and suspended sediment. In an attempt to avoid the use of engineered materials, rock, earth, and wood were used to construct the structures.	In the paper by Wittler et al. (1998) there is no evidence of modelling potential outcomes of the proposed measures. The measures were, however, tested and evaluated on a demonstration reach. Results two years after the start of the demonstration project suggest partial success: barbs worked to stabilise the toe of unstable banks and provided vegetation bases, however, grade-control structures were less successful due to over concentration of flow, and "scour holes more than ten feet in depth formed below structures where backwater from the downstream structure fails to reach the toe of the upstream structure" (Wittler et al., 1998 p88).	Wittler et al., 1998
The River Skjern, Denmark	River channelisation and construction of dykes for land reclamation resulted in high nutrient, organic matter, ochre and sulphate loading of the river, leading to high phytoplankton biomass and low oxygen levels.	Enhance the self-purification properties of the river in order to improve environmental conditions. Improve habitat quality within the river and the riparian areas. Re-create recreational area.	Re-establish 2,100 ha of meadows and reed swamps. Re- meander watercourses. Create a lake and several ponds.	Estimate retention rates for different areas created by the restoration based on other recent studies of similar areas in Denmark. After restoration, estimates of retention for the central restoration area are 1300 tonnes/yr of suspended solids compared with a loss of 1530 in 1994, before restoration, and 10.8 tonnes/yr of total phosphorous compared with a loss of 11.5 in 1994.	Anderson & Svendsen, 1998.
The Waveney River, East Anglia, UK	Channel has a very low gradient which has been further reduced by engineering. Lack of suitable habitats for fish spawning.	Re-create in-channel habitat for two target fish species: dace (*Leuciscus leuciscus*) and chub (*L. cephalus*).	Create 'riffles' which are mimic features based on natural riffles.	One-dimensional hydraulic modelling was undertaken using HECRAS to assess the influence of riffles on water surface elevations. Conclusions from simulations were that bed elevation changes would cause velocity changes, which was a desired outcome of the restoration.	Newson et al., 2002.
The Kissimmee River, Florida, USA	Channelisation and levees for flood control, water level regulation in impoundments, and floodplain drainage have destroyed and degraded most of the fish and wildlife habitat.	Re-create ecosystem integrity through re-establishing natural hydrogeomorphological processes.	Re-establish former hydrological and geomorphological conditions by restoring planform, modifying flow regime, and reintroducing flow through remnant channels.	Results from an initial demonstration project and from modelling various hydrological scenarios were used to plan restoration measures.	Toth et al., 1993; Jungwirth et al., 2002.

The restoration process starts with an assessment of 'damage' to river channels and floodplains (Newson *et al.*, 2002) and collection of baseline data against which the restoration performance can later be compared (Brookes and Sear, 1996; Jungwirth *et al.*, 2002). 'Damage' can result from many different activities, including manipulations altering flow regime and distorting the sediment system, impacting bedforms; direct 'river training' altering the planform and cross section; sediment-related 'maintenance' which may reduce diversity in sediment size; management impacting sediment transport, for example dams may trap sediment; and from secondary impacts from changes in interactions between channel and floodplain affecting riparian vegetation (Newson *et al.*, 2002).

A vision or target conditions (also known as 'Leitbild' (Brookes and Shields, 1996a; Jungwirth *et al.*, 2002)) are then set, which are the desired outcomes of the project. These vary according to the unique circumstances and constraints of each restoration project. In the case of form-mimicry restoration, targets are usually based on reference conditions which are those conditions thought to exist in 'natural' or 'pre-modified' systems. In practice, these may be difficult to establish and approximations are often made based on analogies in space and time. For example, reference conditions can be based on the conditions found in sites that are deemed to be natural or semi-natural (Holl and Cairns, 2002; Jungwirth *et al.*, 2002) (space analogies) or that are thought to have existed prior to human disturbances (Graf, 1996; Jungwirth *et al.*, 2002) (time analogies). Historical reference conditions can be established from palaeoenvironmental investigations of baseline information about the ecological characteristics of unmodified floodplain ecosystems (Dinnin and Brayshay, 1999; Brown, 2002). Reference conditions may also be established from conceptual models (Jungwirth *et al.*, 2002), or from a combination of the above methods (Holl and Cairns, 2002). Realistic reference conditions (Ward *et al.*, 2001), based on a sound understanding of physical and ecological processes, are a prelude to successful restoration (Kondolf, 1998).

Measures that are thought to achieve the vision, or to move the system in the direction of the target conditions, are then proposed. For measures to be effective they need to be based on a sound understanding of how the riparian ecosystem functions (Ward, 1997); incomplete understanding of the complex physical, chemical and biological processes operating in natural river ecosystems limits the effectiveness of any restoration measure (Verdonschot *et al.*, 1998; Zalewski *et al.*, 1998; Ward *et al.*, 2001). This is a challenge for the restoration of forested floodplains, especially small, lowland, temperate forested floodplains, as the processes in these systems are poorly understood. However, characteristics of temperate forested floodplains can be derived from historical sources and near-natural remaining forests, and used as analogues for restoring lowland temperate floodplain forests (Peterken and Hughes, 1995). For example, palaeohydrological and palaeoecological data suggest that "the dynamics of small to medium sized, low-energy, predeforestation floodplains were dominated by disturbance (windthrow, beavers, etc.) and large woody debris" (Brown, 2002 p817). Therefore these would seem important characteristics to restore in such systems. Alternatively, restoration can be viewed as an experiment (Kondolf and Downs, 1996) that aims to improve understanding of the functioning of a river type, and through monitoring, adaptive management is used to 'improve' the restoration project.

In order to identify the ability of the proposed measures to achieve the targets, the system can be modelled with the current conditions and with the proposed changes (Graf, 1996). For example, habitat models such as PHABSIM provide a useful tool for evaluating the potential benefit of proposed restoration activities (Gore *et al.,* 1998). This process allows adaptation of proposed measures if the modelling reveals unforeseen consequences of their implementation. Unfortunately this step is often omitted, especially in the UK, due to the high cost (Sear *et al.,* 1995), with the result that many potentially detrimental or ineffective measures are implemented that could have been prevented with prior modelling. In an attempt to stabilise stream gradient by the installation of in-channel structures on Muddy Creek, Montana, USA, for example (Table 2.1), the deep scour holes that developed below structures could possibly have been prevented had flows been modelled over the grade-control structures prior to their emplacement.

The next step is the physical construction of proposed alterations to the system. There is remarkably little published literature on the actual process of restoration, although slightly more may be available in the grey literature. However, as construction is the process of turning concepts into reality, this stage is vital to the success of the whole restoration project (Mant *et al.,* in press). Catchment-wide negative impacts can arise from inadequate care during the construction phase, such as silt transferred downstream smothering gravels (Brookes, 1989), localised erosion, soil compaction, and pollution associated with using machinery (Mant *et al.,* in press). Appropriate use of machinery is necessary: excavation of a large amount of material may require heavy construction machinery, but finer details of the construction may need to be carried out by hand (Mant *et al.,* in press). Construction contractors must be familiar with the overall aims and objectives of the project and understand the desired end result (Brookes and Sear, 1996). For successful translation of design into practice, good communication between the practitioners responsible for developing concepts and the contractors responsible for construction is essential (Mant *et al.,* in press). Furthermore, the restoration designer (or a representative) may need to be available for on-site supervision during the construction phase in order to make necessary adjustments

(Brookes *et al.,* 1996b; Brookes and Shields, 1996a; Moses *et al.,* 1997). Prior to the onset of construction, site variables need to be considered, for example substrate and weather conditions; construction of most river restoration projects takes place during dry periods as this causes less disturbance, for example to fish spawning and migration (Mant *et al.,* in press). Therefore, the construction phase needs to be carried out as sensitively as possible so as not to cause further damage to the system, with appropriate levels of communication between the various parties involved.

The system then needs to be monitored over a number of years, and post-project appraisals made, which can be used for adaptive management (Brookes and Sear, 1996; Downs and Kondolf, 2002; Caruso, 2006), and to improve the design of future restoration projects. Unfortunately this step is also often omitted (Brookes and Shields, 1996a; Kondolf, 1998; Downs and Kondolf, 2002; Holl and Cairns, 2002; Caruso, 2006), resulting in restoration projects unnecessarily repeating mistakes of past projects. The main reasons for the lack of post-project appraisals are that funding bodies are usually more willing to finance 'implementation' rather than 'studies' (Kondolf, 1998; Holl and Cairns, 2002), and may fear exposure of 'failures' in the restoration (Kondolf, 1998; Holl and Cairns, 2002). Further difficulties with post-restoration appraisals are that, in order to assess restoration projects, baseline data is needed before restoration (Downs and Kondolf, 2002; Holl and Cairns, 2002), and monitoring needs to continue for an extended period after restoration, as, for example, riparian vegetation recovery may take decades to centuries (Gurnell *et al.,* 2002). Consequently, although extended periods of post-project monitoring are ideal, due to the above constraints most restoration projects receive minimal monitoring if any at all.

As a result of the lack of modelling, application of forecasting, and / or short term monitoring, the outcomes of restoration projects are uncertain. A wide range of uncertainties arise from motives, notions and approaches to river restoration, which need to be recognised and dealt with when evaluating restoration success (Wheaton, 2004; Sear *et al.,* in press). The potential significance of uncertainties need to be considered, communicated to stakeholders and the public, and dealt with through adaptive management (learning by doing) (Wheaton, 2004). However, this is rarely done, and most restoration projects ignore uncertainty (Walters, 1997). Wheaton (2004) suggests that if uncertainties are significant they could potentially undermine restoration efforts and erode public support; however this is speculative as, because they have been largely ignored, uncertainties have not been demonstrated to be significant or insignificant.

Various methods are used to evaluate restoration; the method employed depends on the initial aims of the restoration project. For example, if the aim of restoration is the creation of habitats for specific species, then "surveys of channel geomorphology, geomorphological features and physical habitats" (Kronvang *et al.,* 1998, p221) may be useful monitoring tools. If a project aims to restore entire ecosystems, functional measurements (e.g. nutrient flux, migration rates, or hydrological flows) and structural measurements (e.g. species composition and biomass or soil nutrients) need to be made (Holl and Cairns, 2002). Due to the inherent difficulty in measuring functions (Jungwirth *et al.,* 2002), Clarke *et al.* (2003) propose measuring functional habitats, which are easier to identify, and which provide an indication of the potential for these processes. A number of key species, such as invertebrates, fish and aquatic macrophytes, that respond differently to hydrological connectivity and habitat diversity, can be monitored (Buijse *et al.,* 2002). Williams *et al.* (2003), for example, compared biodiversity of different water bodies, including rivers, streams (lotic waterbodies smaller than rivers), lakes, ponds, and ditches, based on macroinvertebrate and macrophyte assemblages. The performance of small-scale restoration projects can be assessed using species richness, or the simple presence or absence of species (Buijse *et al.,* 2002). However, the lack of a common set of environmental attributes to monitor is a recognised difficulty when monitoring restoration projects (Adams and Perrow, 1999). This is partly due to a poor understanding of the dynamic processes operating in river corridors, making it difficult to establish sound 'benchmarks' against which to assess restoration (Adams and Perrow, 1999). This highlights the potential usefulness of using restoration as an experiment, and for the outcomes to be monitored to allow for adaptive management over time.

2.3 Restoration of forested floodplains

2.3.1 Why is it necessary?

The need for floodplain restoration is now widely recognised due to the important role played by the floodplain for river structure and function through geomorphological and hydrological links between channels and floodplains. For example, floodplains play an important role in flood storage (Brown, 2002), increase physical, ecological, and biological diversity (Ward and Tockner, 2001), buffer sediment loads, improve water quality (Van Der Lee *et al.,* 2004), and have aesthetic and recreational value (Petts, 1996; Sterba *et al.,* 1997). Reconstruction of a proper functioning riparian zone can regenerate the whole fluvial system in the long term (Ward and Tockner, 2001; Lehane *et al.*, 2002). Furthermore, it is important to promote the restoration of forested floodplains because they are rare and threatened environments.

In Europe, 90% of the original area of floodplain forest has disappeared (Figure 2.2), and the remaining fragments are in a critical condition (Peterken and Hughes, 1995; FLOBAR, 2003). In Britain, only small patches of true floodplain forest remain (Brown and Quine, 1999), for example in the New Forest (Kerr and Nisbet, 1996; Peterken, 1996; Brown *et al.*, 1997; Harper *et al.*, 1997), and even these have been impacted by humans to some degree (GeoData, 2003). The main reason for the reduction in forested floodplains is an attempt by humans to manage and control fluvial environments (Holmes, 1998). Over the last 800 years, rivers within Europe have been changed due to navigation, flood control, agriculture, hydroelectric power generation, development, domestic and industrial water supply, and pollution (Peterken and Hughes, 1995; FLOBAR, 2003). This has been accomplished through floodplain drainage (Holmes, 1998), widespread dyking, channelisation, sediment management, construction of embankments and dams, and water extraction (FLOBAR, 2003), resulting in either cleared floodplains or floodplains that are disconnected from the channel.

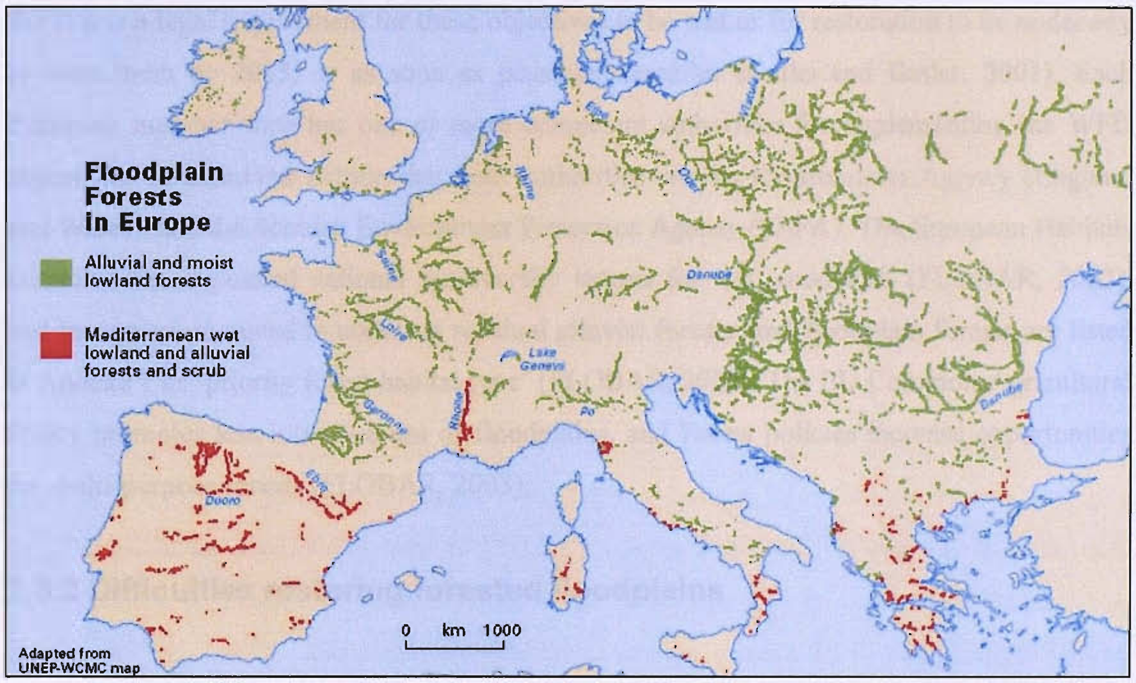

Figure 2.2 Distribution of floodplain forests in Europe, based on data provided by the United Nations Environment Programme-World Conservation Monitoring Centre (UNEP-WCMC), from FLOBAR (2003, p18).

Clearing and disconnecting floodplains from their channels reduces the geomorphological and ecological dynamism of forested floodplains. For example, the area of habitat available for plant and animal species that use the floodplain for rest, nourishment, shelter and as a breeding ground is reduced (Wenger *et al.*, 1990). Channel-floodplain disconnection has resulted in floodplains drying out which has suppressed many pioneer plant communities and reduced production; willow and poplar communities which favour dynamic sites have been particularly affected (Wenger *et al.,* 1990). In many instances floodplains have been invaded by non-native species (Stanford *et al.,* 1996), for example exotic Japanese knotweed (*Fallopia japonica*) and Canadian golden-rod (*Solidago Canadensis),* rendering less opportunity for regeneration of native species (FLOBAR, 2003). Thus the overall effect of channel management is likely to be reduced channel-floodplain connectivity, and hence reduced process dynamism and therefore also reduced diversity in floodplain forests.

Both national and international legislation and organisations (both governmental and non-governmental) are increasingly focused on protecting and enhancing rivers and remaining forested floodplains. For example, the European Community Water Framework Directive (WFD, 2000) provides a framework for implementing restoration projects: every EC member state must provide River Basin Management Plans outlining specific objectives and proposed measures to achieve "good" status of all water bodies (Kallis and Butler, 2001). Under the WFD it is a legal requirement for these objectives to be met or for restoration to be underway to meet them by 2015, or as soon as possible thereafter (Kallis and Butler, 2001). Each European member state has one or more competent authorities for implementing the WFD objectives. In mainland Britain the main authorities are the Environment Agency (England and Wales), and the Scottish Environment Protection Agency (SEPA). The European Habitats Directive has stipulated national biodiversity targets for wet woodlands (FLOBAR, 2003), and recognises the need to conserve residual alluvial forests, and floodplain forests are listed in Annexe 1 as 'priority forest habitat type' (FLOBAR, 2003). The EU Common Agricultural Policy promotes less intensive use of floodplains, and Forest policies increase opportunities for multi-purpose forests (FLOBAR, 2003).

2.3.2 Difficulties restoring forested floodplains

The wide range of legislation and directives promoting restoration is encouraging, but the implementation and success of floodplain forest restoration schemes is severely limited by a combination of factors. There is a poor scientific understanding of the spatial and temporal dynamics and structural and functional features of 'natural' floodplains, especially small, temperate, lowland, forested floodplains with cohesive sediments. Other difficulties arise from: (i) the complex and dynamic nature of such systems (Buijse *et al.,* 2002), for example floods deposit and erode sediment on the floodplain forming mobile habitat mosaics (FLOBAR, 2003); (ii) few remaining 'natural' examples of floodplain forest that can be used as reference conditions for restoration projects (Ward *et al.,* 2001; Brown, 2002; Holl and Cairns, 2002); and (iii) perhaps most significant of all, conflicting interests and the need for co-operation between the wide range of statutory bodies and other stakeholders whose responsibilities and interests encompass aspects of floodplains (Tockner and Schiemer, 1997; Adams and Perrow, 1999; Buijse *et al.,* 2002).

Examples of statutory bodies in England and Wales include the Environment Agency (EA), the Internal Drainage Boards, the Department for Environment, Food, and Rural Affairs (DEFRA), Natural England, and the Countryside Council for Wales. Organisations in Scotland include the Scottish Executive, District Salmon Fishery Boards, the Scottish Environment Protection Agency (SEPA), and Scottish Natural Heritage (SNH). In addition there are multiple stakeholders such as riparian landowners and dwellers, utility companies, conservation organisations, and angling clubs. Consequently, conflicting interests arise surrounding, for example, flood risk management and competing conservations interests (Kerr and Nisbet, 1996). Although co-operation between the various bodies can be challenging, floodplain restoration projects can benefit from the range of organisations involved as they provide many different avenues for funding and opportunities for collaboration (Adams and Perrow, 1999).

Overall then, difficulties in restoring forest floodplains arise from complexity of the physical processes operating on them, in conjunction with high complexity in their management.

2.3.3 Examples of floodplain forest restoration

In the past, restoration of forested floodplains has been largely overlooked. Although floodplains can benefit from river channel restoration, for example through changes in stream flow, channel form and water quality (Adams and Perrow, 1999), floodplain restoration is rarely treated as a distinct element within river restoration projects in the UK (Adams and Perrow, 1999), and floodplain *forest* restoration has been given even less attention (Peterken and Hughes, 1998). Encouragingly, however, more integrated approaches are becoming increasingly common, and some restoration schemes are starting to include floodplain forests.

Floodplain restoration can take various forms, including structural (active restoration, whereby direct structural changes are made) and non-structural (passive restoration, whereby the river is left to do the work) (Adams and Perrow, 1999) (Table 2.2).

Table 2.2 Restoration processes and aims.

Restoration process	Aim
Structural intervention	
Raise channel bed levels. Lower land levels. Remove obstructions on the floodplain, e.g. dykes & levees. Re-meander channelised reaches. Construct wood jams.	Increase channel-floodplain connectivity & thereby increase overbank 'regeneration' flows (Hughes & Rood, 2003) & floodplain geomorphological & hence habitat diversity (Florsheim & Mount 2003).
Remove artificial dams.	Re-establish natural flow regime downstream of dam.
Install in-stream structures, e.g. barbs to trap sediment (Wittler et al., 1998).	Create riparian habitat.
Construction of side channels/secondary channels on the floodplain.	Increase floodplain habitat & ecological diversity (Schropp & Bakker, 1996).
Non-structural intervention	
Landuse changes such as livestock control. Eliminate and control contaminants. Re-establishing native flora and fauna, e.g. re-introduce floodplain forest. Re-establish dynamics between floodplain forests, wood recruitment, and wood jams (Collins & Montgomery, 2002).	Allow natural recovery of damaged ecosystems.

Floodplain restoration is gaining momentum. For example in Germany, after the Elbe floods of 2002 the Government set up the 'Five-Point Programme' marking a shift towards more preventative forms of flood management (FLOBAR, 2003). Objectives included giving rivers more space by relocating dykes, preserving and restoring floodplains and floodplain forests, and controlling urban development to minimise potential damage caused by floods (FLOBAR, 2003). Channel side-arms, which function as a shelter and refuge for riverine organisms during high floods and episodes of acute pollution, were reactivated on the Danube, Austria (Tockner and Schiemer, 1997). Similarly, restoration of the floodplain was considered an important aspect of the restoration project on the Kissimmee River in Florida, USA, which, amongst other procedures, involved restoring flooding to 11000 ha of floodplain (Toth *et al.,* 1993). In Britain, the River Restoration Project on the River Cole re-established former channel form, and the channel was designed to spill more frequently to restore floodplain-channel connectivity (Kronvang *et al.,* 1998; Sear *et al.,* 1998). Thus floodplain restoration is increasingly being included in restoration projects. Table 2.3 lists some recent restoration projects within the UK that have included aspects of floodplain restoration.

Table 2.3 Examples of restoration projects in the UK that have included aspects of floodplain restoration.

River	Location	Key features	Length/area	Cost	Year	Reference
Bear Brook	Aylesbury, Buckinghamshire	Re-meander river and extend wetland for flood storage.	1.0 km	£100 k	1993-1994	Holmes, 1998
Crigyll	Rhosneigr, Anglesey	Reedbed restoration/swamp rejuvenation.	20 ha	£17 k	1995	Holmes, 1998
Quaggy, Chinbrook Meadows	Lewisham, London	Re-meander channelised sections and reintroduce the floodplain as a natural flood storage area.	0.5 km	£104 k	2002	The River Restoration Centre http://www.therrc.co.uk/
Sinderland Brook	Altrincham, Cheshire	Re-meander channelised reaches and re-connect the channel to the floodplain.	1.3 km	£870 k	2004-2005	Potter, 2006
Evenlode	Woodstock, Oxfordshire	Aimed to promote floodplain inundation. Created side-bars and riffles created in the channel and backwaters in the floodplain.	2.0 km	£110 k	2005-2006	The River Restoration Centre http://www.therrc.co.uk/
Glaven	Holt, Norfolk	Increase variation in channel width, depth and flow through installing riffles, narrowing channel, adding wood, creation of mid-stream islands. Re-connected the channel to its floodplain by removing spoil from top of channel banks.	1.0 km	£20 k	2006	The River Restoration Centre http://www.therrc.co.uk/
Tributaries of the Lymington River	New Forest, Hampshire	Restoration of wet woodland though felling conifers on the floodplain; reinstating wood-jams in channels; re-occupation of the former meandering channel; raising channel bed levels (monitoring this restoration project forms the core of this thesis).	600 ha wet woodland 10 km river	£2.9 million	2002-2006	Sear et al., 2006; Millington & Sear, 2007; Kitts, in prep; this thesis

Opportunities for floodplain *forest* restoration within Britain are few, although they are improving (Peterken and Hughes, 1998), and a few floodplain forest restoration projects have been undertaken. For example the 'Wild Rivers' initiative was launched in Scotland by the World Wildlife Fund for Nature in October 1995, with the aim of "allowing rivers freedom to function naturally" (Peterken and Hughes, 1998, p429). In doing so, forests will once more be established on some areas of previously farmed floodplain (Peterken and Hughes, 1998).

Another initiative with plans for planting trees on the floodplain is the Great Western Community Forest on the River Ray near Swindon (Peterken and Hughes, 1998). Archaeologists, however, oppose the initiative as they believe that it threatens the preservation of archaeological features and their context in the landscape (Peterken and Hughes, 1998).

The Milton Keynes Park Trust also planned to restore floodplain woodland on the Ouse at Wolverton (Peterken and Hughes, 1998). Gravel extraction from the floodplain will pay for the restoration and lower the floodplain surface in order to increase the extent and duration of flooding (Peterken and Hughes, 1998). Peterken and Hughes (1998 p431) summarise the proposals: "Channels and pools would be dug into the currently flat floodplain land, creating a mosaic of open water, marsh and potential woodland, but leaving the existing river channel undisturbed. The new floodplain forest would function as a washland, relieving flooding in Newport Pagnell. Woodland would be established both by planting native trees and natural regeneration and the site would remain open to the public as parkland."

2.3.4 Summary

Considering that most lowland floodplains within the UK were once forested (at least before Neolithic times when they were cleared and cultivated) (Brown, 1997), their restoration has been very limited, due to the inherent difficulties of restoring floodplain forests. The main challenge for process-based floodplain forest restoration is that processes and interactions of controlling factors in floodplain systems need to be understood before they can be restored (Verdonschot *et al.,* 1998; Braioni *et al.*, 2001). Scientific understanding of the physical processes operating within some types of river-floodplain system is fairly comprehensive, for example on large, high energy piedmont rivers (e.g. the Fiume Tagliamento in Italy (Gurnell *et al.,* 2000; Gurnell *et al.,* 2001)). However, in small, lowland forested floodplains with channels with cohesive banks there remains very poor scientific knowledge about the physical processes and their interactions with vegetation on the floodplain. Research into these types of river systems has been channel focused, with only one paper (to the author's knowledge) focusing on the floodplain (Jeffries *et al.,* 2003). This lack of scientific understanding renders restoration of these systems particularly difficult.

However, as discussed earlier in this chapter, a comprehensive understanding of reference conditions (Kondolf, 1998) can help to inform restoration measures. Chapter 3, therefore, discusses the literature concerning geomorphological processes operating in semi-natural forested floodplains in order to establish potential reference conditions for small, semi-natural, lowland forested floodplains with channels with cohesive banks. This understanding is later augmented by the identification of specific reference conditions established through field studies within the study catchment (Chapter 5).

Chapter 3. Defining reference conditions (1): floodplains and floodplain forest research

3.1 Introduction

As has been discussed in Chapter 2, to effectively restore forested floodplains we need to understand how natural (or semi-natural) forested floodplains function geomorphologically. Chapter 3 provides a literature review of these processes in order to establish potential reference conditions that can be used as targets for the restoration of forested floodplains. The chapter starts with a discussion of the mechanisms of floodplain inundation, and examines the effects of diverse topography and vegetation on overbank flow hydraulics. This is followed by a discussion of sediment processes, including the locations and mechanisms of sediment deposition on the floodplain, and how they are influenced by diverse floodplain topography and vegetation. Processes of floodplain scour and the development of floodplain channels are then discussed. Focus is then placed on vegetation and its influence on physical and ecological processes, including organic matter cycling, retentiveness and residence times, and methods of studying residence times of organic material. The function of large wood (defined as pieces of wood greater than 10 cm diameter and 1m length (Platts *et al.,* 1987; Piégay and Gurnell, 1997)) as a retentive device, residence times of wood, and other functions of wood are then examined. Based on this scientific context, the chapter concludes by setting out the thesis research agenda and objectives.

3.2 Characteristics and distribution of forested floodplains

Floodplain forests vary globally depending on a combination of factors, including climate, catchment size, land use and soil type, although their exact distribution is uncertain due to lack of information. The Institute of Floodplain Ecology in Rastatt, Germany, conducted a survey within Europe in 1987 which revealed that most countries had incomplete information about their floodplain areas (Wenger *et al.,* 1990). However, what is apparent is that much larger areas of floodplain forest existed in the past, and the current distribution of palaeoenvironmental reconstructions suggest that most European lowland floodplains were densely forested during the Holocene (Brown, 2002, 1996). Due to river developments such as flood protection and hydroelectric power generation, few remain today (Brown *et al.,* 1997). Areas of existing floodplain forest in a few European countries, and threats to / reasons for the loss of floodplain forests are summarised in Table 3.1.

Table 3.1 Summary of areas of existing floodplain forest and threats to / reasons for the loss of floodplain forests in a few European countries, compiled from Wenger *et al.* (1990); Brown *et al.* (1995); Gurnell and Gregory (1995); FLOBAR (2003); Jeffries *et al.* (2003).

Country	Examples of remaining floodplain forests	Threats to remaining floodplain forests/causes of loss of floodplain forests
UK	Very few remaining floodplain forests.	Intensive river management; Arable farming.
	Some remaining semi-natural areas along rivers in the New Forest, southern England.	River channelisation for land drainage; Heavy grazing by ponies and deer; Debris dam removal.
	Along lower reaches of the Spey in northern Scotland.	Flood embankments.
Germany	Large gaps in knowledge about German floodplain forests. Large areas of floodplain forest still remain, e.g. on the middle and northern Upper Rhine, floodplain meadows on the Lower Rhine, east Lower Saxony, especially on the Elbe.	Flood protection; Gravel extraction; Ports; Hybrid popular forests of foreign species e.g. *Juglans nigra;* Hydroelectric power plants.
Austria	Some relatively intact floodplain forest in central mountain regions of east Austria. East of Vienna the Danube/ March/ Thaya floodplains are the largest area of continuous floodplain forest in Central Europe.	Hydroelectric power.
Yugoslavia	Danube, Drava, Sava.	Hydropower plants; Pollution; Agriculture.
Greece	Hardwoods in Aceloos Delta and Kotza Orman. Tamarisk forests: natural sites on estuaries, e.g. on the Louros, Arachthos, Evinos, Axios, Nestos, and Evros Rivers.	River regulation; Agriculture.
Switzerland	No large areas of floodplain forest due to its mountainous character. Some valuable floodplain biotopes: the Doubs Valley in the Swiss Jura mountain chain, the Lower Reuss Valley in northwest Switzerland, and the Maggia in Tessin.	River development Agriculture
Hungary	Currently floodplain forests make up 4.6 % of all Hungarian forests. In the last 20 years approx. one-third has disappeared. Examples of floodplain forest exist along the Danube, Grava, and Raba.	Plans for hydroelectric power.
France	Loire, Durance, Garonne, Rhone, Ain upstream of Lyon.	Government is attempting to develop the Loire and Lower Allier; Pollution; Increased temperature of water due to nuclear power stations.
Ireland	The Gearagh on the River Lee in County Cork, Ireland.	Deforestation; Channelisation; Hydro electric power production.

3.3 Functions and features associated with forested floodplains

Forested floodplains are highly dynamic ecosystems, representing the interface between terrestrial and aquatic environments and they therefore support high levels of biodiversity (Naiman *et al.*, 1993; Gurnell and Gregory, 1995; Peterken and Hughes, 1995; Ward *et al.*, 1999; Hupp, 2000; Ward *et al.*, 2002; Steiger *et al.*, 2005). They contain a mosaic of geomorphological and ecological processes operating over a hierarchy of scales, ranging from the microhabitat (or patch-scale, 10^{-1} m) to the stream system (or catchment-scale, 10^{3} m) (Frissell *et al.*, 1986; Newson and Newson, 2000). Mesoscale physical (hydraulic) biotopes (e.g. pools and riffles) are associated with different flow types (e.g. 'unbroken standing waves' over riffles and 'scarcely perceptible flow' over pools (Newson and Newson, 2000 p204)) which directly influence habitat and biological patterns (Newson and Newson, 2000).

Naiman *et al.* (1993 p210) attribute the high biodiversity observed in forested floodplains to: "1) the intensity and frequency of floods, (2) small-scale variations in topography and soils as a result of lateral migration of river channels, (3) variations in climate as streams flow from high to low altitudes or across biomes, and (4) disturbance regimes imposed on the riparian corridor by upland environments". Lateral accretion is one such disturbance which is an important process for floodplain renewal and biological diversity as it provides new opportunities for pioneering species (Salo *et al.*, 1986; Lawler *et al.*, 1997).

3.4 Types of forested floodplain

The ecology and dynamics of floodplain forests vary with gradient; floodplains of high gradient rivers in mountainous regions, such as the Alps, experience snow melt floods in spring which may cause large amounts of erosion and deposition, destroying trees and significantly altering floodplains in just one event (FLOBAR, 2003). In high energy, confined, headwater rivers, hillslope drainage processes are important (Gurnell, 1997) and floodplain development may be limited by strong hillslope-channel coupling. In lower gradient rivers, floods are often more dependent on rainfall patterns, resulting in less disturbance and in some instances less mobile channels (FLOBAR, 2003). Low-energy rivers tend to have broader floodplains with different zones of vegetation, "reflecting the transition from hydraulically-dominated to hydrologically-dominated vegetation types along transects from the river to the adjacent hillslopes" (Gurnell, 1997 p224). For example, low-gradient meandering streams in the Coastal Plain of south-eastern USA develop broad floodplains that experience frequent and prolonged flooding (up to months) and support bottomland hardwoods (Hupp, 2000).

Forested floodplains may be classified according to their vegetation assemblages; various classification systems exist based on vegetation assemblages (e.g. Table 3.2). Alder (*Alnus)* dominated communities (W5, W6, W7) are the most common types of woodland on British floodplains (Brown *et al.,* 1997).

Interactions between vegetation and geomorphology vary within a longitudinal gradient of energy and according to the level of disturbance experienced by a floodplain. Jeffries (2002) identifies four broad types of forested floodplain based on biotic and abiotic interactions (Figure 3.1): (i) small, steep headwater channels; (ii) large, high energy piedmont channels; (iii) large, lowland channels with cohesive banks; and (iv) small, lowland channels with cohesive banks. Jeffries (2002) goes on to note the very limited scientific understanding of interactions between biotic and abiotic variables in streams within the fourth category, which is the focus of this thesis. However, work by Jeffries (2002) and Jeffries *et al.* (2003) emphasises the important influence that vegetation has on floodplain geomorphology in temperate, lowland forested floodplains, for example, in-channel wood jams increase the number of overbank flows, and floodplain vegetation influences the spatial distribution of overbank sedimentation.

Table 3.2 Examples of different classification schemes for European floodplain forests, from FLOBAR (2003 p19).

EU Habitats (1999)	CORINE-Biotope (1991) + Palaearctic, classif. (1993)	EUNIS classification (2002)	Other classification	Description
91E Residual alluvial forests **(Boreal, Alpine, & temperate Europe)**	44.1 riparian willow 44.2 grey alder forests 44.3 medio-europ, woods include sub-types: 44.13 white willow galleries 44.14 white poplar galleries 44.21 montane grey alder 44.22 sub-montane g.alder 44.31 ash-alder (rivulets) 44.32 fast-flowing rivers 44.33 slow rivers 44.34 northern iberian galleries	G1.1 riparian woodlands (Salix, Alnus) and galleries G1.111 Medioeurop. Willow forests G1.121 montane alder galleries G1.122 dealpine alder galleries G1.123 boreal alder galleries G1.2 fluvial woodlands(Fraxinus, Alnus, Fraxinus, Ulmus) G1.21 riverine woodlands wet at high flows G1.211 rivulets and springs G1.212 fast flowing rivers G1.213 slow rivers G1.214 northern iberian galleries	**NVC- UK:** W5, W5, W7 **German fed. List** 430401 to 430403 **Nordic classif.** 2.2.3.4 2.2.4	Alluvial forests (*Alnus glutinosa, Alnus incana, Prunus padus, Fraxinus excelsoir, Ulmus glabra...)* of temperate and boreal Europe (lowland, piedmont, montane and sub-montane rivers of Alps, Pyranees, Carpathians, Balkans and North Apennine);arborescent galleries of tall willows (*Salix alba, S. fragilis, Alnus, Fraxinus, Populus nigra, Populus alba...)* on heavy soils periodically inundated, well-drained and aerated during low-flows
91F0 mixed hardwood riparian forests **(temperate Europe)**	44.4 mixed oak-elm-ash forests 44.41 and 44.42 (medio-european) 44.43 (sub-Mediterranean.) 44.44 (alluvial plain of the Po river)	G1.2 fluvial woodlands G1.22 mixed(Alnus, Fraxinus, Quercu, Ulmus) G1.221 medio-European G1.222 (residual) G1.223 south-east Europe G1.224 Po river	**Nordic classif.** 2.2.2.3; 2.2.2.6; **German fed.List** 43040501 & 02	Diverse riparian forests of the middle and lower courses of great rivers (Rhone, Loire, Rhine, Danube, Elbe, Weser, Oder, Vistula...), inundated by large floods; mature forests of hardwood trees (*Quercus rober, Fraxinus excelsoir, F. angustifolia, Ulmus laevis, U. glabra, U. minor, Prunus avium, P. padus...)* growing on recent alluvial deposits; soils well drained or remaining wet between high-flow periods; the hydric regime (level of the water table) determines the dominant species (from high to deep levels: *Fraxinus, Ulmus or Quercus)*
92A0 white willow & white poplar galleries of **(Medit. Europe)**	44.17 Mediterranean white willow galleries 44.6 Mediterranean poplar-elm-ash forests (44.61 to 44.64)	G1.1 riparian woodlands (*Salix, Alnus)* G1.31 Mediterranean poplar forests G1.112 Mediterranean tall willows G.3 Med. Mixed woodlands		Riparian forests of the Mediterranean zone dominated by high willows (*Salix alba, S. fragilis)* and poplars (*Populus alba, P. caspica, P. euphratica)*(repartition: France, Greece, Italy, Portugal, Spain)
92B0 riparian formations on intermittent rivers **(Medit. Europe)**	44.5 southern alder galleries; 44.51 44.52	G1.1 riparian woodlands G1.32 *Rhododendron, Alnus* relict galleries G. 134 *Betula* relict galleries		Highly remarkable relict alder galleries (thermo-and meso-Mediterranean zones) with *Alnus glutinosa, A. cordata, Betula sp., Fraxinus angustifolia, Osmunda regalis (*repartition: France, Italy, Spain, Portugal)
92C0 plane & sweet-gum woods **(Medit. Europe)**	44.7 (44.71, 44.72) *Platanus* and *Liquidambar* gallery forests	G1.3 Mediterranean riparian woodlands G1.39 *Liquidambar* woods G1.38 *Platanus* woods		Riparian forests and woods dominated by *Platanus orientalis* and *Liquidambar orientalis;* presebce of *Salix alba, Alnus glutinosa, Celtis australis, Populus alba, Fraxinus ornus, Cercis siliquastrum.* (Greece, Sicilia)

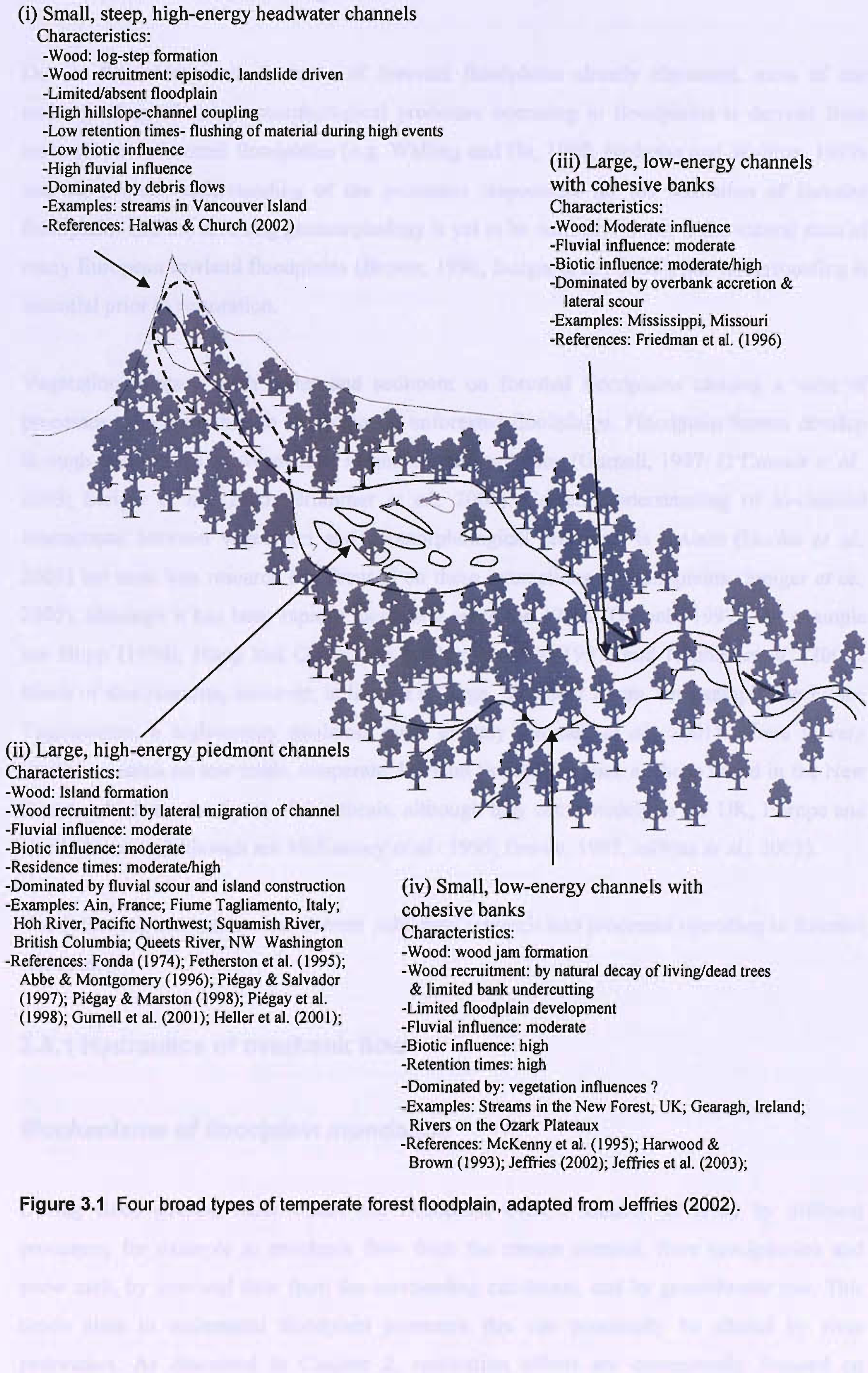

Figure 3.1 Four broad types of temperate forest floodplain, adapted from Jeffries (2002).

3.5 Processes operating in forested floodplains

Due to the widespread clearance of forested floodplains already discussed, most of our understanding of the geomorphological processes operating in floodplains is derived from research on unforested floodplains (e.g. Walling and He, 1998; Nicholas and Walling, 1997a and b); a clear understanding of the processes responsible for the formation of forested floodplains and the resulting geomorphology is yet to be derived. As this is the natural state of many European lowland floodplains (Brown, 1996; Steiger *et al.*, 2005), this understanding is essential prior to restoration.

Vegetation interacts with water and sediment on forested floodplains causing a suite of processes to operate that do not occur on unforested floodplains. Floodplain forests develop through interactions between flow, sediment and vegetation (Gurnell, 1997; O'Connor *et al.*, 2003; Steiger *et al.*, 2005; Brummer *et al.*, 2006). Current understanding of in-channel interactions between vegetation and geomorphological processes is limited (Hooke *et al.*, 2005) but even less research has focused on these interactions on floodplains (Steiger *et al.*, 2005), although it has been rapidly increasing since the 1980s (Gurnell, 1997), for example see Hupp (1996); Hupp and Osterkamp (1996); Hughes (1997) and Hughes *et al.* (2001). Much of this research, however, is limited to large, piedmont rivers, for example the Fiume Tagliamento, a high-energy piedmont river in Italy (Gurnell *et al.*, 2001). There is very limited research on low order, temperate, lowland floodplains such as those found in the New Forest, which are the focus of this thesis, although they occur widely in the UK, Europe and North America (although see McKenney *et al.*, 1995; Brown, 1997, Jeffries *et al.*, 2003).

The following sections review current published research into processes operating in forested floodplain.

3.5.1 Hydraulics of overbank flow

Mechanisms of floodplain inundation

During flood events, water enters the floodplain from a number of areas by different processes; for example as overbank flow from the stream channel, from precipitation and snow melt, by overland flow from the surrounding catchment, and by groundwater rise. This thesis aims to understand floodplain processes that can potentially be altered by river restoration. As discussed in Chapter 2, restoration efforts are conceptually focused on repairing 'damage,' which usually means wider, deeper and more uniform channels. The damage caused, therefore, is primarily a reduction in overbank flow from the stream channel, and it is this linkage that this section focuses upon. This section also discusses how the overbank distribution of such flow is complicated by diverse floodplain topography and vegetation.

Channel capacity

Floods spill overbank when discharge exceeds channel capacity. Leopold *et al.* (1964) suggest that on average this occurs every 1.5 years, although it depends on climatic conditions and varies between rivers (Gordon *et al.,* 1992). There are a number of variables that determine the local position at which discharge first exceeds channel capacity and overbank flow is initiated. Firstly, overbank flows occur where banks are lowest, for example in breached levees or abandoned cut-offs open at one end (Lewin *et al.,* 1979; Hughes, 1980); secondly, they may occur where the local water surface is elevated or ponded, for example due to in-channel obstructions such as bridges or wood jams (Gippel, 1995a; Brummer *et al.,* 2006) or due to superelevation of the water surface as a result of flow structures (Bathurst *et al.,* 1977). Channel capacity (and, therefore, the likelihood of floods spilling overbank) is determined locally by hydraulic geometry, channel planform, channel roughness (including bedforms, wood and vegetation), and topography of the river bank (levees, old channels and tree throws).

Bedforms, for example pool-riffle sequences, function as roughness elements in the stream channel, influencing surface water slope, therefore flow level and the potential for floodplain inundation. At low flow, riffles act as weirs, ponding flow in upstream pools (Clifford and French, 1998), therefore water slopes are steeper over riffles than pools (Emery, 2003), which might suggest that overbank flow would occur at lower discharges over riffles than pools. However, as discharge increases and riffles are 'drowned' the difference in water slope is reduced (Emery, 2003), and as bankfull discharge is approached, the low flow hierarchy in flow velocity is reversed; the 'velocity reversal hypothesis' (Keller, 1971). Reversal of water surface slope was observed in a study of a single pool-riffle couplet on the River Llwyd, UK (Emery, 2003). The author notes, however, that this may be due to characteristics of the specific site; the pool section had a narrower width than the riffle section. This argument is supported by Carling (1991), who suggests that there is insufficient evidence of the ubiquitous occurrence of flow reversal in a range of channel geometries, although it may occur if riffles are considerably wider than pools. Thus the influence of bedforms on the surface water slope and the potential for floodplain inundation varies depending on local channel characteristics.

Bank vegetation also reduces channel capacity, hence it increases the potential for floodplain inundation. Darby *et al.* (1997) found that increases in the height of flexible vegetation increased flood elevation for a given flow discharge. For example, an increase in height of vegetation from 0.05 m to 2.0 m resulted in a rise in flood elevation from 2.61 m to 2.82 m for a discharge of 40 $m^3 s^{-1}$ in a steep channel. The effects of flexible vegetation on flood elevation are amplified as channel gradient and bed material size decrease. For example, at a discharge of 15 $m^3 s^{-1}$ and an increase in vegetation height from 0.05 m to 2.0 m, a channel with a gradient of 0.010 experienced an increase in stage of 0.12 m; whereas in a channel with a gradient of 0.001, stage increased by 0.26 m. This is because high gradient channels may have sufficient stream power to deform flexible vegetation and hence reduce its roughness coefficient; also, coarse bed material associated with steep channels has a greater effect on roughness than finer material associated with lower gradient channels (Darby *et al.,* 1997). Furthermore, for high channel gradients and coarse bed material, low vegetation may *reduce* channel roughness due to vegetation bending during high energy flows, providing a smoother boundary (Darby *et al.,* 1997). Overall, however, increases in the extent and height of vegetation generally reduce discharge capacity for a given flood stage.

Secondary flows and upwelling cause superelevation of the water surface which promotes floodplain inundation (Figure 3.2). A brief summary of the main processes involved in secondary flows follows: water moving through a meander bend is subjected to centrifugal forces that direct flow radially outwards against the outer bank (Allen, 1970; Bathurst *et al.,* 1977; Markham and Thorne, 1992), causing it to accumulate and become superelevated (Markham and Thorne, 1992). "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" (Jeffries, 2002 p15). Transverse flow circulation induces a spiralling motion along the direction of flow (Markham and Thorne, 1992). A smaller cell of reverse circulation at the outer bank of meander bends may also be present (Bathurst *et al.,* 1977; Thorne *et al.,* 1985) (Figure 3.2). Bathurst *et al.* (1977) and Bathurst *et al.* (1979 cited in Markham and Thorne, 1992) attribute this cell to the interaction between the main secondary flow cell and the outer bank. These secondary flows which cause superelevation of the water surface increase the likelihood of floodplain inundation in their vicinity. Therefore, superelevation of the water surface on the outside of meander bends may initiate floodplain inundation in these locations at lower discharges than bankfull, although this will depend on the height of the outer bank.

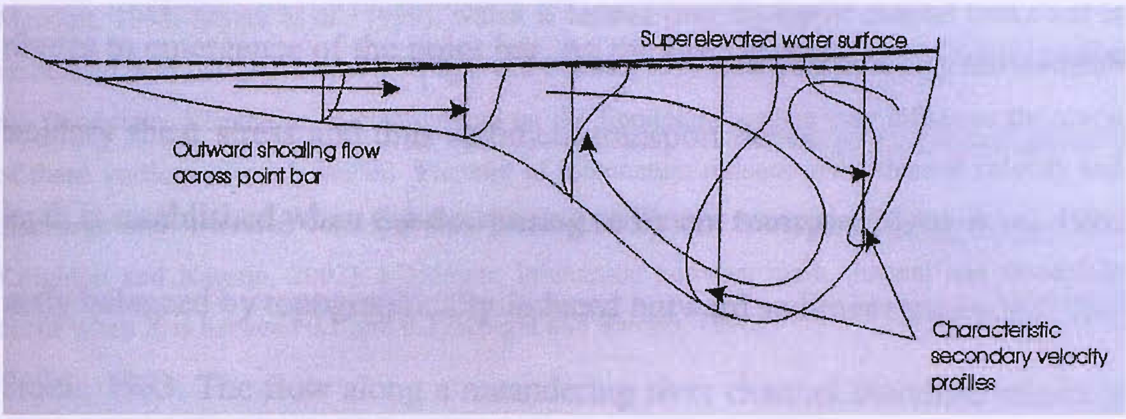

Figure 3.2 Secondary flow structures in a river bend apex, after Markham and Thorne (1992).

Hydraulic conditions during overbank flows, both in the channel and on the floodplain, are poorly understood. This is largely because overbank flows involve complex interactions between additional processes and pathways (Knight and Shiono, 1996; Knighton and Nanson, 2002). A basic summary of current understanding of the hydraulics of overbank flows is presented here.

At bankfull stage there is a sharp discontinuity in the relationship between stage and discharge because of the initiation of overbank flow and rapid expansion of flow across the floodplain (Hughes, 1980; Knighton and Nanson, 2002). As flow is spread over a much greater area, an increase in discharge may lead to a negligible increase in stage. Deeper flow in the channel than on the floodplain leads to a velocity gradient that in turn creates vertical vortices (Sellin, 1964 cited in Knighton and Nanson, 2002) and momentum transfer from channel to floodplain (Figure 3.3) (Myers *et al.,* 1999). There is a strong dependence of floodplain processes on relative depth of floodplain and channel flow (Knighton and Nanson, 2002). The ratio of channel water height to floodplain water height can be defined as:

$$X = ((H-h)/H) \qquad (1)$$

Where X is the ratio of channel water height to floodplain water height, H is bankfull channel depth (m), and h is floodplain water depth (m) (Knight and Shiono, 1996). Prior to overbank flow initiation X = 1. As the floodplain becomes inundated X decreases, however floodplain flows remain shallower than main channel flows. Knighton and Nanson (2002) argue that, due to this difference in depth and to increased resistance on floodplain flows from topographic variation and vegetation, floodplain flow velocities remain slower than main channel velocities. This velocity gradient produces an interaction between main channel flow and floodplain flow, characterised by high turbulence and shear (Knight and Shiono, 1996; Marriott, 1998; Myers *et al.*, 1999), which is located over the top of channel banks and is associated with vertical vortices (Knight and Shiono, 1996) that transfer energy and matter to the floodplain. Vegetation in-channel and on the floodplain surface may influence the shape of these vortices (Gippel, 1995a). Transfer of momentum reduces main channel velocity and discharge and increases corresponding parameters on the floodplain (Myers *et al.*, 1999; Knighton and Nanson, 2002). Maximum interaction between main channel and floodplain occur when X is between 0.1 and 0.3 (Knight and Shiono, 1996).

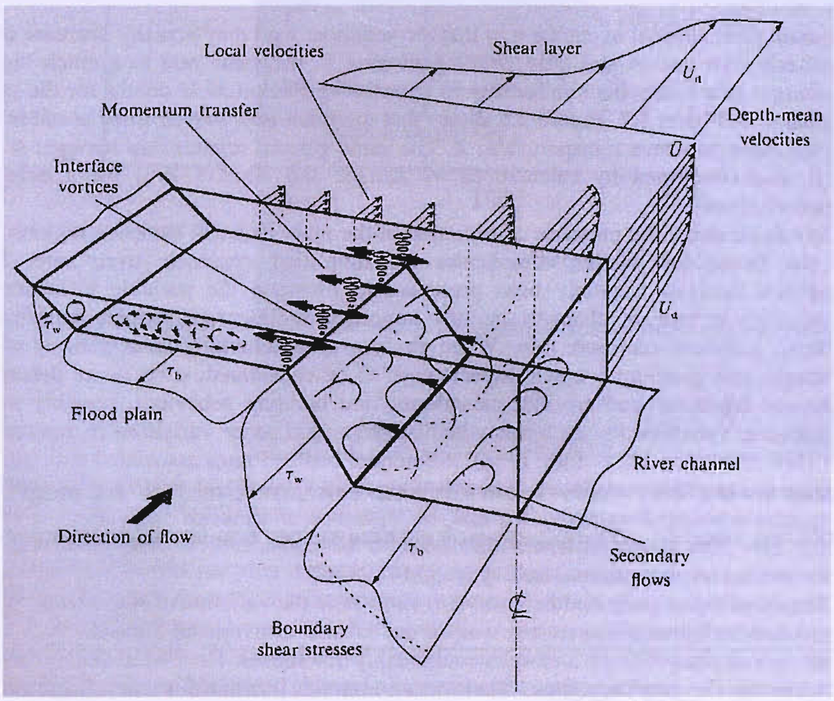

Figure 3.3 Interactions of in-channel and floodplain flow, from Knight and Shiono (1996 p150).

Although processes operating in the zone of interaction between channel flows and floodplain flows are not fully understood, various 1, 2 and 3-dimensional models have been proposed (e.g. Knight and Shiono, 1996 and references therein; Nicholas and McLelland, 1999). Nicholas and McLelland (1999) combined modelling techniques and direct field measurements of flow velocities in a backwater zone on the River Culm, UK, to illustrate the presence of flow recirculation and lateral flow convergence within a backwater (Figure 3.4). Both data sources "highlight the existence of a free-shear layer at the mixing interface between the two flows which is characterised by high levels of turbulent kinetic energy. This provides evidence for hydraulic mechanisms responsible for promoting suspended sediment supply to, and rapid sedimentation within, such backwater recirculation zones" (Nicholas and McLelland, 1999 p25). Therefore, vertical flows transfer fluid, momentum and fine sediment from the main channel to the floodplain, and the distribution of the areas where this occurs depend on past processes (e.g. old channels), vegetation, and roughness elements in the channel (e.g. bars, and pools and riffles). This suggests that Figure 3.3 is an engineering model of overbank flows, whereas Figure 3.5 represents a natural model of factors influencing the process of overbank flow.

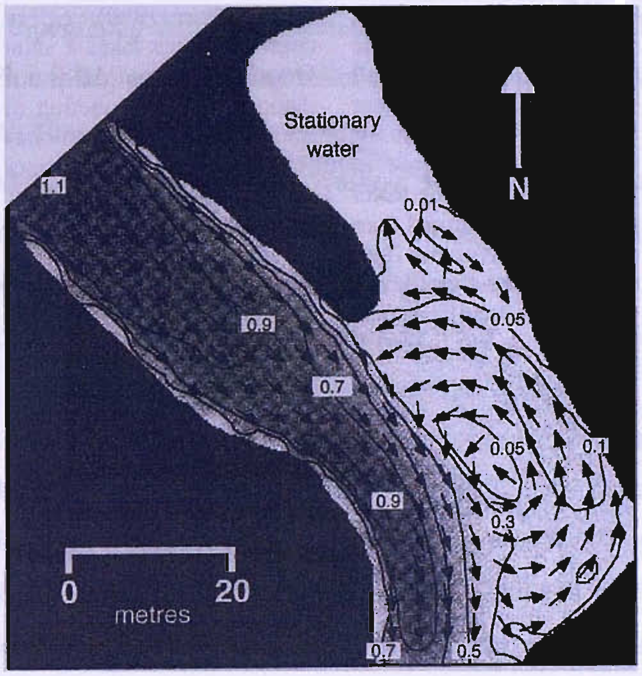

Figure 3.4 Pattern of simulated horizontal mean velocity (m s^{-1}) at the water surface. Contours indicate velocity magnitude and vectors indicate flow direction, from Nicholas and McLelland (1999 p20).

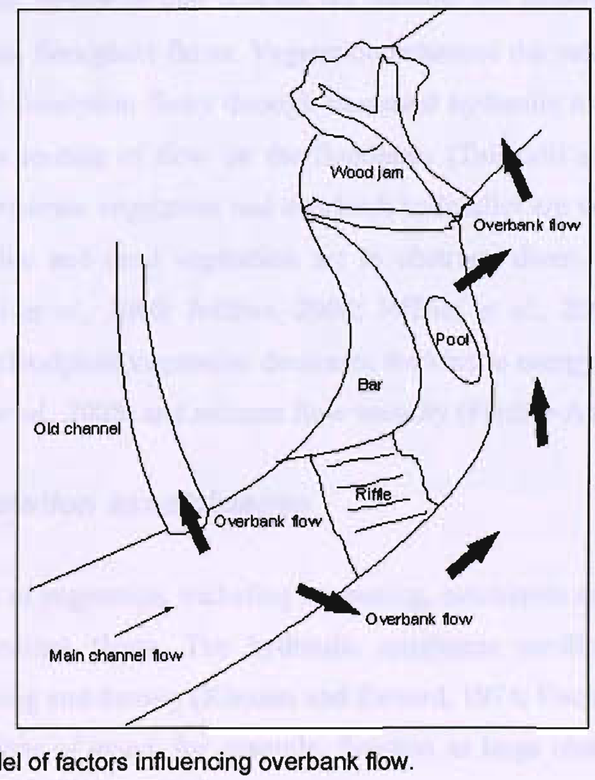

Figure 3.5 Natural model of factors influencing overbank flow.

Influence of floodplain topography and vegetation on floodplain flow hydraulics

Hydraulics of overbank flows are complicated by interactions between flow and complex topography and vegetation found on many floodplains. Interactions between the inundating flow and floodplain topography will be discussed first, and then the influence of vegetation will be addressed. Floodplain geometry and relief play a large part in controlling patterns and timings of inundating flow (Lewin, 1978; Hughes, 1980; Bates *et al.,* 1992; Miller, 1995; McCartney and Nanden, 1995; Nicholas and Walling, 1997a). Nicholas and Walling (1997a) propose a model to predict the spatial pattern of floodplain inundation level based on variations in floodplain topography. The model is then used to relate flow hydraulics to sediment deposition, which will be discussed in Section 3.5.2.

During the initial stages of overbank flooding, flow is ponded in topographically low areas such as low-lying depressions (Nicholas and Walling, 1997a). As flood levels rise, higher areas become inundated and subsequently shallow drainage ditches begin to convey flow, connecting discrete inundation zones (Nicholas and Walling, 1997a). As flood levels continue to rise, emergent areas shrink, "and floodplain water begins to flow less as a collection of separate flow streams and more as a single unit in the general direction of the valley bed slope" (Nicholas and Walling, 1997a p67).

A shortcoming of this model is that it does not include the effects of vegetation which significantly influences floodplain flows. Vegetation enhances the velocity gradient between the main channel and floodplain flows through increased hydraulic roughness (Myers *et al.,* 1999), and influences routing of flow on the floodplain (Tabacchi *et al.,* 2000). However, interactions between riparian vegetation and overbank hydraulics are very complex (Tabacchi *et al.,* 2000). Both live and dead vegetation act to obstruct, divert and facilitate flow on floodplains (Tabacchi *et al.,* 2000; Jeffries, 2002; Jeffries *et al.,* 2003). Through its large hydraulic roughness, floodplain vegetation decreases the kinetic energy of floods (Tabacchi *et al.,* 2000; Friedman, *et al.,* 2005) and reduces flow velocity (Fischer-Antze *et al.,* 2001).

Structure of vegetation assemblages

The specific structure of vegetation, including its spacing, patchiness and composition, affects its influence on overbank flows. The hydraulic roughness coefficient of vegetation is influenced by its spacing and density (Klassen and Zwaard, 1974; Fischer-Antze *et al.,* 2001). Trees and accumulations of wood, for example, function as large obstacles, increasing flow turbulence and forcing flow to be routed around them (Klassen and Zwaard, 1974), thus influencing the spatial patterns of flows (Piégay, 1997). Organic material may be pushed up against vegetation during floods, further increasing the hydraulic roughness (Klassen and Zwaard, 1974). Patchy vegetation, for example pioneer species, or assemblages of different types of vegetation, increase the heterogeneity of flow patterns over floodplains, and hence encourage the development of preferential flow pathways (Thorne *et al.,* 1997). Homogenous forests such as poplar plantations create lower flow resistance, whereas heterogeneous forests associated with disturbance and succession encourage turbulent zones (Tabacchi *et al.,* 2000). Furthermore, the transverse profile of vegetation distribution on a floodplain affects its influence on floodplain hydraulics (Figure 3.6) (Tabacchi *et al.,* 2000). Thus it has been demonstrated that different characteristics of vegetation influence overbank flows, highlighting the high complexity of interactions between the two variables.

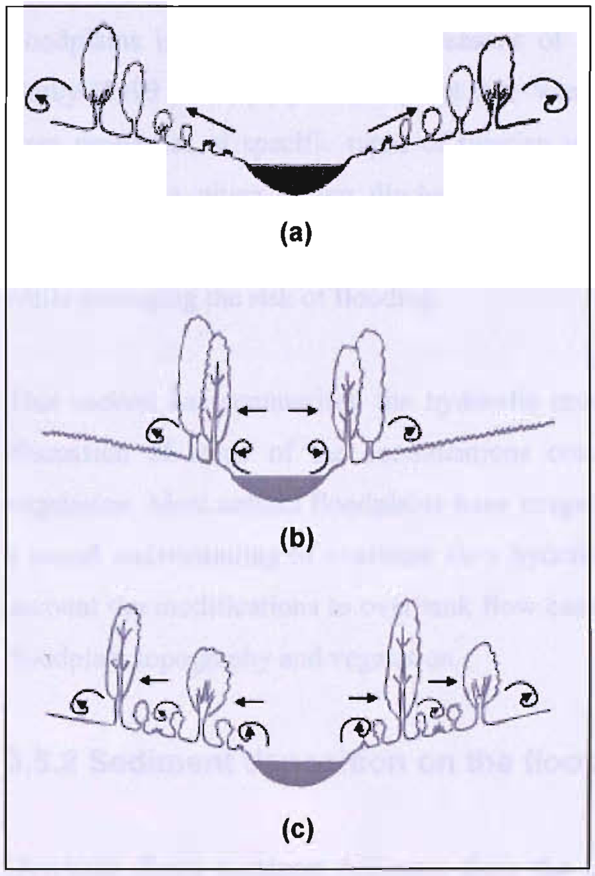

Figure 3.6 Hypothetical influences of riparian vegetation patterns on turbulence during overbank floods. Horizontal arrows indicate lateral resistance to flow and spiralling arrows indicate turbulences. (a) Regular transverse profile simulating progressive succession, minimal lateral resistance and minimal turbulence. (b) Sharp, dense and narrow corridor (tree line) with high lateral resistance and high turbulence at both internal and external edges. (c) Wide, heterogeneous corridor (more common profile in natural rivers), inducing a better dissipation of kinetic energy but favouring numerous small-scale turbulences, from Tabacchi *et al.* (2000 p2964).

Effects of vegetation on overbank flow height

The influence of vegetation on overbank flows partly depends on flow height, as already discussed, however, vegetation itself can influence flow height. Floodplain vegetation increases flood elevation by acting as a friction factor, (Klassen and Zwaard, 1974; Darby, 1999) and, therefore, in some circumstances raises flood risk in the immediate vicinity (Darby, 1999) (although downstream flood risk may be reduced due to attenuation of flood peaks (Friedman *et al.*, 2005)). Consequently, vegetation is often removed from floodplains in flood-sensitive areas (Darby, 1999). The affect on flood elevation varies with type of vegetation (Petryk *et al.*, 1975); flexibility (Knighton and Nanson, 2002) and fragility (Tabacchi *et al.*, 2000). The roughness caused by vegetation depends on its height and stiffness coefficient, which is a composite parameter derived from its density, elasticity, shape and bendiness (Kouwen, 1988; Fathi-Maghadam and Kouwen, 1997). Because vegetation on floodplains is often desirable for reasons of aesthetics, habitat quality and water quality, Darby (1999 p453) proposes a model that "can be used to determine the extent of cover and stem properties of specific types of riparian vegetation before the friction factor and flood elevation of a given design discharge are increased to unacceptable levels," rendering it possible to select vegetation with specific characteristics for floodplains with high flood risk while managing the risk of flooding.

This section has summarised the hydraulic processes of overbank flows. It has included a discussion of some of the complications created by diverse floodplain topography and vegetation. Most natural floodplains have irregular topography and some form of vegetation; a sound understanding of overbank flow hydraulics in such environments needs to take into account the modifications to overbank flow caused by the interactions between the flow and floodplain topography and vegetation.

3.5.2 Sediment deposition on the floodplain

Overbank flows transport sediment from the channel to the floodplain. Since vegetation significantly influences overbank flows through its function as a roughness element (Myers *et al.*, 1999; Friedman *et al.*, 2005), and through its ability to obstruct and divert flows (Tabacchi *et al.*, 2000; Jeffries *et al.*, 2003), it follows that patterns of sediment transport and storage are also influenced by vegetation.

Within the literature, a range of geomorphological features found on floodplains have been identified that are created through either overbank sediment deposition or erosion or a combination of both processes. Various classifications for these features exist according to (i) origin (Allen, 1970; Brown, 1996), (ii) scale (Lewin, 1978), (iii) sedimentology (Brown, 1996), and (iv) location (Zwolinski, 1992). In light of increasing recognition of the important role that vegetation plays influencing floodplain processes (e.g. Jeffries *et al.,* 2003), Table 3.3 lists geomorphological features that have been shown to be strongly influenced by vegetation in forested floodplains. A brief description of the main processes forming the features is also given.

The influence of vegetation on floodplain deposition has been largely omitted from studies of floodplain deposition (e.g. Lambert and Walling, 1987; Nicholas and Walling, 1997a; Walling and He, 1998; Marriott and Alexander, 1999). Most floodplains, however, contain some form of vegetation that, at least to some extent, influences the processes of sediment deposition. These interactions are very complex (e.g. Jeffries *et al.,* 2003) and consequently have received only limited scientific investigation. The rest of this chapter examines processes of floodplain deposition in the absence of vegetation, and then goes on to suggest how these processes are modified by floodplain vegetation. Processes of floodplain scour are then mentioned, followed by a detailed discussion of features found on floodplains that are predominantly formed by floodplain scour.

Table 3.3 Geomorphological features strongly influenced by vegetation that occur in forested floodplains.

Geomorphological feature	Processes forming feature	References
Floodplain wood jams	Result from trees on the floodplain falling in situ; from redistribution of wood on the floodplain by overbank flow; and from wood rafted onto the floodplain from the channel during overbank flow.	Hickin, 1984; Piégay et al., 1998.
Linear accumulations of wood on the floodplain parallel to the channel	Result from mobilisation and deposition of wood during overbank flows.	Hickin, 1984; Piégay, 1997; Piégay et al., 1998.
Sand shadows	Areas of raised topography on the floodplain located in the wake of obstacles, particularly trees. Result from the obstacle sheltering an area of low water velocity downstream of it, promoting sediment deposition and hindering erosion of the floodplain surface.	Zwolinski, 1992; Jeffries et al., 2003.
Tree throw pits	Depressions on channel margins caused by roots being ripped out of the ground when trees fall, often due to bank undercutting.	Davis and Gregory, 1994; Brown et al., 1995; Brown, 1997
Floodplain channels / sloughs	Result from floodplain scour due to overbank flow being constricted by vegetation and/or irregular topography (e.g. relict channels).	Harwood and Brown, 1993; Brown et al., 1995; Piégay, 1997; Piégay and Gurnell, 1997; Piégay et al., 1998; Jeffries et al., 2003; Fagan and Nanson, 2004.
Channel cut-offs	Form when the main channel cuts across a meander neck; may be initiated/promoted by in channel wood jams forcing overbank flow across a meander neck.	Lewin and Manton, 1975; Lewis and Lewin, 1983; Brown, 1996; Gay et al., 1998; Gay et al., 1998; Bridge, 2003.
Anastomosed islands	Islands of floodplain (often vegetated) surrounded by channels. Caused by channel avulsion due to channel blockage (e.g. from wood jams or ice blockage, or from aggradation in the channel).	Knighton and Nanson, 1993; Brown, 1998; Leeder, 1999.
Braided islands	Islands of deposited material within the main channel, usually submerged at bankfull stage; may be stabilised by vegetation.	Leeder, 1999; Gurnell et al., 2000; Bridge, 2003.

Lateral and Vertical accretion

Floodplains are generally considered to be principally constructed by a combination of lateral accretion of in-channel coarse deposits and vertical accretion of finer overbank deposits (Figure 3.7). However, in-channel deposits are not always coarse and overbank deposits are not always fine; for example silt and clay may be deposited in-channel in dead water zones (Brown, 1996). In addition, in certain circumstances such as in a high-energy piedmont river, overbank transport of gravels has been observed (Piégay *et al.,* 1998), and Asselman and Middelkoop (1995), Brown (1983) and Gomez *et al.* (1998) also recorded bedload transport across the floodplain. Nevertheless, lateral and vertical accretion are the main ways in which floodplain sedimentation has been studied and will be discussed in the following paragraphs.

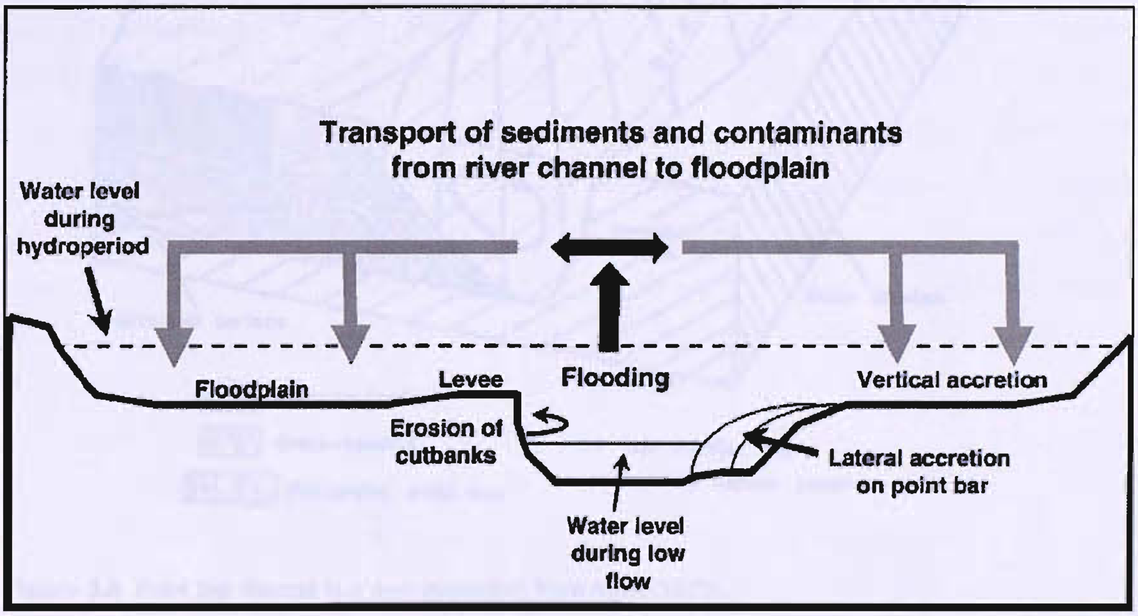

Figure 3.7 Lateral and Vertical accretion, adapted from Hupp (2000 p2998).

The relative importance of lateral and vertical accretion for floodplain development has been discussed extensively within the literature. For example, in the 1950s lateral accretion was generally thought to be more important than vertical accretion. Wolman and Leopold (1957) suggested that floodplains were formed primarily by lateral accretion, mainly of coarse grained particles, on the inside of meander bends, topped by vertical accretion of fine grained, suspended material, deposited during overbank flows. Lateral accretion of point bars on the inside of meander bends and erosion on the outside banks are the primary processes driving meander migration (Howard, 1996) (Figure 3.8). These processes are derived from secondary circulation of flow (Figure 3.2). Howard (1996 p29) summarised the main processes of meander development: "The primary causative factor for meander development is the secondary circulation created by channel planform curvature, which leads to asymmetry of flow and bed topography in bends. Flow momentum causes greater shear stresses on the outer bank in a long bend, leading to enhanced erosion and concomitant point-bar deposition on the inside bank."

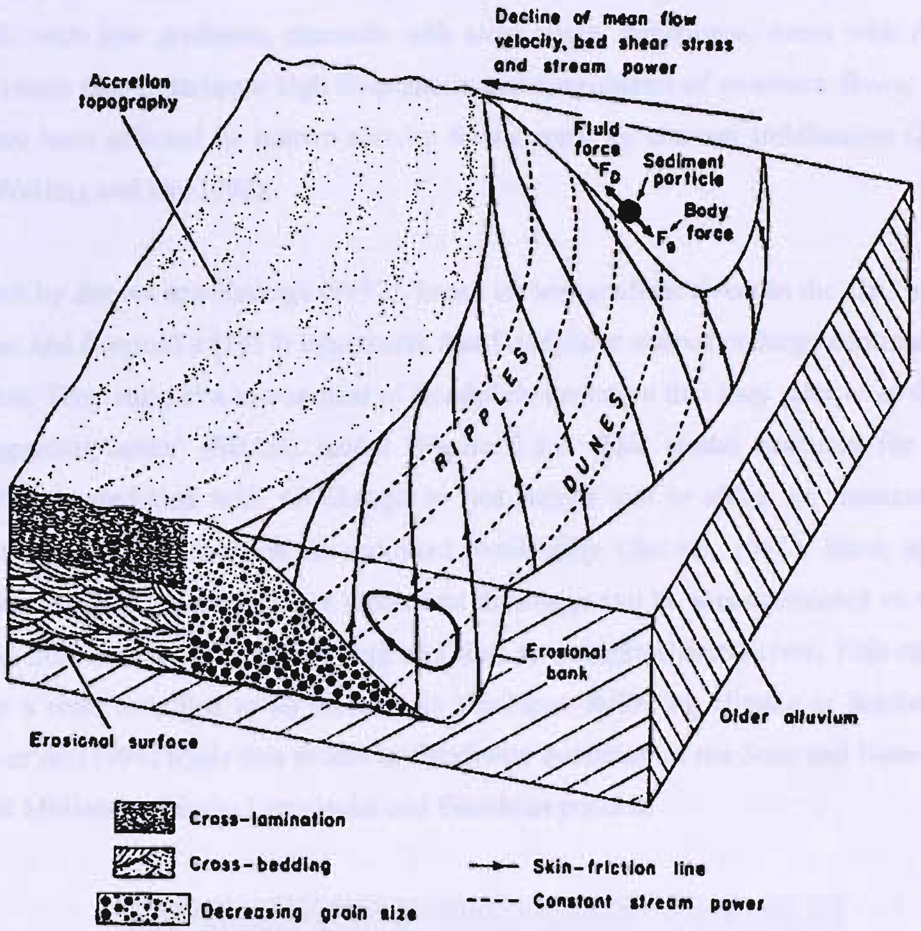

Figure 3.8 Point bar deposit in a river meander, from Allen (1970).

In order to investigate the relative importance of lateral and vertical accretion, Wolman and Leopold (1957 p100) constructed a hypothetical model of floodplain development based on the assumption that "each time a stream overflows a given level it deposits a specific thickness of material". This increase in floodplain height was then combined with computed flood frequencies to calculate the hypothetical time needed for the floodplain to reach a given elevation. The hypothetical model was tested on Brandywine Creek, an active floodplain in Pennsylvania, which, from radiocarbon dating, was thought to be a minimum of 1450 years old. It was found that if the hypothetical model held true, the floodplain should have been four feet higher than it was. Thus Wolman and Leopold (1957) concluded that lateral accretion dominated over vertical accretion.

Research on other floodplains, however, has revealed the importance of overbank, vertical accretion for floodplain development (e.g. Nicholas and Walling, 1997a and b; Mddlekoop and Asselman, 1998; Jeffries *et al.*, 2003; Friedman *et al.*, 2005). Vertical accretion is particularly prevalent in the following situations: the middle and lower reaches of rivers, channels with low gradients, channels with slow lateral movement, rivers with rising base levels, rivers that experience high frequencies and magnitudes of overbank flows, and rivers that have been affected by human activity for example by channel stabilisation (Zwolinski, 1992; Walling and He, 1998).

Research by Brown and Keough (1992), based on low gradient rivers in the UK, undermines Wolman and Leopold's (1957) hypothesis that floodplains cannot undergo continued vertical accretion. They suggest a mechanism of floodplain evolution that they refer to as the 'stable-bed aggrading-banks' (SBAB) model (Figure 3.9). This model accounts for continued floodplain aggradation with no change in bed height due to either an increase in flood magnitude, or to an increase in sediment availability (Brown, 1996). Bank aggradation increases bankfull capacity, hence a constant discharge can be accommodated as the system changes from braided to anastomosing and then to a single-channel river. This method also enables a river to adjust to an increase in discharge following climate or landuse change. Brown *et al.* (1994) apply this model to floodplain evolution of the Soar and Nene valleys in the East Midlands over the Lateglacial and Flandrian periods.

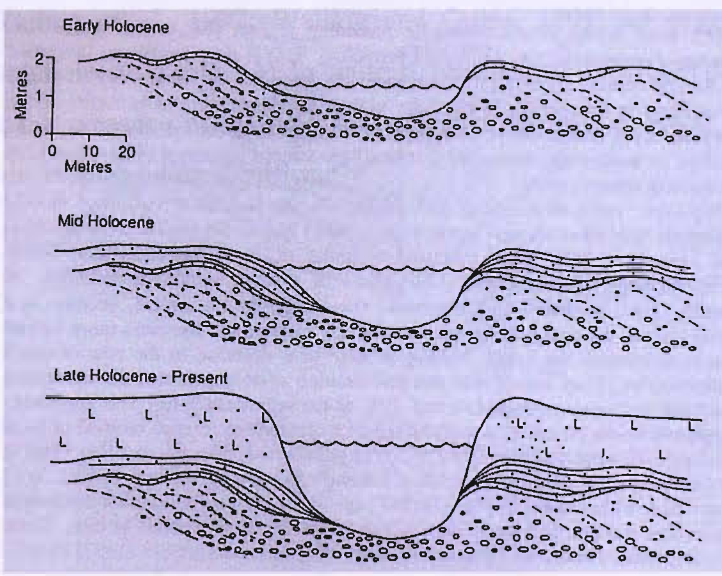

Figure 3.9 Stable-bed aggrading-banks model of floodplain and channel evolution, which facilitates continued increase in floodplain elevation and a constant recurrence interval of overbank events due to the increase in flow passing down the primary channel as secondary channels silt up, from Brown (1996 p100).

A similar mechanism of Holocene floodplain evolution is discussed by Hagedorn and Rother (1992) for the small Ilme River in the uplands of Lower Saxony, Germany. At the start of the Holocene the river was braided, then the lower and middle reaches became meandering due to vertical accumulations caused by woodland clearing and soil erosion in the Early Middle Ages. Vertical accretion then decreased due to decreased overbank flows caused by increasing channel capacity (Hagedorn and Rother, 1992).

The relative importance of lateral and vertical accretion can change over time and varies from one floodplain to another, depending on the timescale in question. For example, Friedman *et al.* (2005) used tree-rings to date floodplain sediments and determine the historic record of sediment deposition rate for a cross-section of the floodplain on the Rio Puerco, a rapidly accreting arroyo (a straight sided, flat-floored periodic watercourse cut in alluvium (Mayhew and Penny, 1992)) in New Mexico. The authors found that from 1936 to 1986 sediment deposition occurred mainly by lateral accretion, narrowing the channel, and from 1986 to 2000 it was mainly by vertical accretion.

Rates of overbank vertical accretion are difficult to estimate due to their spatial and temporal variability and the unpredictability of overbank events (Walling *et al.,* 1996). However, methods such as sediment traps (e.g. Lambert and Walling, 1987; Asselman and Middelkoop, 1995), post event topographic surveys (Walling *et al.,* 1996), monitoring downstream decreases in suspended sediment (e.g. Lambert and Walling, 1987) and dating floodplain material (e.g. Walling *et al.,* 1992; Walling and Quine, 1993) all suggest low rates of overbank sedimentation (see Table 3.4). In contrast, results from Jeffries *et al.* (2003) in Table 3.4 indicate that the presence of hydraulically effective in-channel wood jams can locally increase floodplain sedimentation significantly.

Table 3.4 Rates of vertical accretion recorded for selected lowland rivers, adapted from Jeffries *et al.* (2003) and Walling (1999).

Amount of overbank deposition			River and location	Source
Per flood	Last 33 yrs	Last 100 yrs		
kg m^{-2}	kg m^{-2} a^{-1}			
0.0-26.04[b]			Highland Water, England	Jeffries et al. (2003)
0.097-6.78[a]			Cole, England	Briggs (1999)
0.004-4.414[a]			Brede, Denmark	Kronvang et al. (1998)
0.52-1.93			Meuse, Netherlands	Asselman and Middelkoop (1995)
0.36-1.57			Waal, Netherlands	Asselman and Middelkoop (1995)
0.008-0.721			Culm, England	Nicholas and Walling (1995)
0.008-0.227			Culm, England	Lambert and Walling (1987)
0.185			Mississippi, Mississippi	Gomez et al. (1998)
0.11-0.25			Meuse, Netherlands	Middelkoop and Asselman (1998)
0.11-0.3			Waipaoa, New Zealand	Gomez et al. (1998)
0.008-0.24			Fyrisån, Sweden	Gretener and Strömquist (1987)
	12.2	14.2	Severn, England	Walling (1999)
	9.5	10.4	Ouse, England	
	8.8	10.1	Usk, Wales	
	8.6	9.5	Severn, England	
	7.0	9.3	Torridge, England	
	6.0	6.5	Taw, England	
	5.6	4.3	Tone, England	
	5.1	7.1	Adur, England	
	5.1	6.4	Thames, England	
	5.1	4.5	Start, England	
	5.1	4.0	Axe, England	
	4.6	6.6	Warwickshire Avon, England	
	4.5	4.2	Exe, England	
	4.0 (est.)		Culm, England	Siggers et al. (1999)
	3.9	4.8	Arun, England	Walling (1999)
	3.9	3.3	Bristol Avon, England	
	3.5	3.2	Culm, England	
	2.8	3.3	Severn, England	
	2.1	4.6	Vyrnwy, Wales	
	1.5	2.8	Wye, Wales	
	1.5	2.3	Medway, England	
	1.1	1.4	Rother, England	
	0.4	0.4	Dorset Stour, England	

[a] Restored rivers, readings taken between 1 to 3 years after restoration.

[b] Process influenced by a wood jam.

Sediment transport onto the floodplain

The primary route by which sediment is transported onto floodplains is via overbank flows from the main channel. The main mechanisms by which sediment is transferred from the main channel to the floodplain during overbank flows is through convective, diffusive (Marriott, 1998; Middelkoop and Asselman, 1998) and advective transport. Diffusive transport takes place as follows: the momentum transfer mechanism (discussed in Section 3.5.1), generated by a velocity gradient between channel and floodplain flows, transfers suspended sediment as well as energy, in the form of turbulent eddies, from the channel to the floodplain (Allen, 1985; Pizzuto, 1987; Marriott, 1998; Middelkoop and Asselman, 1998). Convective transport occurs when a flow component is perpendicular to the main channel (Middelkoop and Asselman, 1998), often caused by in-channel secondary currents (Marriott, 1998), and may transport suspended sediment across the floodplain. Convective transport is particularly important on meander bends (James, 1985), and may result in asymmetric floodplains due to the floodplain on one side of the channel receiving more sediment deposition than the other side (James, 1985). Coarse sediment may be advected up or out of the channel bank by traction as bedload, and deposited near the channel margin (Marriott, 1998; Middelkoop and Asselman, 1998; Adams *et al.,* 2004).

Sediment deposition

According to the diffusion models of James (1985) and Pizzuto (1987), the majority of sediment is transported by turbulent eddies that form at the interface between the channel and floodplain, and which then detach themselves and diffuse towards low velocity areas of the floodplain. Floodplain flows are often incapable of transporting the same amount of sediment as the main channel due to their shallow depths and high flow resistance and therefore low competence, hence sediment is deposited near the interface between the channel and floodplain, with coarser grains deposited first due to their relatively high fall velocity (James, 1985; Pizzuto, 1987; Asselman and Middelkoop, 1995; Marriott, 1998). In the absence of complex topography and vegetation, the thickness of overbank deposits and the calibre of sediment deposited are considered to decrease exponentially with distance from the channel (Pizzuto, 1987; Zwolinski, 1992; Marriott and Alexander, 1999).

Influence of floodplain topography on sediment deposition

The diffusion effect explains the general pattern of decreasing overbank deposition with increasing distance from the main channel. However, within this general pattern there may be significant local variability (e.g. Walling and He, 1998; Marriott and Alexander, 1999) which is not explained by the diffusion effect. The spatial variability of overbank deposition is controlled by a combination of floodplain topography, frequency and patterns of inundation and magnitude of local suspended sediment concentrations (Nicholas and Walling 1997a; Lambert and Walling, 1987). Simple diffusion models of floodplain deposition fail to replicate the spatial variability in deposits, grain size, and hence physical habitat as they do not take into account the local variations in topography that exist on natural floodplains. Floodplains have highly irregular surfaces that may exert a considerable influence on the movement of overbank flow (Lewin, 1978; Hughes, 1980), and hence on the location of overbank deposition (Asselman and Middelkoop, 1995). Nicholas and Walling (1997a p60) argue that previous models of floodplain sedimentation "have been unsuccessful in terms of replicating the high degree of spatial variability of both hydraulic conditions and sedimentation patterns identified in the field." They propose a model for floodplain inundation sequences and patterns of deposition that incorporates floodplain topographic complexity, which they believe exerts a dominant control over both inundation sequences and patterns of overbank deposition on natural floodplains (Nicholas and Walling, 1997a). Using a 2-dimensional hydrodynamic model and field data, they found that suspended sediment transport processes within the channel belt were dominated by longitudinal convective currents, resulting in high concentrations of suspended sediment and high rates of overbank deposition in this area. Outside the channel belt convective currents were perpendicular to the channel and weaker, therefore suspended sediment transport was dominated by diffusive mechanisms. Sediment concentrations and deposition rates were highly spatially variable, with patterns controlled by local and distant floodplain topography (Figures 3.10 a and b).

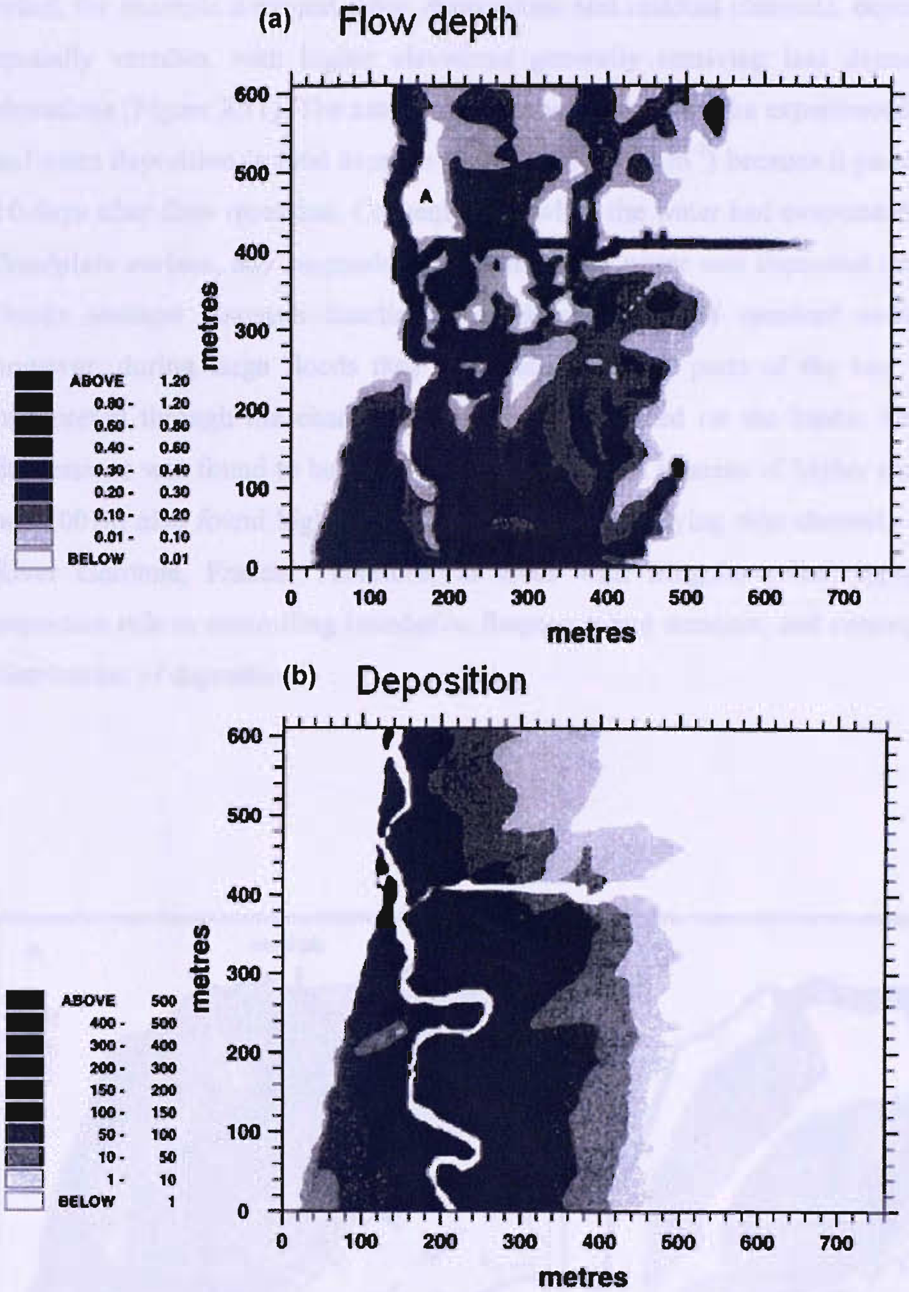

Figure 3.10 (a) Predicted pattern of flow depth for a water level of 2.35 m; (b) Predicted pattern of total deposition amounts (g m^{-2}) for a single flood event, from Nicholas and Walling (1997a).

Floodplain topography plays an important role in determining inundation frequency and duration, which in turn influences sediment deposition. Considerable variation in patterns of deposition associated with floodplain topography was also observed by Middelkoop and Asselman (1998) in the Rhine-Meuse delta in the Netherlands (Figure 3.11). In areas with fairly uniform relief and little variation in inundation duration, an exponential decrease in deposition with distance from the main channel was observed, conforming to the diffusion models of Allen (1985), Pizzuto (1987) and James (1985). However, in areas with irregular relief, for example a natural dyke, depressions and residual channels, deposition was highly spatially variable, with higher elevations generally receiving less deposition than lower elevations (Figure 3.11). The area immediately behind the dyke experienced large amounts of sediment deposition (a total average weight of 3.86 kg m^{-2}) because it ponded water for 5 to 10 days after flow recession. Consequently, when the water had evaporated or infiltrated the floodplain surface, any suspended sediment in the water was deposited there. During small floods residual channels functioned as depressions and received sediment deposition; however, during large floods they were activated and parts of the bed were eroded and transported through the channel before being deposited on the banks. Deposition in local depressions was found to be 50 to 100 % greater than in areas of higher elevation. Steiger *et al.* (2001a) also found high rates of deposition in low-lying side channels on a reach of the River Garonne, France. Therefore, in areas with irregular relief, topography plays an important role in controlling inundation frequency and duration, and consequently the spatial distribution of deposition.

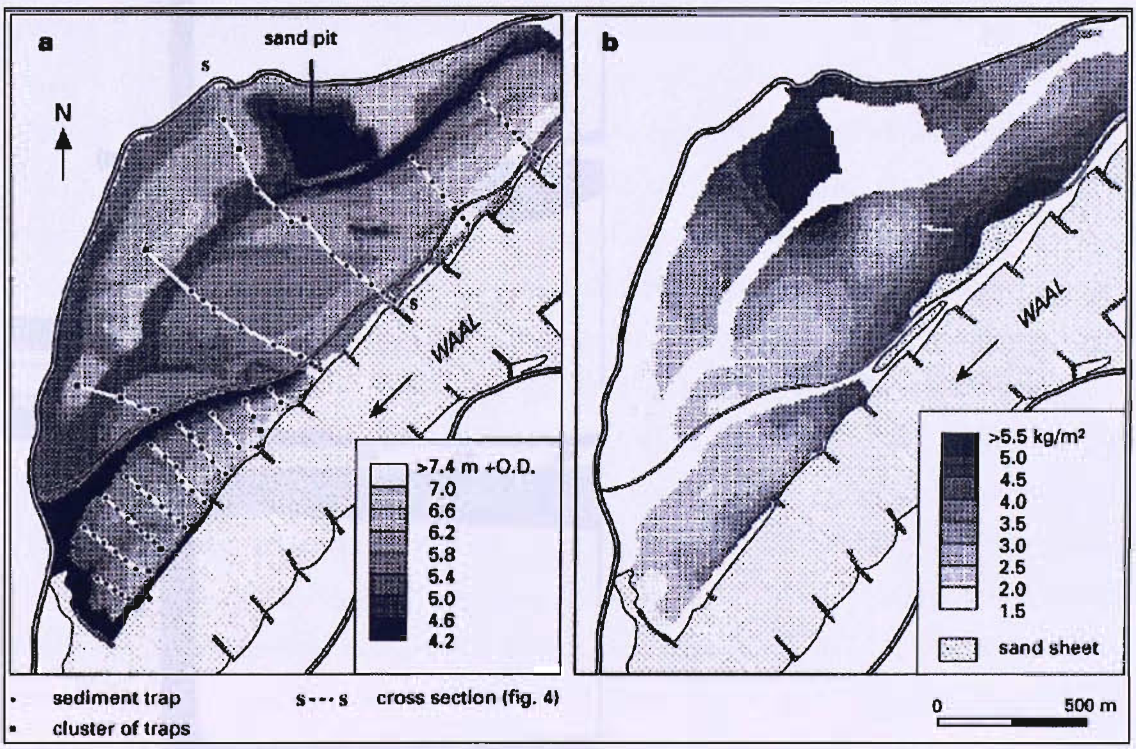

Figure 3.11 (a) Floodplain elevation and (b) sediment accumulation on the River Waal, Netherlands, from Middelkoop and Asselman (1998 p568).

Grain size distribution of overbank deposits

According to diffusion models of overbank sedimentation, mean grain size decreases exponentially with distance from the channel; sand is deposited near the channel banks, and material gradually gets finer with increased distance from the channel (Marriott, 1996). However, analyses of overbank deposits from a flood on the River Severn, UK, revealed a marked change in the pattern of variation in mean grain size and the standard deviation that began 20 m from the channel bank, with a decrease in proportion of sand in favour of silt, although sand was present throughout the transects which varied from 200 to 600 m (Marriott, 1996) (Figure 3.12). Coarse grained sediment was deposited near the channel-floodplain interface due to turbulent transfer of suspended sediment overloading floodplain flows (Marriott, 1996). Marriott (1996) suggests that the sharp decrease in mean grain size at 20 m from the channel may represent the areal extent of the interaction zone between channel and floodplain flows, hence the limit to which large amounts of sand is deposited.

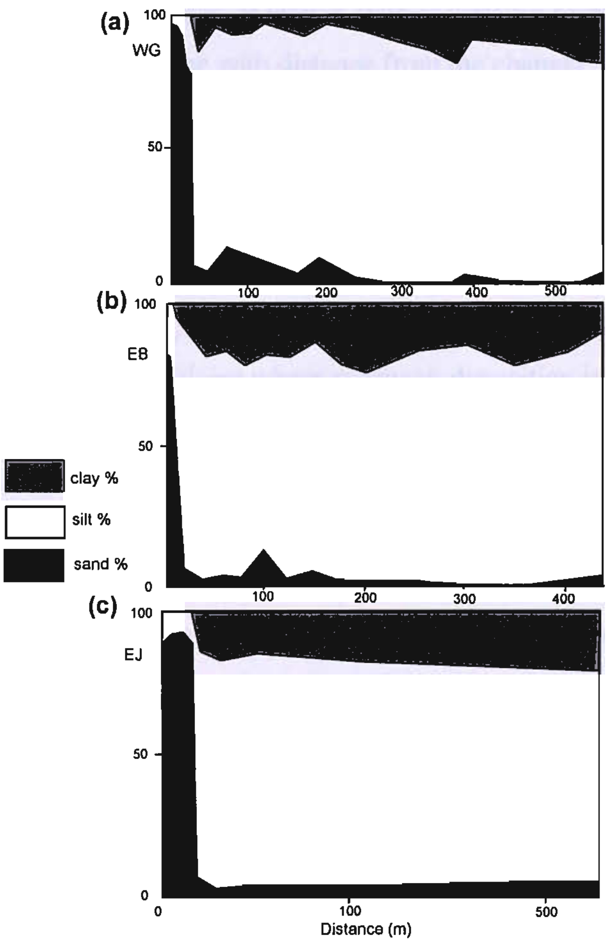

Figure 3.12 Graphs showing the variation in sand, silt and clay with distance from the channel bank for three cross sections, from Marriott (1996 p70).

Figure 3.12 shows some spatial variability in grain size of overbank deposits, especially (a) and (b), which is consistent with the findings of other researchers (e.g. Nicholas and Walling, 1997a; Asselman and Middelkoop, 1995). Steiger *et al.* (2001b) observed high variability in the sand content of overbank deposits on the River Severn, UK. Nicholas and Walling (1997a) found that near-channel deposits consisted predominantly of coarse fractions, which they attribute to high fall velocities of coarse particles in a rapidly decelerating environment. Further from the main channel the dominant size fraction was 32-63 µm. Asselman and Middelkoop (1995) found that the exponential decrease in deposition with distance from the channel that occurred in regions of uniform relief was most apparent in the sand fractions of deposits; silt and clay deposition decreased much more gradually. In areas that were susceptible to ponding during flood recession, particle fall velocity was not important as, given adequate time, all of the sediment contained in the ponded water was deposited due to the 'trapped' nature of the water (Nicholas and Walling, 1997a).

So, although local variations exist, studies have shown that, in general, the grainsize of overbank deposits decreases with increasing distance from the main channel, due to reduced flow competence with distance from the channel.

Influence of vegetation on overbank deposition

Although the inclusion of topographic variations renders Nicholas and Walling's (1997a) model more physically realistic than early diffusion models, it has yet to be applied to forested floodplains where overbank deposition is influenced by both live and dead vegetation in the channel and on the floodplain (Steiger *et al.*, 2005). Unlike classic models of floodplain deposition, whereby sediment deposition decreases with increased distance from the channel (e.g. James, 1985; Pizzuto, 1987), Jeffries *et al.* (2003) found no clear lateral gradient of sediment deposition away from the channel on the Highland Water, and they argue that vegetation (live and dead) and topography cause an alternative spatial variability to the lateral diffusion concept of overbank flow and sedimentation. Piégay (1997 p194) also observed that floodplain flows were complicated by vegetation-induced variations in energy and direction, leading to "a patchwork of morphosedimentary and vegetation units." Unlike earlier models of sedimentation which ignore the effects of vegetation, the above research suggests that vegetation has an important influence on the distribution of sedimentation on forested floodplains, and hence needs to be incorporated into models of floodplain sedimentation.

Wood affects floodplain deposition in two ways: (i) accumulations of wood in the channel may form wood jams which partially block the channel, decreasing its bankfull capacity and consequently increasing overbank flow frequency hence the potential for floodplain deposition and erosion (Gurnell, 1997; Piégay and Gurnell, 1997; Jeffries *et al.,* 2003; Brummer *et al.,* 2006). For example, at a wood jam on the Highland Water in the New Forest, UK, bankfull discharge occurred at 0.55 $m^3 s^{-1}$, but 100 m downstream in the absence of a wood jam it was 2.2 $m^3 s^{-1}$ (Sear *et al.,* 2000); (ii) live vegetation and accumulations of wood on the floodplain influence overbank flow routing and therefore the potential distribution of floodplain sedimentation (Jeffries *et al.,* 2003). This highlights a shortfall in Nicholas and Walling's (1997a) model: assumptions in one of the equations on which the model is based are "that floodplain flow moves in a direction parallel to the longitudinal axis of the valley floor and that the elevation of water surface is constant along lines running perpendicular to the axis" Nicholas and Walling (1997a p61). This is not necessarily the case on forested floodplains, where vegetation influences floodplain flow routes. Harwood and Brown (1993) and Piégay *et al.* (1998) found that organic material on floodplains controls the direction in which water and sediment vectors traverse the floodplain. On the rivers Ain, Ardeche and Ouveze, France, Piégay (1997) found that wood accumulations on the floodplain played an important role in concentrating overbank flow into floodplain channels with variable orientation.

Trees and shrubs on the floodplain function as obstacles, causing overbank flow deformation, which may result in 'obstacle marks' (Nakayama *et al.,* 2002). These marks are generally in the form of scour on the upstream side of an obstacle and a sediment tail, or sand shadow on the lee side (Zwolinski, 1992; Nakayama *et al.,* 2002; Jeffries *et al.,* 2003). These features have been observed in a range of environments, for example on semi-natural floodplains in the New Forest, southern England (Jeffries *et al.,* 2003), in ephemeral streams in the Negrev, southern Israel (Karcz, 1968), and around ice blocks in glacial outwash in Greenland (Russell, 1993). According to Karcz (1968) and Allen (1984) obstacle marks are formed by localised flow acceleration upstream of an obstacle caused by secondary flow currents that are induced by flow diversion around an obstacle. This increases bed or floodplain surface shear stresses upstream of an obstacle promoting erosion and inhibiting sediment deposition in this area, but leads to flow separation downstream of the obstacle, reducing bed shear stresses in this area and hence promoting sediment accumulation (Nakayama *et al.,* 2002) and the development of sand shadows. The width and length of sand shadows depends on the size of the obstacle (Zwolinski, 1992). Accumulations of wood on the floodplain may have a similar influence on sediment deposition but this has not been widely studied (although see Piégay *et al.,* 1998).

Living vegetation such as trees, shrubs and grasses on channel banks affects overbank sedimentation by disrupting flow vortices between channel and floodplain flows, and by decreasing the discharge at which overbank flow first occurs (discussed in Section 3.5.1). Both living and dead vegetation on the floodplain influence overbank deposition by increasing the hydraulic resistance to flow, which in turn decreases flow velocities, hence promoting deposition (Tabacchi *et al.,* 2000). Various studies (e.g. Nanson and Beach, 1977; Hickin, 1984; Friedman *et al.,* 2005) have demonstrated an increase in sedimentation under the presence of floodplain vegetation. Piégay and Salvador (1997) for example, found that forest expansion in the 1920s on the Ubay River floodplain, France, reduced channel width through increasing hydraulic roughness and bar stabilisation. However, in the Piedmont region of the United States, Hession *et al.* (2003) have found that channels with forested riparian zones are wider than channels with no riparian zones. McBride *et al.* (2005 and 2006) conducted flume experiments to investigate possible causes for these differences in width by simulating forested vegetation using wooden dowels and non-forest using synthetic grass. They measured three-dimensional velocities during overbank flows to determine turbulent kinetic energy (TKE), and therefore potential erosion, and found that TKE was nearly double under forested vegetation than non-forest. Therefore they conclude that channels bordered by riparian forests may be wider than their non-forested counterparts due to increased erosion caused by higher TKE promoted by trees.

The effect of vegetation on floodplain sedimentation depends on vegetation size, shape, flexibility, orientation and density (Bridge, 2003), as well as leaf surface characteristics (Brown and Brookes, 1997). Therefore different types of vegetation have different affects on overbank sedimentation (Brown, 1996; Brown and Brookes, 1997). For example, after an overbank flow, Brown and Brookes (1997) observed nettles on the floodplain covered in sediment, but adjacent grass leaves had no visible sediment. The authors suggest that the high frequency of herbs with leaf hairs (e.g. nettles, willowherb, comfrey, meadowsweet) may have a functional role as part of an adaptation to high rates of overbank deposition. Wilson (1967) found that different grasses trapped different amounts of suspended sediment from flooding water. However, Mansikkaniemi (1985) found no difference in the amount of sediment trapped by different vegetation, and suggests that the siting of sediment traps had an overriding influence on sediment deposition (see Chapter 6).

As discussed above, vegetation has been largely omitted from floodplain models due to uncertainties about its influence on floodplain processes. Where it has been included it is represented as a constant roughness element and is therefore only applicable to floodplains with uniform vegetation such as grass (Brown, 1996). A useful way of including vegetation in floodplain models would be to define a 'trap efficiency' for different types of vegetation, which could be spatially distributed in a floodplain model (Brown, 1996).

The ability of grass to trap suspended sediment in flowing water is utilised in vegetation filter strips (VFS), which are grass covered areas on slopes, used to trap sediment from run-off and so reduce erosion (Abu-Zreig, 2001). Abu-Zreig (2001) used a computer model to understand the factors that influence trapping efficiency (TE) of grass in VFSs. The following variables were studied: filter length (length of grass strip), slope angle, Manning's roughness, soil type, and sediment class. Filter length was found to have the greatest influence on TE; the average TE for a length of 15 m was 95% compared with 30% for a length of 1 m. Incoming sediment characteristics also had a significant influence on TE: silt was more easily trapped than clay, for example the TE of clay for 1 m and 15 lengths was 0% and 47% respectively, whereas over the same lengths for silt TE was 40% and 92% respectively. Increasing the Manning's *n* (grass density) only increased TE slightly, although the increase was greater for shorter distances; for example increasing *n* from 0.04 to 0.4 for a filter length of 1m only increased TE by 20%, whereas increasing *n* by the same amount for a filter length of 15m resulted in only a 5% increase in TE. Contrary to these findings, however, Van Dijk *et al.* (1996) argue that grass density is an important influence on the ability of grass strips to filter sediment. Slope angle and soil type had a negligible impact on TE (Abu-Zreig, 2001).

Although vegetation affects local rates of deposition, under certain conditions reach-scale geomorphology and hydrology may moderate or override the impact of vegetation (Steiger *et al.,* 2001b). This is demonstrated by research on sediment deposition along channel margins of a reach of the River Severn, UK (Steiger *et al.,* 2001b). Higher deposition rates were observed on grazed pasture vegetation which has a lower roughness coefficient than riparian woodland and poplar plantation. However, the grazed pasture was located on the inside of a meander bend, whereas riparian woodland and poplar plantation were located on the outside bend, thus planform position appears to have an overriding influence on sedimentation patterns. Hupp *et al.* (1993) found that mean rates of sediment deposition were related to stream gradient, stream power, percent of wetland, hydroperiod and land use. Kleiss (1996) observed that 90% of the variation found in sedimentation was accounted for by distance from the main channel, flood duration and tree basal area. Walling and He (1997) found that rates of deposition reflected controls by local hydrogeomorphological conditions such as channel geometry, overbank flow patterns, floodplain morphology and micro-topography. Therefore flood characteristics, for example peak discharge and flood hydrograph shape interact with morphology of the riparian corridor to produce the spatial pattern of overbank deposition (Steiger *et al.,* 2001b).

From the literature discussed it is apparent that hydrological, geomorphological and vegetative factors influence the complex spatio-temporal patterns of sediment deposition, and hence spatio-temporal heterogeneity, of floodplains. It is argued that in small, temperate, lowland forested floodplains (e.g. those found in the New Forest) vegetation can have an overriding influence on the hydrological and geomorphological processes e.g. in reaches where hydraulically effective wood jams dominate channel and floodplain processes (Brown *et al.,* 1995; Jeffries *et al.,* 2003).

3.5.3 Processes of floodplain scour

In addition to depositing sediment on the floodplain, overbank flows also remove and re-distribute sediment from the floodplain through erosion (Steiger *et al.,* 2005). For example, during large floods, floodplain stripping may interrupt vertical accretion (Warner, 1992; Nanson, 2004). Even during smaller overbank events, erosion from overbank flow may occur in certain locations on the floodplain, although this is an area not well researched (Dietrich, 2006 pers comm.). Erosion appears to be most important during the early stages of overbank floods, when it is focused on channel banks and at floodplain edges (Zwolinski, 1992). As floodplains become inundated, erosion and deposition of older sediments on the floodplain takes place (Zwolinski, 1992).

A detailed review of the mechanics of soil erosion is beyond the scope of this thesis, but soil erosion mechanisms will be discussed briefly. Soil erosion is initiated when shear stresses exerted by a force on the soil (e.g. flowing water) exceed the shear strength of the soil (Dunne *et al.,* 1995; Carling *et al.,* 1997). On hillslopes, sheet flow is channelled into rills and gullies, increasing water velocity and shear stress, and consequently increases soil erosion (Dunne *et al.,* 1995). Flow concentration is initiated when advective processes (e.g. wash and channel flow), promoted by irregular microtopography (Lane *et al.,* 1988; Kirkby, 2001; Dunkerley, 2004), exceed diffusive processes (e.g. rainsplash, soil creep and bioturbation) which move sediment into depressions (Dunne *et al.,* 1995). In a similar way, scour occurs on the floodplain where overbank flow is accelerated in narrow areas (Bridge, 2003), such as breaches, crevasses and chutes (Zwolinski, 1992). Overland flow is strongly inhibited by plant cover (Moss and Walker, 1978; Davenport *et al.,* 1998), and similarly, overbank flow and scour is concentrated where vegetation is sparse (Bridge, 2003).

Interactions between vegetation and flowing water could be considered analogous to interactions between vegetation and air flow. Vegetation protects a surface from aeolian (or fluvial) erosion by extracting momentum from air (or water) flow, and absorbing a proportion of shear stress, therefore reducing the shear stress on the erodible surface (Lancaster and Baas, 1998). Dense vegetation may substantially reduce erosion, although low densities of vegetation may increase local scour around an element due to the development of local vortices (Lancaster and Baas, 1998). On sand surfaces sparsely vegetated with salt grass (*Distichlis spicata*) at Owen's Lake, California, sand flux decreased exponentially with vegetation cover. Sand flux reduced to 10% of equivalent bare sand amount when the cover of salt grass was greater than 12% and to 5% when the cover was 17.5% (Lancaster and Baas, 1998). Therefore vegetation both protects the floodplain surface from erosion and promotes erosion in specific locations through locally concentrating flow.

3.5.4 Avulsion, meander cut-offs and floodplain channels

Channel avulsion has been defined in various ways, for example by Goudie *et al.* (1985 p41) as "the diversion of a river channel to a new course at a lower elevation on its floodplain as a result of floodplain aggradation"; by Slingerland and Smith (1998) as the abrupt abandonment of a channel belt for a new course at a lower elevation; and by Makaske (2001 p149) as "flow diversions that cause the formation of new channels on the floodplain". In this thesis it is used in the same way as by Makaske (2001) and is understood to be the process by which flow diversion causes the formation of new channels on the floodplain, and is complete when the old channel is abandoned in favour of the new channels. The avulsion may 'fail' if the new channels are subsequently abandoned (Makaske, 2001). Flow diversion occurs when flow is forced onto the floodplain either due to reduced channel capacity caused by channel-belt aggradation (e.g. Brooks *et al.,* 2003), or due to a channel blockage (such as a wood jam or ice-blockage) (e.g. Maser and Sedell, 1994; Makaske, 2001; Abbe and Montgomery, 2003; O'Conner *et al.,* 2003; Brummer *et al.,* 2006).

In this thesis, the 'new channels' that form on the floodplain are termed 'floodplain channels' (e.g. Brummer *et al.,* 2006). They can be viewed as a 'stage' in the avulsion process, although complete avulsion may not occur for a number of reasons. Firstly, it may 'fail' due to removal of the in-channel blockage resulting in abandonment of the floodplain channels (See Section 5.3.6 on the evolution of floodplain channels). Secondly, the floodplain channels may continue to co-exist with the main channel, only being occupied during flood events. Possible reasons for floodplain channels not developing into main channels could be low erosive power of overbank flows, or low erodibility of the floodplain material due, for example, to the presence of dense root networks in forested floodplains (Brown, 1997; Gay *et al.,* 1998; Church, 2005 pers comm; Gurnell, 2006 pers comm.).

Floodplain channels also form across meander bends, and this may happen in the presence or absence of in-channel blockages. Such channels may capture the flow from the main channel, resulting in channel cut-offs (Gay *et al.,* 1998). Alternatively, cut-offs can form as a consequence of bank erosion and meander progression, whereby a new channel is not actually cut into the floodplain, but the channel banks separating two meander bends gradually become completely eroded until flow is able to go directly from one meander bend to the next without travelling around the meander loop. From observations made on Welsh rivers, Lewis and Lewin (1983) found that most cut-offs occurred across tight meander bends. These processes of avulsion and channel cut-offs can be significant for maintaining a multiple channel (anastomosing) system, e.g. as found in the Gearagh, southwest Ireland (Harwood and Brown, 1993) and the Queets River, Washington (Abbe and Montgomery, 2003).

Floodplain channels appear in various forms and on a range of scales, and have been referred to using different terminology, for example 'ephemeral channels' (Jeffries *et al.,* 2003), 'floodplain surface channels' (Fagan and Nanson, 2004), 'flood channels' (Harwood and Brown, 1993; Brown *et al.,* 1995; Brown, 1997), 'side channels' (Steiger and Gurnell, 2002), 'residual channels' (Middelkoop and Asselman, 1998), 'sloughs' (Hupp, 2000), 'micro/secondary channels' (Piégay *et al.,* 1998), 'gullies' (Smith and Pearce, 2002), 'chutes' (Gay *et al.,* 1998), and 'auxiliary channels / anabranches' (Miller, 1991) (Table 3.5). The above mentioned channels are fundamentally similar in that they are formed by floodplain scour from overbank flow (as opposed to gullies formed by hillslope runoff). However, the specific scouring processes vary, although only limited research has investigated these processes.

Table 3.5 Classification of floodplain channels.

Terminology	Form & scale	Origin & maintenance	Primary process forming channels	Physiographic conditions	Reference
Floodplain-surface channels	2 types: (a) braided (perhaps better referred to as anastomosed as surface separating channels is floodplain material rather than mobile bars, as assumed in a braided pattern (Knighton & Nanson, 1993)); widths of 4-32m & (b) reticulate; widths of 2-8.5m; many nearly right angled confluences; occur with gilgai development.	Form "where overbank flow is sufficiently energetic to incise them or to preferentially retard deposition, forming low areas which develop into channels" (Fagan & Nanson, 2004 p108). Controlled by the same variables as control the main channel: flow discharge, valley gradient, sediment load & sediment erodibility.	Surface erosion	Cooper Creek, Queensland, Australia: semi-arid, with patchy and ephemeral vegetation.	Fagan & Nanson, 2004.
Micro/ secondary channels	Large number of channels, smaller ones show great lateral change & are short lived. Orientation varies, but primarily in line with main valley axis.	Erosion of floodplain surface & formation of micro-channels between trees and wood. Micro-channels relocate as wood is moved by floods.	Surface erosion	River Ain, France. Vegetation: temperate riparian forest consisting of a mosaic of stands of various ages, including trees, marshlands and shrubs.	Piégay et al., 1998.
Chute cut-offs	Form across meander necks. Width: 10^1 m, depth: about 2m, length: 10^2 m.	(i) Ice-jams cause overbank flow; (ii) headward erosion occurs as overbank flows re-enter the main channel; (iii) migration upstream of headward erosion forming a gully in its wake; may be slowed by roots on the floodplain.	Headward erosion	Powder River, Montana: ice-jams in winter and snow-melt floods during spring. Vegetation: dominated by Cottonwood trees (*Populus sargentii*).	Gay et al., 1998.
Gullies	Channels with open ends downvalley. Up to 208m long, 139m wide and 3.5m deep. Gullies have an escarpment at u/s end.	As above	Headward erosion	Milk River, Montana, USA. Vegetation: spatially discontinuous riparian forest, dominated by plains cottonwood (*Populus deltoides*).	Smith & Pearce, 2002.

Terminology	Form & scale	Origin & maintenance	Primary process forming channels	Physiographic conditions	Reference
Auxiliary channels/ anabranches	1-7 auxiliary channels may be present at a site. Downstream reaches of gullies are similar in size to primary channel: several metres wide & up to 1.5m deep; upstream reaches of gullies are much shallower than primary channel: e.g. 0.2m compared with 0.7m respectively at Mill Creek.	Avulsion through the following processes: (i) in-channel aggradation reduces channel depth & capacity; (ii) overbank flow occurs more frequently; (iii) sediment deficient overbank flow incises into floodplain, producing a gully with lower gradient & elevation than main channel; (iv) gully extends upstream by headward erosion & captures drainage system, converting previous main channel into an anabranch. Headward erosion may be limited by tree roots.	Surface & headward erosion.	Tributaries of the Ohio River in south-central Indiana. Vegetation: Hardwood forest.	Miller, 1991.
Flood-channels	Flood channels generally either run parallel to main channel or up to 45^0 from it. Under 2m in width; shallow; act as traps for sediment and wood.	(i) Wood jams cause water to back-up up stream; (ii) tree root masses & tree-throw pits play an important role in partitioning flow & overbank velocity distribution; (iii) flow is concentrated into flood-channels which advance by headwall scour (knick point) until impeded by tree roots.	Surface & headward erosion.	Gearagh, southwest Ireland. Temperate lowland vegetation.	Brown, 1997; Harwood & Brown, 1993; Brown et al., 1995.
Ephemeral channels	Network of shallow, bifurcating micro-channels on the floodplain around wood jams. May contain exposed roots. Main channel avg.depth 0.9m, width, 5m. Ephemeral channels range in width from <0.5m to 3m, and depth from <0.1m to 0.7m.	Uncertain, possibly either (i) scour on the floodplain surface; (ii) linear deposition to create intermediate low lying areas; (iii) relict channels maintained by overbank flow.	Uncertain.	New Forest: Temperate, lowland woodland, UK.	Jeffries, 2002; Jeffries et al., 2003.

Terminology	Form & scale	Origin & maintenance	Primary process forming channels	Physiographic conditions	Reference
		Observations made in relation to sediment deposition			
Side-channels	No information	High variability in sediment accumulation; decrease in sedimentation with distance from the side channel inlet; side channel is important for transporting suspended sediment across the floodplain.	Not specified	Garonne River, France. Vegetation: riparian woodland & cultivated poplar plantations.	Steiger & Gurnell, 2002.
Residual channels	No information	Sediment is conveyed into channel if channel is not closed off from main channel; during low discharge sediment may accumulate in channel; during larger floods sediment may be eroded from, & transported through, channels, resulting in sand deposited on channel banks.	Not specified	River Waal, Netherlands. Vegetation: mainly pasture, some local trees and a few fields of arable land.	Middelkoop & Asselman, 1998.
Sloughs	Bifurcating sloughs.	Highest deposition near sloughs & their anabranches.	Headward erosion	South-eastern USA. Vegetation: forested wetland (bottomland hardwoods).	Hupp, 2000.

Table 3.5 Continued.

From a review of the limited literature that exists on floodplain channels, they appear to fall into two broad categories based on the primary process responsible for their development: (i) headward erosion; and (ii) surface erosion (Table 3.5); although these two processes are not mutually exclusive, and channels may form by a combination of both processes.

Channels predominantly formed by headward erosion do not have distinguishable entry points from the main channel to the floodplain, but the point of exit from the floodplain to the main channel is clearly marked (e.g. see 'sloughs' (Hupp, 2000), Figure 3.13). These channels form primarily by headward erosion (Warner, 1997) at the point of re-entry to the main channel; the upstream limit of these channels may be characterised by a step / escarpment.

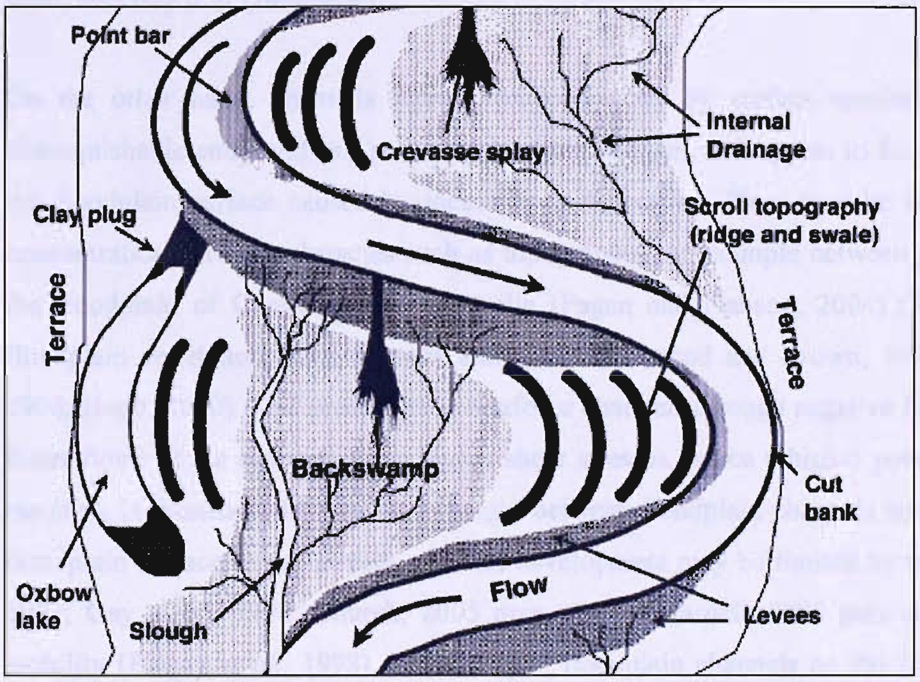

Figure 3.13 Headward eroding floodplain channels or 'sloughs', from Hupp (2000 p2998).

The steep drop (channel bank) that floodplain flows encounter on re-entry to the main channel, acts like a waterfall or knick point. The high gradient increases the erosive power of the flow causing the bank / knick point to remain vertical, but to migrate upstream, leaving a floodplain channel in its wake (Gay *et al.,* 1998) (Figure 3.14). This is the process suggested to be responsible for the creation of floodplain channels on the Powder River, Montana (Gay *et al.,* 1998), tributaries of the Ohio River, Indiana (Miller, 1991), and the Milk River, Montana (Smith and Pearce, 2002).

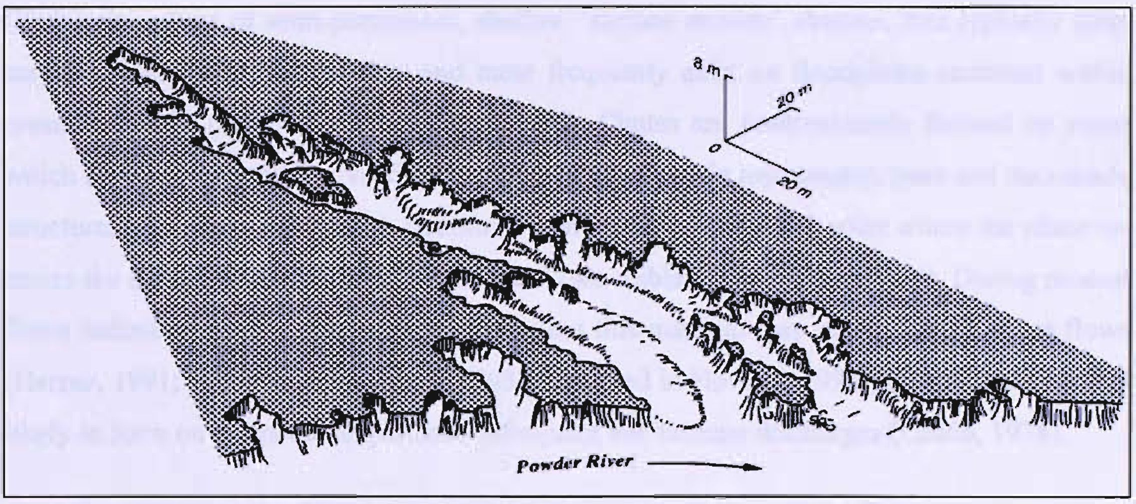

Figure 3.14 Upstream migration of a knick point leaving a floodplain channel in its wake on the Powder River, from Gay *et al.* (1998 p656).

On the other hand, channels formed predominantly by surface erosion may have both distinguishable entry and exit points to the main channel, and appear to form by scour across the floodplain surface caused by local flow acceleration. Flow may be accelerated due to concentration between obstacles such as topography, for example between gilgai mounds on the floodplain of Cooper Creek, Australia (Fagan and Nanson, 2004) (Figure 3.15), and floodplain vegetation, such as trees and wood (Harwood and Brown, 1993; Piégay *et al.*, 1998; Hupp, 2000). This process may reinforce channels through negative feedback, whereby faster flows in the channels have higher shear stresses, hence a higher potential for erosion, resulting in increased differences in height between floodplain channels and the surrounding floodplain surface. Alternatively, channel development may be limited by tree roots (Brown, 1997; Gay *et al.*, 1998; Church, 2005 pers comm.; Gurnell, 2006 pers comm.) and wood mobility (Piégay *et al.*, 1998). For example, floodplain channels on the River Ain, France, were found to be related to the location of accumulations of wood on the floodplain which changed annually, therefore so did the location of floodplain channels (Piégay *et al.*, 1998).

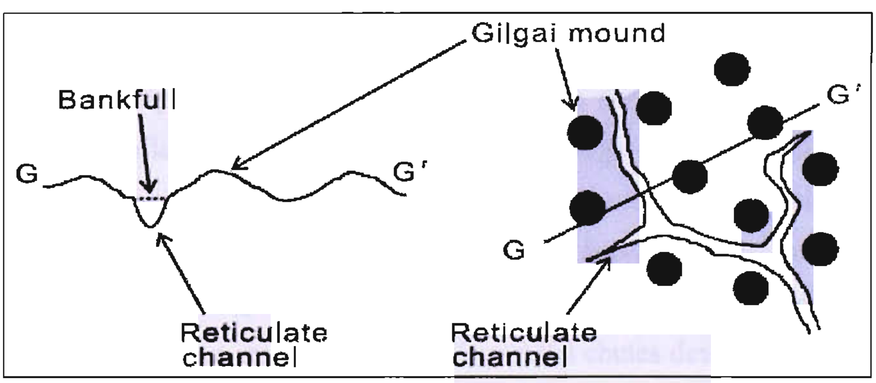

Figure 3.15 Topography (gilgai) influence floodplain channel development on the floodplain on Cooper Creek, Australia, from Fagan and Nanson (2004 p114).

Chutes are a type of semi-permanent, shallow 'surface erosion' channel, that typically form across coarse, point bar deposits and most frequently exist on floodplains enclosed within meander bends, (Howard, 1996) (Figure 3.16). Chutes are predominantly formed by scour which may be triggered by "vortices generated by floodplain topography, trees and man-made structures" (Howard, 1996 p20). Sediment is often deposited at the point where the chute re-enters the main channel, forming 'chute bars' (see Table 3.5 and Figure 3.16). During modest flows sediment may be deposited in chutes, but this material may be eroded by larger flows (Harper, 1991; Miller and Parkinson, 1993, both cited in Howard, 1996), thus chutes are most likely to form on rivers that experience infrequent but extreme discharges (Lewin, 1978).

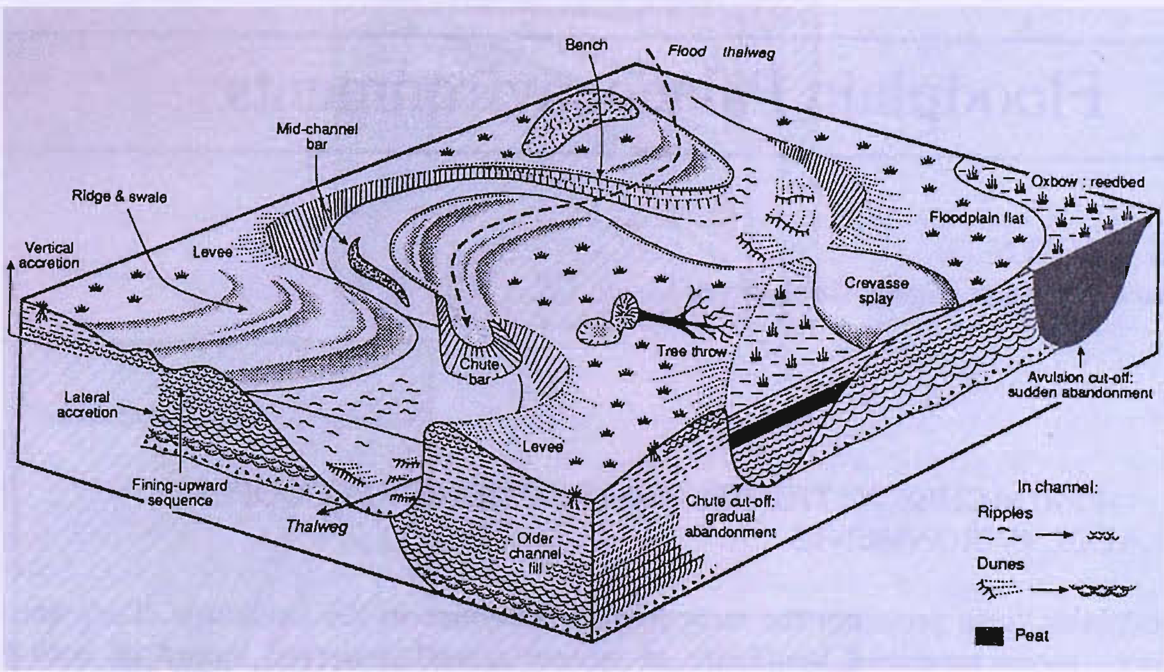

Figure 3.16 Block diagram showing chutes across point bars, from Brown (1996 p96).

Warner (1997) discusses chute development in southeast Australia in relation to hydrological regimes that alternate between flood-dominated regimes (FDRs: up to 50 years when high-frequency and high-magnitude floods prevail) and drought-dominated regimes (DDRs: flooding of lower frequency and magnitude for similar periods of time). The alteration between regimes is reflected in overbank adjustments through alluvial stripping. Three types of stripping were observed (see Figure 3.17): (i) stripping across meander chutes caused by overbank flows cutting across the floodplain at meander bends. A series of chute channels may develop, with depths varying from those reaching basal gravels to high-level, grassed depressions, containing some sand and wood; (ii) parallel chutes develop where a secondary channel is cut on one side of, and parallel to, the main channel to accommodate high flows;

and (iii) convex bank erosion which is found when stripping occurs adjacent to the main channel.

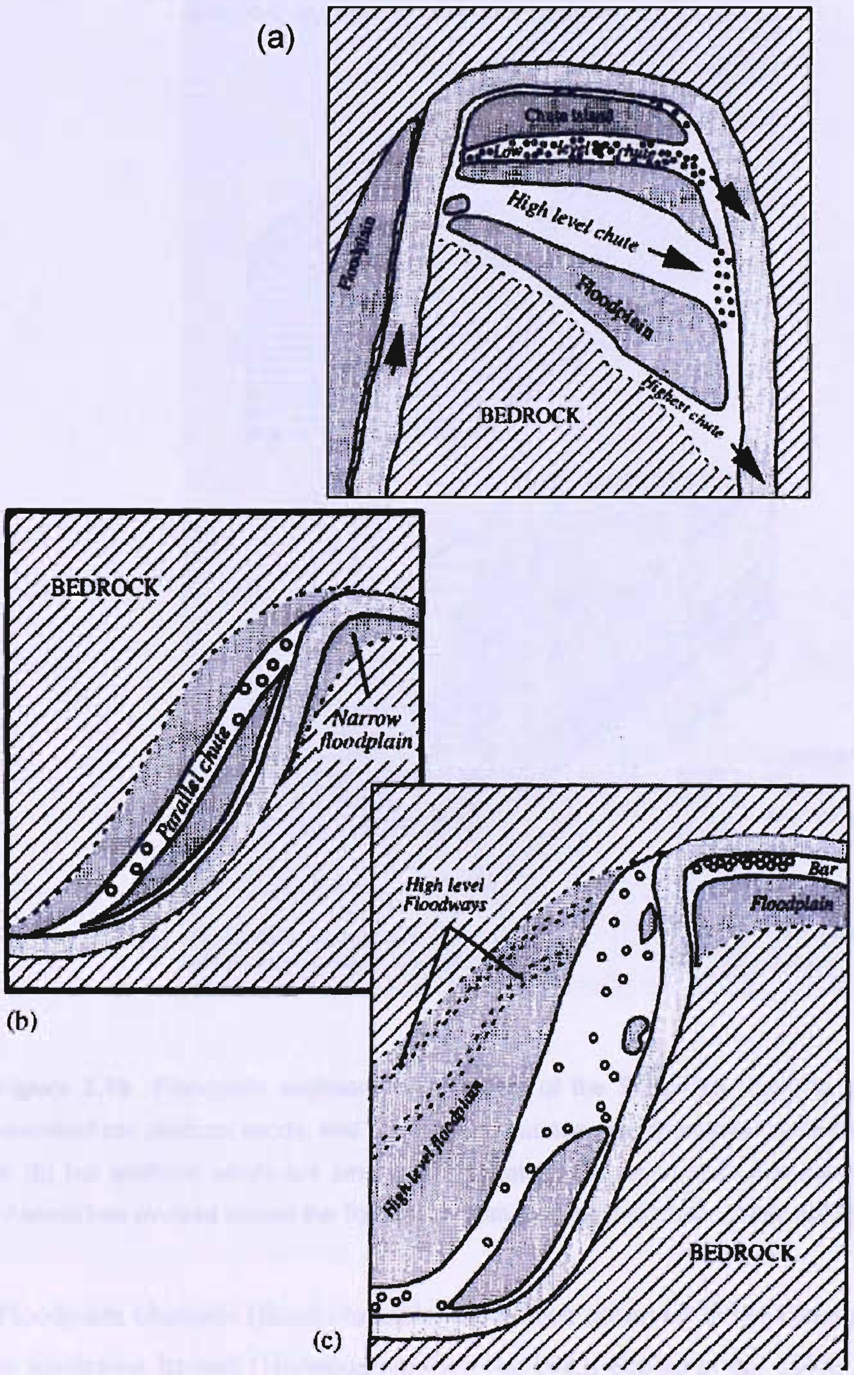

Figure 3.17 Types of alluvial stripping (a) across meander chutes (b) parallel chute (c) convex bank erosion and parallel chute, form Warner (1997 p269).

Chute channels perform an important role in floodplain development on the Squamish River, a high-energy, gravel-bed river in British Columbia (Brierley and Hickin, 1992). Brierley and Hickin (1992) suggest that chute channels develop on bars and strip away coarse bar deposits, which are then in-filled with low-energy, vertically accreted fine deposits, resulting in a layer of fine deposits on top of coarse alluvial gravels (Figure 3.18).

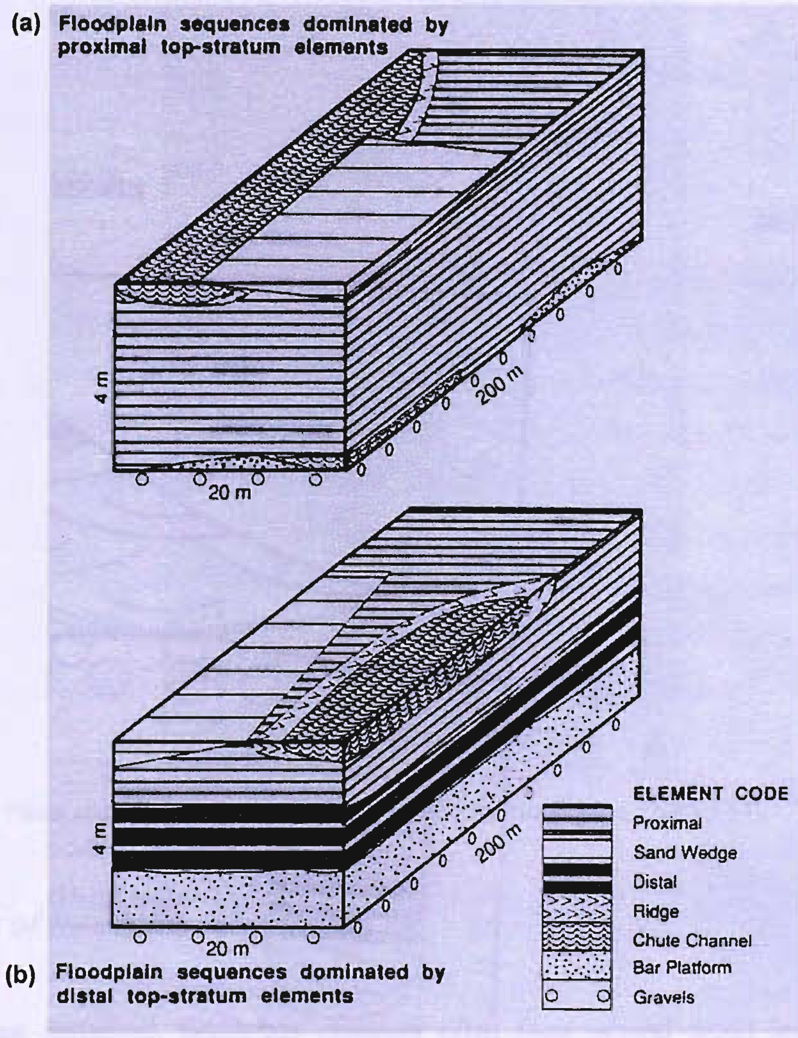

Figure 3.18 Floodplain sedimentology models of the Squamish River, in (a) chute channels have reworked bar platform sands, and floodplain sequences are dominated by vertically accreted fine sands; in (b) bar platform sands are preserved beneath distal top-stratum fine sands and silts, as the main channel has avulsed across the floodplain, from Brierley and Hickin (1992 p385).

Floodplain channels (flood channels) have been observed in the Gearagh, a floodplain forest in southwest Ireland (Harwood and Brown, 1993; Brown *et al.*, 1995; Brown, 1997) (Figure 3.19). The main channel pattern is anastomosing, with flood channels distributing discharge and energy across channels during floods (Brown *et al.*, 1995). These channels are thought to develop by a combination of headward and surface erosion (Harwood and Brown, 1993;

Brown *et al.*, 1995; Brown, 1997) as follows: (i) water backs up upstream of wood jams; (ii) tree root masses and tree throw pits (Table 3.3) control velocity distributions and partition and concentrate overbank flow into flood channels; (iii) flood channels advance by headward scour until impeded by tree roots.

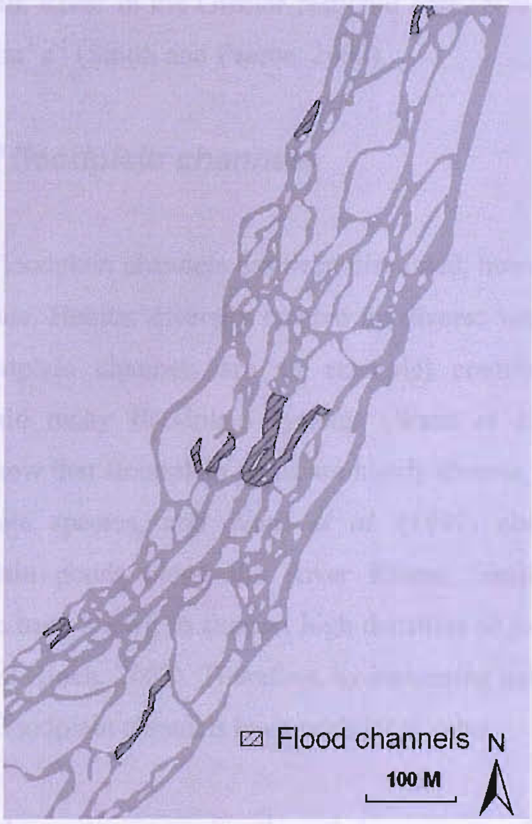

Figure 3.19 Flood channels in the Gearagh, adapted from Brown *et al.* (1995 p 57).

Location of floodplain channels

As has been discussed, floodplain channels often form around wood jams (Keller and Swanson, 1979; Jeffries *et al.*, 2003; Brummer *et al.*, 2006) and across meander necks (Gay *et al.*, 1998; Smith and Pearce, 2002). However, little research has focused upon what factors control their precise location, although Gay *et al.* (1998) and Smith and Pearce (2002) suggest that the location is determined by in-channel blockages; Brown (1996) argues that it is determined by tree throw; Piégay *et al.* (1998) suggest that trees and wood accumulations on the floodplain determine the location of floodplain channels, and Fagan and Nanson (2002) propose that it is determined by floodplain topography. Thus there appear to be different drivers determining the precise location of floodplain channels depending on the specific environment.

The development of floodplain channels often appears to rely on some form of channel-blockage or a tight meander bend to force flow onto the floodplain in order to scour floodplain channels. Therefore, floodplain channels are likely to be most common in small, sinuous streams which are easily blocked, particularly by wood jams. However, floodplain channels are not confined to small streams, for example they are associated with ice accumulations in the Milk River in the Glacier National Park, NW Montana, a river whose discharge can reach 220 m^3 s^{-1} (Smith and Pearce, 2002).

Ecological value of floodplain channels

The geomorphology of floodplain channels has been discussed, however, floodplain channels also have ecological value. Habitat diversity created by diverse water bodies within a river system (of which floodplain channels are an example) contributes to high levels of biodiversity found within many floodplain systems (Ward *et al.,* 1999). For example, Williams *et al.* (2003) show that floodplain pools are highly diverse, supporting a large range of plant and invertebrate species, and Ward *et al.* (1999) observed rich invertebrate assemblages in floodplain ponds along the River Rhone. Similarly, side-channels and floodplain channels have been shown to support high densities of juvenile salmon (e.g. Roni *et al.,* 2002; Giannico and Hinch, 2003). Therefore, by increasing habitat diversity, and hence floodplain biodiversity, floodplain channels have ecological value.

This section has focused on processes of sediment deposition and erosion on floodplains. Locations and processes of sediment deposition and erosion, and the influence of vegetation on these processes have been discussed, along with resulting geomorphological features, particularly floodplain channels.

3.5.5 Vegetation and physical and ecological processes

Vegetation influences physical and ecological processes operating on forested floodplains (see Table 3.6). The influences of vegetation on processes of sediment deposition and erosion have been discussed in the previous two sections. In the past these interactions were largely ignored due to difficulty in quantifying them (Hickin, 1984). Physical processes also influence vegetation. In ecological terms, physical processes can be viewed as disturbances, e.g. flooding, sediment deposition and erosion. These processes influence floodplain geomorphology and therefore habitat (e.g. the type of landform and characteristics of associated sediments), and hence determine the type of vegetation that can be established and persist in different areas of the floodplain (Hughes, 1997).

Table 3.6 Influences of vegetation on physical and ecological processes on forested floodplains and their rivers.

Main type of process	Vegetation function	Reference
Physical	Source of wood that physically interacts with water & sediment.	Gregory et al., 1991; Fetherston et al., 1995.
Physical	Provides storage sites for organic matter, water & sediment.	Gregory et al., 1991; Gurnell et al., 2002.
Physical	Stabilises floodplains by binding sediment & increases sedimentation by retarding water velocity as it passes over it.	Featherstone et al., 1995 Friedman et al., 2005.
Physical	Bank vegetation creates marginal deadwaters in the channel around tree roots and fallen trees.	Newson et al., 1998.
Physical	Influences channel bed and bank erosion & deposition.	Hickin, 1984; Gregory, 1992; Hughes, 1997; Lawler et al., 1997; Bendix & Hupp, 2000; Wallerstein, 2003.
Ecological / Physical	Shades floodplain & channel.	Gregory et al., 1991.
Ecological	Source of particulate organic matter.	Gregory et al., 1991; Harmon et al., 1986; Gurnell et al., 2002.
Ecological	Regulates nutrient storage & transformation.	Harmon et al., 1986; Gregory et al.,1991

An example of interactions and feedbacks between physical processes, floodplain characteristics and vegetation follows (Figure 3.20): floods help form floodplain topography via erosion and deposition, but the distribution of floodwater over the floodplain is influenced by the topography (Nicholas and Walling, 1997a) (Figure 3.20a). When vegetation is considered (Figure 3.20b) the interactions are further complicated: physical characteristics of the floodplain such as sediment size and moisture content influence vegetation (Winterbourn and Townsend, 1980; Hughes, 1997), which in turn affects the physical processes of deposition and erosion, thus the cycle continues. Friedman *et al.* (2005) for example, describe how sediment deposition and forest growth on the Rio Puerco, New Mexico, are promoted by each other; sediment deposition provides an ideal seed bed for tamarisk forest (*Tamarix ramosissima*), which in turn reduces flow velocities and so increases bank stability and promotes sediment deposition.

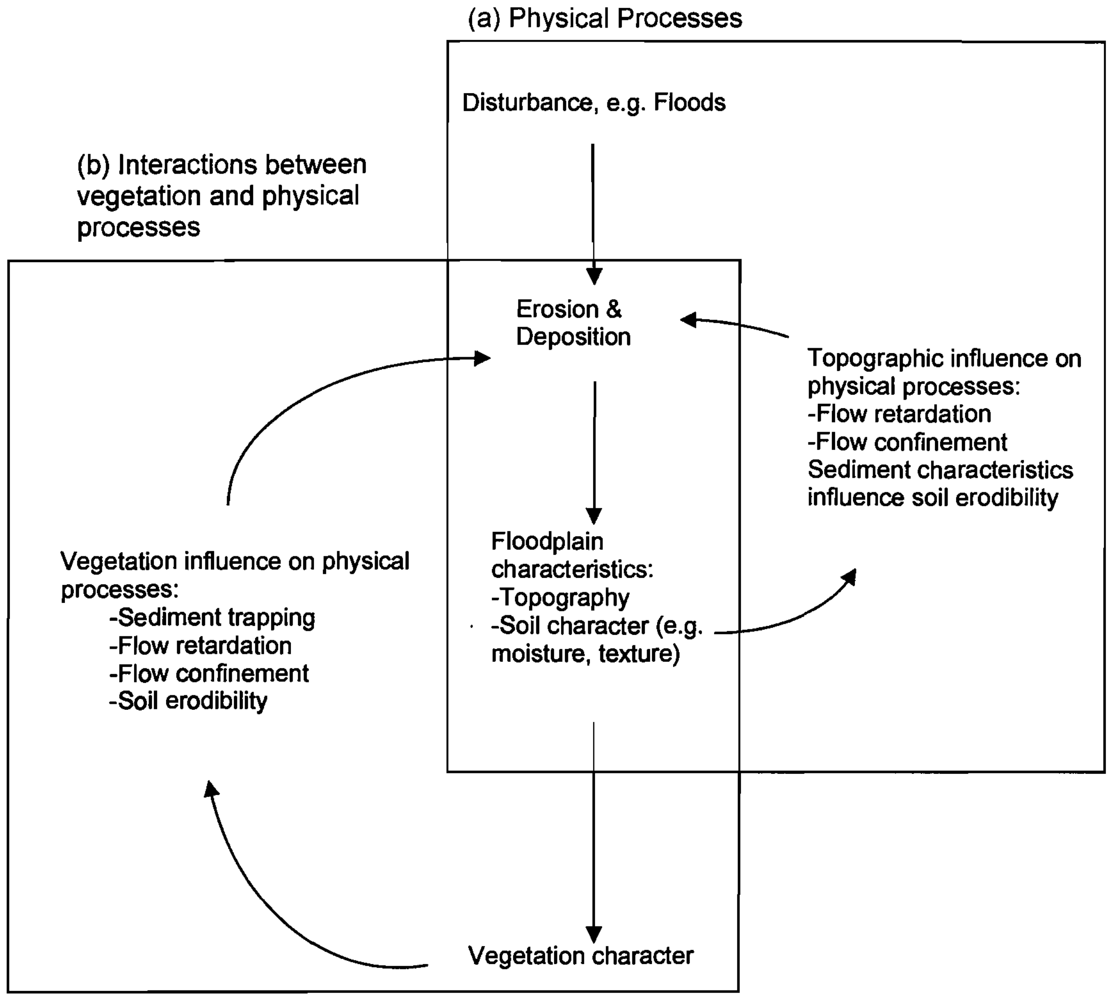

Figure 3.20 (a) Interactions between disturbances and floodplain characteristics; (b) interactions complicated by vegetation.

Floodplain disturbances, such as flooding, that promote habitat diversity on forested floodplains, are dependent upon channel-floodplain connectivity. Connectivity can be defined as "the ease with which organisms, matter or energy, traverse the ecotones between adjacent ecological units" (Ward *et al.,* 1999 p129). Hydrological connectivity (Amoros and Bornette, 2002) refers to the degree to which water bodies on a floodplain are connected by water pathways to the channel. In this thesis, however, channel-floodplain connectivity focuses mainly on the ability of in-channel water to flow onto its floodplain during high flows. As flood disturbance is often defined by the degree of channel-floodplain connectivity, the intermediate disturbance hypothesis can be understood in terms of connectivity, whereby very high and very low levels of connectivity reduce habitat diversity and hence biodiversity, with maximum biodiversity existing in areas of intermediate connectivity (Ward *et al.,* 1999). This hypothesis explains high habitat diversity found on undamaged forested floodplains, where channel-floodplain connectivity is generally moderate with floodplains receiving overbank flow on a number of occasions per year and local factors (e.g. wood jams) increasing this frequency; and low habitat diversity found on floodplains that are disconnected from their channel and on floodplains that are inundated by water on a frequent basis, for example on braided rivers. River control measures, such as channelisation, reduce channel-floodplain connectivity and hence floodplain geomorphological activity, which in turn limits sites available for vegetation regeneration. For example, the numbers of black poplars (*Populus nigra* L.) found on European floodplains have been markedly reduced because river control influences the sex ratios of black poplar by altering the habitat available to male and female plants which have different hydrological and sedimentological requirements (Hughes *et al.*, 2000). A study on an alluvial island in the River Great Ouse, England indicated that female and male black poplar have overlapping tolerances to sediment type in terms of porosity and moisture availability, but males are more tolerant of desiccation than females, and females prefer wetter and more nutrient-rich sites, especially sites containing nitrogen and phosphorous, possibly due to their need for a greater reproductive biomass than males (Hughes *et al.,* 2000). Therefore the drying out of a floodplain from reduced channel-floodplain connectivity may reduce the potential for regeneration of female plants of black poplar, thereby reducing overall diversity.

Nutrient buffering and vegetation type

Nutrient limitation on forested floodplains may control the type of vegetation on floodplains and therefore associated processes. However, vegetation can also buffer excess nutrients.

Prolonged overbank flooding may lead to anaerobic soil conditions that promote denitrification of nitrates into gaseous nitrogen by denitrifying bacteria (Dobson and Frid, 1998). A lack of nitrate may limit vegetation growth on forested floodplains (Dobson and Frid, 1998), and therefore "wetland communities typically support plant species with alternative sources of nitrates, including, in Europe, alder (*Alnus glutinosa*) and bog myrtle (*Myrica gale*) which maintain a symbiotic relationship with nitrogen-fixing bacteria in their root nodules" (Dobson and Frid, 1998 p166). Thus a specific type of vegetation may be dominant and its particular physical structure will influence physical processes accordingly.

Alternatively, nutrients may be in excess in some streams, for example due to runoff from agricultural land, which may lead to "blooms" of algae growth and water eutrophication. Wetlands are valuable for improving water quality and are efficient at buffering the effects of excess nutrients (Gregory *et al.,* 1991) and can improve groundwater quality (Dobson and Frid, 1998). A small proportion of excess nutrients are used by plants, for example phosphates; excess nitrates are converted into gaseous nitrogen by nitrifying bacteria, and lost into the atmosphere; and vegetation may trap nutrients in suspension causing them to settle into the sediment (Dobson and Frid, 1998). From research on the Lubrzanka River, Poland, Zalewski *et al.* (1998) suggest that reaches with diverse habitat structure, e.g. pools and riparian ecotones, may reduce the risk of eutrophication by efficiently consuming phosphorous; compared to less diverse sandy-bottomed channelised reaches, which showed much lower phosphorous-consumption abilities. Similarly, Doyle *et al.* (2003) suggest that reaches with high habitat diversity have higher levels of nutrient, sediment, and organic matter retentiveness, and therefore have more potential for storage and consumption.

The nutrient buffering potential of different floodplain environments will influence biodiversity and therefore needs to be accounted for when attempting to understand the interactions between ecological and physical processes.

Organic matter cycling

Floodplain forests are characterised by (a) high levels of nutrient and matter processing, and (b) high biodiversity. Nutrient and matter processing provide an important source of organic material for aquatic ecosystems (Gregory *et al.,* 1991). High biodiversity ensures varied types of organic material, which is therefore likely to promote a wide variety of invertebrates and higher organisms (Smock *et al.,* 1989). Energy for nutrient / matter processing is derived from sunlight, and is transformed into organic substrates by photosynthesis (Allan, 1995). This energy, in the form of organic material, is then available for cycling through different stages in the aquatic ecosystem. In small forested streams the input of coarse particulate organic matter (CPOM), such as leaf litter, is the primary source of energy to the aquatic ecosystem (Bilby and Likens, 1979; Winterbourn and Townsend, 1980). Once it is in the stream, CPOM (>1 mm) is degraded to fine particulate organic matter (FPOM) (1 mm to 0.45 μm), then to dissolved organic matter (DOM) (<0.45 μm), and ultimately to carbon dioxide through mechanical and biological processes (Bilby and Likens, 1979). Allan (1995) summarises the stages in leaf decay to FPOM: during the first stage leaves fall, become wet, and soluble organic and inorganic constituents are leached out; the second stage is characterised by a period of microbial colonization and growth; during the final stage leaves are fragmented mechanically and by invertebrates into FPOM.

Chemical constituents of organic substrates cycle between the environment and the biota. "Nutrient cycling describes the passage of an atom or element from a phase where it exists as dissolved available nutrient, through its incorporation into living tissue and passage through perhaps several links in the food chain, to its eventual release by excretion and decomposition and re-entry into the pool of dissolved available nutrients" (Allan, 1995 p295). Wood is an important component in nutrient cycles and carbon budgets as large fluxes of organic matter occur in and out of the pool of nutrients that wood represents; wood is therefore a persistent stable nutrient supply to many streams (Harmon *et al.*, 1986). Nutrients that are generated at one location typically may be transported downstream before being re-cycled. Therefore, although nutrients are re-used many times, each cycle is displaced downstream from the previous one. The term 'nutrient spiralling' describes the inter-dependent processes of nutrient cycling and downstream transport (Webster and Patten, 1979, cited in Allan, 1995; Winterbourn and Townsend, 1980). In areas of high channel-floodplain connectivity, overbank flows deposit nutrients and seed propagules onto the floodplain (Hughes, 1997), promoting vegetation regeneration and the production of more organic material through photosynthesis; thus organic matter cycling continues, and there is a turnover of vegetation that influences and is influenced by physical processes.

Ecological functions of large wood

Organic material in the form of large wood increases channel-floodplain connectivity, promotes nutrient cycling, and has an important influence on physical habitat (Gippel, 1995a) and ecology (Gurnell *et al.,* 2002). Large wood creates heterogeneous habitats (Gurnell *et al.,* 2002) which are important for many terrestrial and aquatic animals such as reptiles, birds, mammals (Harmon *et al.,* 1986), macroinvertebrates and fish (Lienkaemper and Swanson, 1986; Keller and Macdonald, 1995; Keller *et al.,* 1995; Piégay and Gurnell, 1997). For example the pools created by large wood are important refugia for anadromous fish (Keller *et al.,* 1995; Abbe and Montgomery, 1996; Lehane *et al.*, 2002). Wood is a source of CPOM (Allan, 1995; Gurnell *et al.,* 2002), and a substrate for autotrophs, including green algae, diatoms, blue-green algae, lichens, liverworts, mosses, clubmosses, horsetails, ferns, gymnosperms, and angiosperms (Harmon *et al.,* 1986).

Large wood is also important for floodplain ecology, although this has received less research than in-channel ecology. Large wood on floodplains directly influences ecology, for example by providing habitats, sites for nutrient cycling, tree seedling establishment, nitrogen fixation by bacteria and fungi in the wood and shade for microsites (Harmon *et al.,* 1986). Buried wood may also have great ecological importance (Gurnell *et al.*, 2000).

Retention / residence times of organic material

"Geomorphic and hydraulic processes, riparian vegetation, and aquatic biota are linked functionally through processes of retention" (Gregory *et al.,* 1991 p547), and retention times provide a good method for understanding the interactions between physical processes and vegetation. Ecological processes within lotic environments depend upon temporary retention and recycling of nutrients (Triska *et al.,* 1989). Residence times are defined here as the length of time that material remains within a stream or reach, and retentiveness is the ability of a stream or reach to keep material within it. If organic material is to be used by aquatic biota it needs to be retained within a stream, as does inorganic matter to form physical habitats (Gregory *et al.,* 1991). High retentiveness allows organic matter to accumulate and to be processed to small particles and dissolved organic carbon (DOC) before it is transported downstream (Bilby and Likens, 1980; Bilby, 1981; Naiman, 1982; Allan, 1995). "Shredders", who feed on CPOM, appear in greater abundance in streams or reaches which are retentive, i.e. have long residence times (Winterbourn and Townsend, 1980). High retentiveness also increases the amount of organic matter respired by consumers (Allan, 1995) and ecosystem processing is enhanced relative to downstream export (Allan, 1995). Undisturbed watersheds are highly retentive (Naiman, 1982), and measures of habitat variability, channel morphology and channel dynamics can be revealed by nutrient, sediment, and organic matter retention times (Doyle *et al.,* 2003). "In the absence of retention devices the stream functions more like a pipe, allowing inputs to be flushed from the system" (Allan, 1995 p270), leaving less opportunity for nutrient cycling, less biodiversity, less diverse physical habitats and altered channel and floodplain processes.

High geomorphological complexity has been shown to increase retention of organic matter, (e.g. Sheldon and Thoms, 2006), as have various strictures such as wood jams (Bilby and Likens, 1980; Daniels, 2006), trees and large rocks (Harmon *et al.,* 1986), shallow areas of channel over bars, and narrow sections of channel (Braudrick *et al.,* 1997). Braudrick *et al.* (1997) propose that a stream's ability to retain wood of a given size is a function of its 'debris roughness,' (or 'wood roughness') which varies with the ratios of wood diameter/channel depth and wood length/channel width. The authors acknowledge, however, that ideally other factors need to be included in calculating 'debris roughness,' for example obstruction spacing and sinuosity.

Large wood as a retention device

In forested rivers, large wood and wood jams play an important role in increasing retention times of water, sediment, nutrients, organic matter and wood. Large wood in the channel creates areas of low flow-velocity by decreasing shear stress through the creation of step-pools (Fetherston *et al.,* 1995). These low shear stress areas become sites for sediment storage and organic and nutrient storage and processing (Harmon *et al.,* 1986; Smock *et al.*, 1989; Fetherston *et al.,* 1995; Keller *et al.*, 1995; Piégay & Gurnell, 1997; Lehane *et al.,* 2002). Large wood buffers downstream pulses of sediment, allowing it to 'trickle' through, except when catastrophic flushing occurs (Swanson and Lienkaemper, 1978; Megahan, 1982). For example, Smith *et al.* (1993) observed a four-fold increase in bedload transport resulting from removal of large wood from a small gravel-bed stream in western North America. Wood jams are particularly important for organic matter storage after autumn leaf fall (Smock *et al.,* 1989). Increasing organic matter and nutrient storage increases energy and nutrient availability to aquatic biota, which potentially increases secondary production (conversion of plant material into animal biomass) (Smock *et al.,* 1989; Piégay and Gurnell, 1997). In an experiment in headwater streams on the Coastal Plain of southeastern USA, Smock *et al.* (1989) found that wood jams were very important for reducing the distance travelled by leaves: 99% of leaves were retained in a section of the Buzzards Branch stream, southeastern USA, which had wood jams, whereas only 11% were retained in a section with no jams (see Table 3.7). Wood jams therefore increase retention of CPOM (Bilby and Likens, 1980; Bilby, 1981), and hence increase the potential for nutrient cycling and detritus processing (Winterbourn and Townsend, 1980). Low velocity areas associated with large wood provide sites for propagule colonisation which may create islands of riparian vegetation (Fetherston *et al.,* 1995). As vegetated islands establish they further increase local roughness which slows flow, further increasing the suitability for vegetation colonisation (Fetherston *et al.,* 1995), and resulting in an overall increase in wood, water and sediment retention.

Controls on residence times of wood

Wood retention is controlled by a number of different variables, such as the nature and management of the riparian zone (Gregory *et al.,* 1991) and active channel (Gurnell *et al.,* 2000), the flow or stream power regime, and location within the catchment (Gregory *et al.,* 1991).

Wood breaks down and decays very slowly, with estimated breakdown times dependent on the size of wood (twigs less than 1cm decay in about 5-10 years, wood 5-10 cm diameter in about 50 years, and larger trees in 100-250 years) (Allan, 1995). The rate of wood decomposition depends on climate, oxygen availability, exposure or burial (Allan, 1995), tree species and density (Gurnell *et al.,* 2002). Due to these slow decay rates, wood mobility must play an important role influencing residence time. Mobility may also lead to the break up of smaller pieces of wood, thereby increasing decomposition rates, and further increasing mobility.

Movement of wood is a complex process determined by a number of variables, including: flow regime (Gurnell *et al.,* 2002), wood characteristics, e.g. size, shape, density (buoyancy) (Gurnell *et al.,* 2002), length (Lienkaemper and Swanson, 1986), burial (Harmon *et al.*, 1986) (which is influenced by calibre and quantity of sediment mobilised, transported and deposited (Gurnell *et al.,* 2002)), rooting (Harmon *et al.*, 1986), stage of decay (Harmon *et al.*, 1986; Gurnell *et al.,* 2002), position and orientation (Harmon *et al.*, 1986), and channel characteristics, e.g. planform, dimensions, flow velocity distribution, and geomorphological characteristics (Gurnell *et al.,* 2002). The size of the stream in relation to length of wood plays an important role in the retention and effect of wood on the stream (Swanson and Lienkaemper, 1978; Hickin, 1984; Harmon *et al.*, 1986; Gurnell *et al.*, 2002). In small rivers, for example, where channel width is less than the average length of wood, pieces of wood do not tend to travel far from where they enter the channel, whereas in large rivers (where the channel width is larger than all the wood entering the channel) wood is retained for shorter periods along channel margins (Gurnell *et al.,* 2002). In small temperate streams in the New Forest, for example, the proportion of partial jams increased and the proportion of complete jams decreased with increasing channel size due either to a larger river being able to transport larger pieces of wood (Piégay and Gurnell, 1997) or to an absence of wood. In larger rivers, stream discharge becomes an important factor in wood retention, and intermediate sized pieces of wood are only retained if structures (e.g. trees, channel morphology) are available to brace them against the flow (Gurnell *et al.,* 2000). In high energy environments there are usually fewer potential sites for wood deposition, hence residence time of wood tends to be relatively short (Piégay and Gurnell, 1997).

In small streams, large wood retention is predominantly controlled by input and decay. Wood input to the floodplain and channel is either chronic (Smith *et al.,* 1993), whereby small amounts of wood are added at frequent intervals due to natural tree mortality or gradual bank undercutting (Fetherston *et al.*, 1995), or episodic (Smith *et al.,* 1993), whereby a large amount of wood may be added infrequently due to catastrophic windthrow, fire or severe floods (Fetherston *et al.*, 1995). Wood input may also occur through transport from upstream reaches (Swanson and Lienkaemper, 1978; Fetherston *et al.*, 1995; Gurnell *et al.*, 2002), and remobilisation from the floodplain (Piégay *et al.*, 1998). Riparian input of wood depends on connectivity of channel and floodplain, on distance from the channel (Harmon *et al.*, 1986) and on vegetation characteristics.

Tree mortality is dependent on tree age, wind, fire, insects, disease, suppression and competition, stream undercutting of banks, and mass movements (Harmon *et al.*, 1986). Vegetation species also affects the residence time of wood, for example, species that reach larger sizes produce longer-lived wood than smaller ones. Therefore, conifers produce longer-lived wood than hardwood species, and conifers also have slower decay rates (Fetherston *et al.*, 1995).

Input of wood into rivers varies temporally on seasonal, annual, and successional time scales. For example, Gregory (1992) estimated that the input of large wood from the 1987 hurricane led to wood jam accumulations on a small stream in the New Forest, UK, of 42.8 tonnes compared with 4.28 tonnes between 1982 and 1983. Little wood is contributed in a year after a big event, and older trees contribute more large wood than younger ones (Harmon *et al.*, 1986; Smock *et al.*, 1989). Therefore, input of large wood and the significance of jams to stream functioning are influenced by successional changes in riparian vegetation (Smock *et al.*, 1989). However, successional dynamics of riparian vegetation are in turn influenced by the retention time of wood, as large wood traps sediment on which vegetation colonises, and acts as 'nurse logs' that woody species colonise (Fetherston *et al.*, 1995).

Once formed, wood jams are self perpetuating, i.e. once present in the channel they encourage the development of more wood jams through a number of processes (Figure 3.21). Stable wood jams play an important role in trapping mobile wood (Keller *et al.*, 1995; Piégay and Gurnell, 1997; Abbe and Montgomery, 2003); the higher the number of stable wood jams in a reach, the slower wood transport is likely to be because pieces of wood are unable to by-pass the wood jams and therefore become incorporated into them, rendering them even more impermeable, hence more efficient. For example, Piégay and Gurnell (1997) found that a large number of jams developed on the Highland Water immediately after clearing of the large wood in the channel; possibly illustrating the high mobility of wood when no jams are present to trap it, or that trapping sites became available again. Furthermore, as wood jams build up and become more effective, they encourage overbank flow (Brown, 1998; Abbe and Montgomery, 2003), providing the opportunity to transport wood from the floodplain into the channel, which may be incorporated into wood jams, rendering them more effective. Wood jams also focus flow on certain parts of the bank, increasing local erosion (Gregory, 1992; Downs and Simon, 2001) which may cause undercutting and tree fall, thus increasing wood recruitment to the channel (Keller *et al.*, 1995).

Overall then, large wood, especially in the form of wood jams, is a function of a complex set of biotic and abiotic variables that plays a central role in the connectivity and ecological processes of forested floodplains.

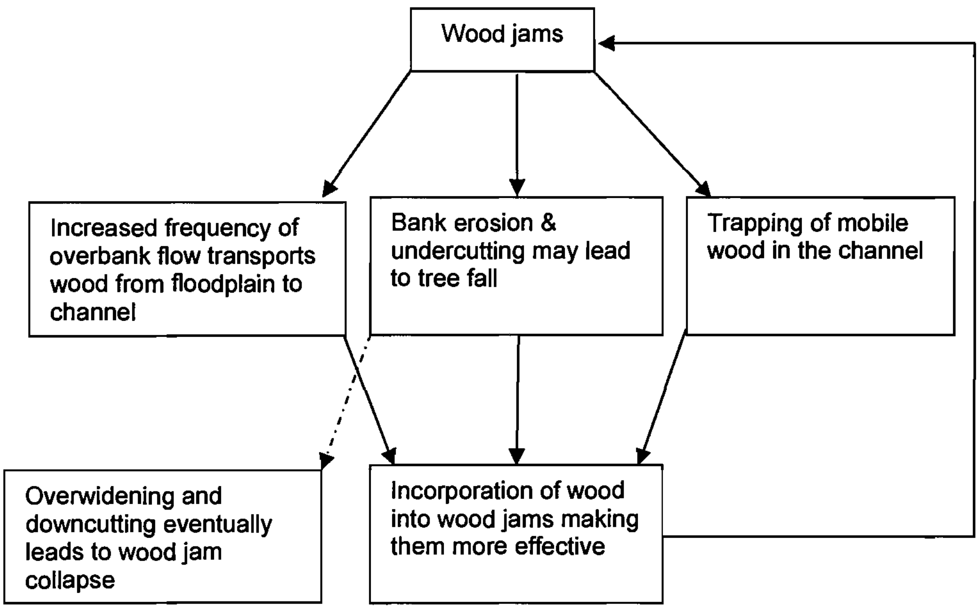

Figure 3.21 A conceptual model of the self-perpetuation of wood jams.

Methods of studying retention times of organic material

It is imperative to understand residence times of wood because these are the fundamental units of wood jams found within the channel and on the floodplain. Wood *enters* a river or reach either directly from fallen trees or branches in the channel and on the floodplain, or it is transported by the river from upstream (Swanson and Lienkaemper, 1978; Fetherston *et al.*, 1995; Gurnell *et al.*, 2002), or it is emplaced by humans; it is *stored* within a reach for varying lengths of time, ranging from minutes/hours to decades or even centuries; it *leaves* a river or reach either through decay, through downstream transport (Gurnell *et al.*, 2002), through being rafted onto the floodplain, through incorporation into floodplain sediments, or through direct management. Thus residence times of wood are dependent on wood loadings (Swanson and Lienkaemper, 1978), mobility (Bilby, 1984), and decay rates (Allan, 1995).

Consequently, different methods have been used to infer retention times of organic material, for example, transport distances (Bilby, 1984), transport loads (Kronvang, 1992) and budgets (Keller *et al.,* 1995), which leads to difficulties comparing studies from different regions (Table 3.7).

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Table 3.7 Different methods used to estimate retention of organic material.

Organic matter (size not specified)	Location	Disturbance	Reference
Load transported (tonnes/year)			
300	Aarhus river, Denmark	Strongly regulated	Kronvang, 1992
655	Lyngbygaards River, Denmark	Strongly regulated	Kronvang, 1992
Mean annual storage in wood jams (g/m^3)			
922	Colliers Creek, coastal plain of southeastern USA	Unknown	Smock et al., 1989
3356	Buzzard's Branch, coastal plain of southeastern USA	Unknown	Smock et al., 1989
Wood (various sizes)			
Age			
12-112 yrs	Headwater streams in the great Smokey Mountains, North Carolina	Undisturbed	Hart, 2002
70 yrs	Shaheen River in Maybeso Creek, on Prince of Wales Island, Alaska	Unknown	Bryant, 1980
100 to more than 200 yrs	Tributaries of Redwood Creek, northwestern California	Undisturbed	Keller et al., 1995
100-200 yrs	A guess for average rates	n/a	Allan, 1995
240 +/- 40 yrs	Tonghi Creek, southeastern Australia	Undisturbed	Webb & Erskine, 2003
10 000	Stanley River, Tasmania	Undisturbed	Nanson et al., 1995
Mean distance moved (m) of wood / dowelling			
0.4 - 80	Streams in the Southern Appalachian Mountains in western North Carolina, USA	Semi-natural & logged	Webster et al., 1994
4.78	Gravel-bed flume	n/a	Braudrick & Grant, 2001
20-175	Turitea Stream, Palmerston North, New Zealand	Some semi-natural sections & some disturbed	James & Henderson, 2005
73.25	Salmon Creek, Washington	After in-channel wood had been cleared	Bilby, 1984
Wood loadings			
0.129 m^3 m^{-2} of channel	Tributaries of Redwood Creek, northwestern California	Disturbed	Keller et al., 1995
0.167 m^3 m^{-2} of channel	Tributaries of Redwood Creek, northwestern California	Undisturbed	Keller et al., 1995
Majority of values 100-1000 m^3 ha^{-1}		Little/no disturbance	Gippel, 1995a
193 m^3 ha^{-1}	Creeks on the Prince of Wales Island, Alaska	Unknown	Swanson et al., 1985 cited in Harmon et al., 1986
576 m^3 ha^{-1}	Tonghi Creek, southeastern Australia	Undisturbed	Webb & Erskine, 2003
677.77 m^3 ha^{-1}	Creeks in coastal British Columbia, Canada	Unknown	Hogan, 1985 & Toews & Moore, 1982 both cited in Harmon et al., 1986

	Location	Disturbance	Reference
Storage			
65% of the annual input of wood remained and 35 % was exported out of the system	Highland Water, New Forest	Little disturbance	Gregory, 1992
CPOM			
% of leaves retained in a reach			
99% of leaves were retained in a section of river which had wood jams	Coastal plain of southeastern USA	Little disturbance: pre-wood jam removal	Smock et al., 1989
Only 11% were retained in a section with no dams.	Coastal Plain of southeastern USA	Disturbed: post wood jam removal	Smock et al., 1989
Distance travelled by leaves			
Leaves and small wood may travel <10 m and are then retained or buried, unless flood, then may travel >100m		Unknown	Allan, 1995
3.6 m in 1st order streams, 16.6 in 3rd order streams	Agüera basin, northern Spain	Unknown	Larrañaga et al., 2003
Mass exported			
58kg dry mass ha^{-1}	Hubbard Brook, New Hampshire	Little disturbance: pre- wood jam removal	Bilby, 1981
210kg dry mass ha^{-1}	Hubbard Brook, New Hampshire	Disturbed: post wood jam removal	Bilby, 1981
FPOM			
Mean transport distance			
5-10 m under very low flows in small channels		Unknown	Webster et al., 1987 and Jones and Smock, 1991, cited in Allan, 1995:
100-200m	A second order stream in New York	Unknown	Miller and Georgian, 1992, cited in Allan, 1995.:
630m	Salmon River headwaters, velocity 0.29m/s	Unknown	Cushing et al., 1993 cited in Allan, 1995
800m and 580m	A small Idaho stream, velocity 0.27 m/s	Unknown	Cushing et al., 1993 cited in Allan, 1995
Average transport 4-8 km day^{-1}		Unknown	Cushing et al., 1993 cited in Allan, 1995
Annual dry mass exported			
738 kg	Hubbard Brook, New Hampshire	Little disturbance: pre-wood jam removal	Bilby, 1981
4550 kg	Hubbard Brook, New Hampshire	Disturbed: post wood jam removal	Bilby, 1981

Wood loading or budgets provide insights into the flow of material through a river system. As channel width and drainage area increase downstream, wood loading generally decreases (Keller *et al.,* 1995). In temperate streams of the New Forest, Gregory (1992) estimated that 65% of the annual input of wood remains and 35% was exported out of the system (Table 3.7). "The ultimate export of large organic debris occurs in the form of fine particulate and dissolved matter resulting from breakdown of wood by the action of decomposer organisms, invertebrates, and snails. Organic matter in a log in a stream high in the mountains will eventually pass through many organisms' gut tracks in the course of transport down river to the sea" (Swanson and Lienkaemper, 1978 p3).

Mobility of wood can be estimated over short distances by measuring the distance moved over a period of time (rapid movement represents a short residence time). Bilby (1984) monitored wood movement in Salmon Creek, Washington, in order to study the effects of clearing wood from the channel after logging had taken place. 74 pieces of large wood were tagged and monitored over the winter of 1980-81. During the first period of high flow, nearly 60% of tagged pieces moved. Movement was related to discharge, timing of high discharge events, morphology of channel and length of wood.

3.5.6 Summary

Pristine rivers are highly retentive, with most organic inputs being processed to small particles before they are released downstream (Naiman, 1982). River modifications such as channelisation have reduced the ability of many streams to retain organic material, making them function more like conduits, allowing inputs to be rapidly flushed through the system (Bilby and Likens, 1980; Gregory *et al.,* 1991; Allan, 1995; James and Henderson, 2005). Therefore, within modified rivers, there is less opportunity for organic material to be used as a food source; and the energy it contains is more easily lost from the system (James and Henderson, 2005). Restoration projects need to reverse this process and make streams more retentive (James and Henderson, 2005).

This review has demonstrated that, in forested floodplains, channel and floodplain geomorphology and ecology are intricately linked. In-channel geomorphological diversity promotes retention of organic material (Nakamura and Swanson, 1994; Allan, 1995; Braudrick and Grant, 2001) and the establishment of wood jams which are beneficial to stream ecology (Gurnell *et al.,* 2002). Wood jams also promote channel-floodplain connectivity (Gregory *et al.,* 1994; Jeffries *et al.,* 2003) and hence overbank deposition and erosion, leading to geomorphologically diverse floodplains (Jeffries *et al.,* 2003). The distribution of overbank flooding and sedimentation influences floodplain vegetation (Gregory *et al.*, 1985; Jeffries *et al.*, 2003), which in turn influences channel and floodplain geomorphological processes, e.g. through the development of wood jams.

3.6 Reference conditions

Based on the scientific literature, this chapter identified hydrogeomorphological and ecological processes that operate in natural (or semi-natural) forested floodplains, and discussed their interactions, enabling the identification of potential reference conditions that can be used to guide restoration of a forested floodplain. The following is a list of these reference conditions that floodplain forest restoration could aim to restore:

- Geomorphologically diverse channels with wood jams present (Gregory, 1992).
- Long residence times of organic material (specific length varies from one system to another) (Nakamura and Swanson, 1994; Allan, 1995; Braudrick and Grant, 2001), promoting high nutrient processing and diverse ecology (Gurnell *et al.*, 2002).
- Frequent overbank flow, particularly in the presence of wood jams (Gregory *et al.*, 1994; Jeffries *et al.*, 2003).
- Diverse floodplain geomorphological processes (overbank sediment deposition and erosion) creating complex floodplain geomorphology (e.g. floodplain channels) (Jeffries *et al.*, 2003).
- Diverse vegetation on the floodplain linked to geomorphological processes, e.g. seedlings establish in sediment deposits (Hughes *et al.*, 2000).

3.7 Research context

This literature review has identified a lack of scientific understanding of the hydrogeomorphological and ecological processes and interactions operating in forested floodplains, particularly in small, temperate, lowland forested floodplains such as those found in the New Forest. This understanding is essential in order restore such systems effectively. This thesis attempts to partially fill the identified research gap by furthering our understanding of the geomorphological processes, and the influence that vegetation has on geomorphological processes that operate on forested floodplains in the New Forest, southern England. This was achieved through monitoring the geomorphological performance of the LIFE 3 restoration project. A detailed study of hydraulics and hydrological and ecological processes and interactions is beyond the scope of this thesis, but research is currently being conducted into these processes by other researchers (e.g. see Sear *et al.,* 2006; New Forest LIFE 3 Final Technical Report, 2006; Kitts, in prep).

As discussed in Chapter 1, this research aims to monitor floodplain geomorphological dynamics before and after the restoration of a small, temperate, lowland, forested floodplain, and in doing so, to increase current understanding of the geomorphological processes operating on forested floodplains. The objectives of the research are listed in Chapter 1.

Chapter 4. Methods and study site

4.1 Introduction

The aim of this chapter is to provide details of the LIFE 3 restoration project and the study site in which it was undertaken. The chapter starts with an overview of the methodological approach adopted in the thesis. It then discusses the background to the LIFE 3 restoration project, and describes restoration monitoring, monitoring techniques, and the importance of baseline data for restoration design and monitoring. An overview of the study site is then given, including information on its geology, topography, land use, vegetation and conservation status. Details of the LIFE 3 restoration project are then discussed, followed by descriptions of the research methodology and the specific study sites. The chapter concludes with a timeline of the restoration monitoring that was undertaken at each site.

4.2 Methodological approach

The following overall methodological approach was adopted in order to achieve the objectives set out in Chapter 4. Chapters 2 and 3 identified the research gap that this thesis addresses; namely to gain a greater understanding of geomorphological dynamics, and the influences of vegetation on geomorphological processes that operate on forested floodplains in the New Forest, through monitoring the geomorphological performance of the LIFE 3 restoration project. However, to set up the restoration monitoring, reference conditions in natural (semi-natural) forested floodplains needed to be established in order to identify which processes to monitor (Kondolf and Downs, 1996). General reference conditions were initially established from the scientific literature (Chapter 3 - Objective 1); they were refined to make them appropriate for the study site through field based investigations of semi-natural forested floodplains within the New Forest (Chapter 5 - Objective 2 (i)). These reference conditions were used to identify processes to monitor in order to identify the impacts of the restoration on floodplain geomorphological dynamics (Chapter 5 - Objective 2 (ii)). Monitoring of these processes took place before and after the restoration (Chapters 6, 7 and 8 – Objective 3). To determine if reference conditions were recreated by the restoration (or at least if processes are moving towards reference conditions), and to further our understanding of the processes that operate under reference conditions, monitoring was conducted at a restored site, a control site, and at semi-natural analogue sites. Finally, the restoration of floodplain processes was evaluated through the construction of; (i) a conceptual model of natural floodplain processes;

(ii) a conceptual model of restored floodplain processes; and (iii) an evaluation of the restoration, discussing constraints and recommendations (Chapter 9 - Objective 4).

4.3 Background

Since the 1840s, a large proportion of the streams in the New Forest (particularly those flowing through inclosures) have been periodically straightened and dredged in order to improve drainage (Tuckfield, 1980; Tubbs, 2001) and to allow conifers to be planted (Gurnell and Sweet, 1998). Straightening and dredging has resulted in habitat fragmentation, reduced ecological and geomorphological diversity in the streams, and it has triggered detrimental adjustment processes that affect reaches of previously good quality wet woodland (e.g. channel deepening and consequent disconnection of the channel and floodplain through upstream migration of knick points). Within these heavily modified reaches there has been very limited natural adjustment of channel planform and cross section, and these reaches are still characterised by reduced wood loadings and low habitat diversity (GeoData, 2003).

Since the mid-1980s, there has been a move away from further drainage and attempts have been made to restore some of the damage that the drainage works have caused to the streams and mires (Tubbs, 2001). LIFE 2 (*'Securing Natura 2000 objectives in the New Forest'*), for example, (which ran from 1997 to 2001) was an EU funded project that focused on restoring valley mires. During LIFE 2 it became apparent that the mires could not be restored effectively in isolation from the rest of the stream. This led to a third restoration project, LIFE 3 (*'Sustainable wetland restoration in the New Forest'*) (2002-2006), which was funded by the EU and UK project partners (English Nature, Environment Agency, Forestry Commission, Hampshire County Council, The National Trust and RSPB). LIFE 3 (see http://www.newforestlife.org.uk) aimed to secure and increase the extent of wet woodland and bog woodland within the forest. Monitoring the geomorphological dynamics resulting from the LIFE 3 restoration project forms the core of this thesis.

4.4 LIFE 3 Restoration monitoring

4.4.1 Restoration monitoring

Restoration philosophy and approaches have been discussed in Chapter 2. The need for monitoring and post-project appraisals which can be used for adaptive management (Brookes *et al.*, 1996b; Downs and Kondolf, 2002; Caruso, 2006) was highlighted, as was the fact that this step in the restoration process is often omitted (Kondolf, 1998; Downs and Kondolf, 2002; Holl and Cairns, 2002; Caruso, 2006), resulting in restoration projects unnecessarily repeating mistakes of past projects.

The ultimate aim of river restoration is to improve the physical and ecological state of rivers. Typically this is referenced to a target state (see Chapter 2, Section 2.2.5) (a concept enshrined within the Water Framework Directive). This target state may be historical or represented by an existing undisturbed reach or river. A challenge associated with this approach is that we often do not have sufficient knowledge of the physical processes operating within the target state on which to base decision making during the design of restoration projects. This effectively renders restoration projects the status of uncontrolled experiments (Kondolf and Downs, 1996). If we accept this situation, then it becomes clear that one of the most important aspects of a river restoration project is the monitoring programme.

Key elements to monitoring river restoration projects are highlighted in Sear *et al.* (2006) and include:

- A comprehensive baseline survey that quantifies the variables to be monitored prior to the restoration.
- Clear and unambiguous project objectives and related targets against which to monitor "success".
- Sufficient budget to permit the level of monitoring necessary to achieve the objectives of the monitoring programme.
- Monitoring at appropriate frequency and over sufficiently long timescales to meet the objectives of the project and monitoring programme targets.

Scientifically meaningful conclusions about the effectiveness of restoration can only be drawn where it is possible to distinguish the effects of restoration from natural system dynamics (Downes *et al.*, 2002). In order to achieve this goal, this research used the Before, After, Control, Impact (BACI) approach. This involved environmental monitoring at two anthropogenically modified (channelised) sites before and after restoration (the site to be restored and a control site). This component of the research allowed an assessment to be made of the impact of restoration on modified channels. However, in order to assess whether the restored channel achieved the aim of replicating the processes found on semi-natural forest floodplains, a third semi-natural reference site was monitored at the same time as the other sites (before and after restoration).

The monitoring programme investigated geomorphological and hydrological processes – this thesis focuses on the geomorphological processes on the floodplain; in-channel geomorphological processes are reported in Sear *et al.* (2006), and hydrological processes are discussed in Sear *et al.* (2006) and Kitts (in prep.).

The initial objectives of the geomorphological monitoring programme were *'to demonstrate a change in geomorphological processes on the floodplain analogous with those found in other wet woodland sites within the catchment'* (Sear *et al.,* 2006). Specifically, the targets of the monitoring were to identify whether or not diverse erosional and depositional habitats developed on the floodplain post-restoration that were typical of analogue reaches within the catchments.

The following features and processes were monitored:

1. Changes in channel sinuosity.
2. Changes in the frequency of overbank flow (monitored using crest gauges).
3. Patterns and rates of overbank sediment deposition were monitored through the use of Astroturf sediment traps. Artificial vegetation traps were also used to monitor the influence of low-level floodplain vegetation on overbank deposition.
4. Patterns and rates of floodplain erosion were monitored through the use of erosion pins in the floodplain surface.
5. In order to quantify the potential supply of fine sediment to the floodplain, fine sediment transport was monitored – the impacts of restoration on fine sediment transport within the channel were also ascertained.
6. The effects of restoration on small wood dynamics (pieces < 1 m length and 0.1 m diameter) were monitored through the use of artificial wood tracers.

The field experiments were structured using the same hierarchical architecture displayed by natural river systems (Frissell *et al.*, 1986), with monitoring undertaken at scales ranging from the catchment to the individual patch (Figure 4.1 and Table 4.1).

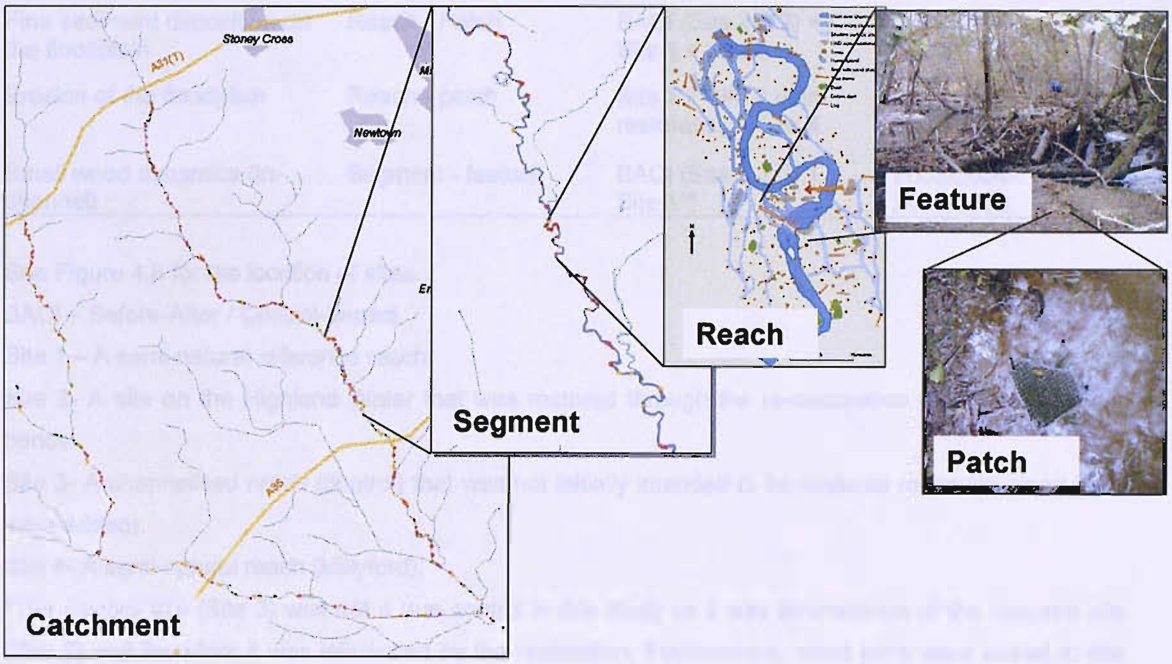


Figure 4.1 Hierarchical scales adopted for the LIFE 3 geomorphological monitoring programme (after Frissell *et al.*, 1986).

Table 4.1 Summary of the geomorphological monitoring programme on the Highland Water.

Variable Monitored	Scale	Monitoring design	Dates
Fine Sediment transport in channel & supply to floodplain	Catchment – Reach	*BACI (Site 2 & 3) + Site 1	2003/2004-2005/2006
Fine sediment deposition on the floodplain	Reach - Patch	BACI (Site 2 & 3) + Site 1 + Site 4	2003/2004-2005/2006
Erosion of the floodplain	Reach - patch	Site 1 + Site 2 post restoration + Site 4	2003/2004-2005/2006
Small wood dynamics (in-channel)	Segment - feature	BACI (Site 2 & 3) + Site 1**	2003/2004-2005/2006

See Figure 4.8 for the location of sites.

BACI – Before-After / Control-Impact.

Site 1 – A semi-natural reference reach.

Site 2- A site on the Highland Water that was restored through the re-occupation of former meander bends.

Site 3- A channelised reach (control) that was not initially intended to be restored (although wood jams were added).

Site 4- A semi-natural reach (Millyford).

*The Control site (Site 3) was not a true control in this study as it was downstream of the restored site (Site 2) and therefore it was influenced by the restoration. Furthermore, wood jams were added to this site during the restoration.

** The reference site (Site 1) was not a true reference as some of the wood moved into an area where bed levels were raised during the restoration (see Section 4.7.1).

4.4.2 Baseline Data

Unlike most restoration projects, LIFE 3 could draw upon a wide range of existing research undertaken within the School of Geography at the University of Southampton, including independent scientific research into wood jam dynamics, floodplain and channel processes, and catchment hydrology dating back to the 1970s. In addition, a full fluvial audit of the Highland Water and Blackwater was undertaken, with the specific aim of identifying the degree of channel modification and suitable restoration sites and targets (GeoData, 2003). This background information was invaluable in the restoration design and monitoring.

4.5 Study area

4.5.1 Overview

The LIFE 3 project was based within the Highland Water and the Blackwater catchments in the New Forest (Figure 4.2). Details of each catchment are given in Table 4.2.

Table 4.2 Catchment characteristics (from GeoData, 2003).

Characteristic	Highland Water	Blackwater
Catchment area (km^2)	25.23	25.52
Total stream length (km)	44.33	30.17
Drainage density (km/km^2)	1.76	1.18
Length of main stream (km)	10.59	12.11
Relief (m, max to min)	97 (105 to 15)	80 (95 to 15)
Slope (m/m)	0.0092	0.0066
Solid geology	Barton clay and sand	Barton clay and sand
Drift geology	Alluvial silt and gravels	Alluvial silt and gravels
Valley soils	Wet alluvial brown earth	Wet alluvial brown earth
Land cover	Forest / heathland	Forest / heathland
Land management	Forestry / commoning	Forestry / commoning

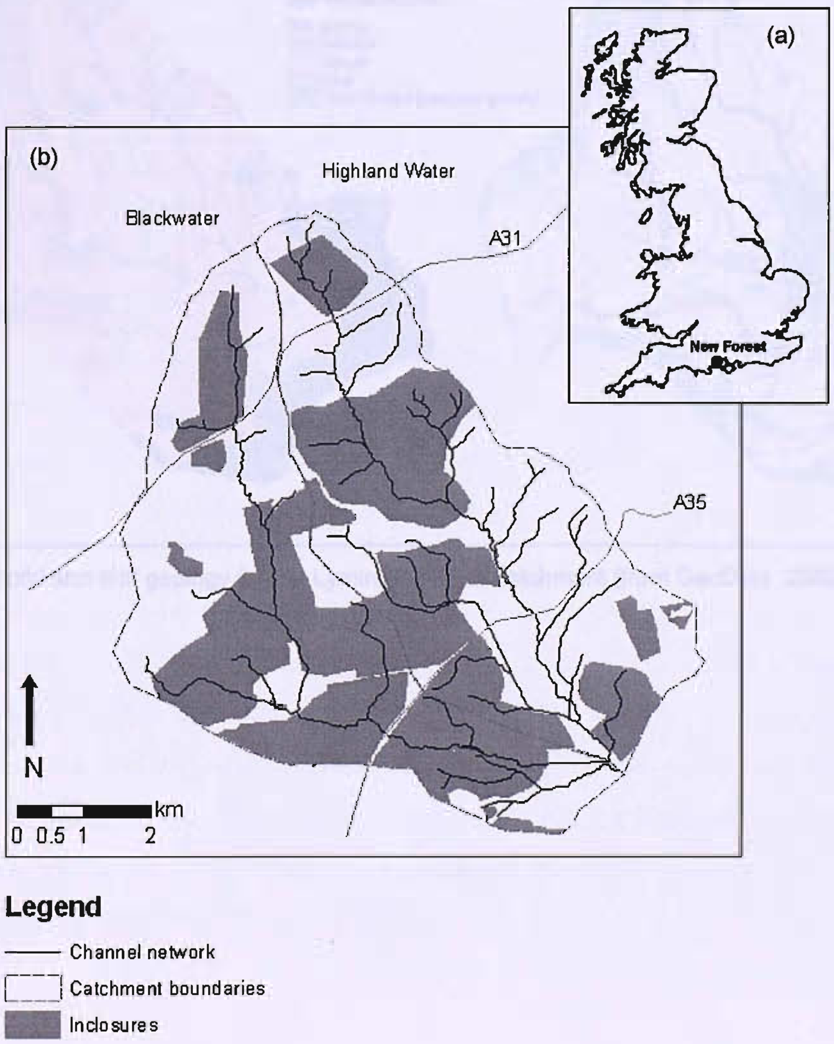


Figure 4.2 Location of the Highland Water and Blackwater study catchments (a) in the UK; (b) in the New Forest.

4.5.2 Geology

The solid geology underlying the Highland Water and the Blackwater in the upper part of both catchments is Barton Clays and both rivers then cross into Barton Sands (Figure 4.3). The channels flow through drift deposits of alluvium, with a distinct surface layer of fines (usually clay-rich) with a lower layer of gravels (Figure 4.4). In some areas (e.g. around Millyford Bridge) this alluvium is more extensive than in other parts of the network, which probably reflects a lower valley gradient. Where the channels are deeply incised (usually in the head waters) the solid clay geology is exposed (Figure 4.4).

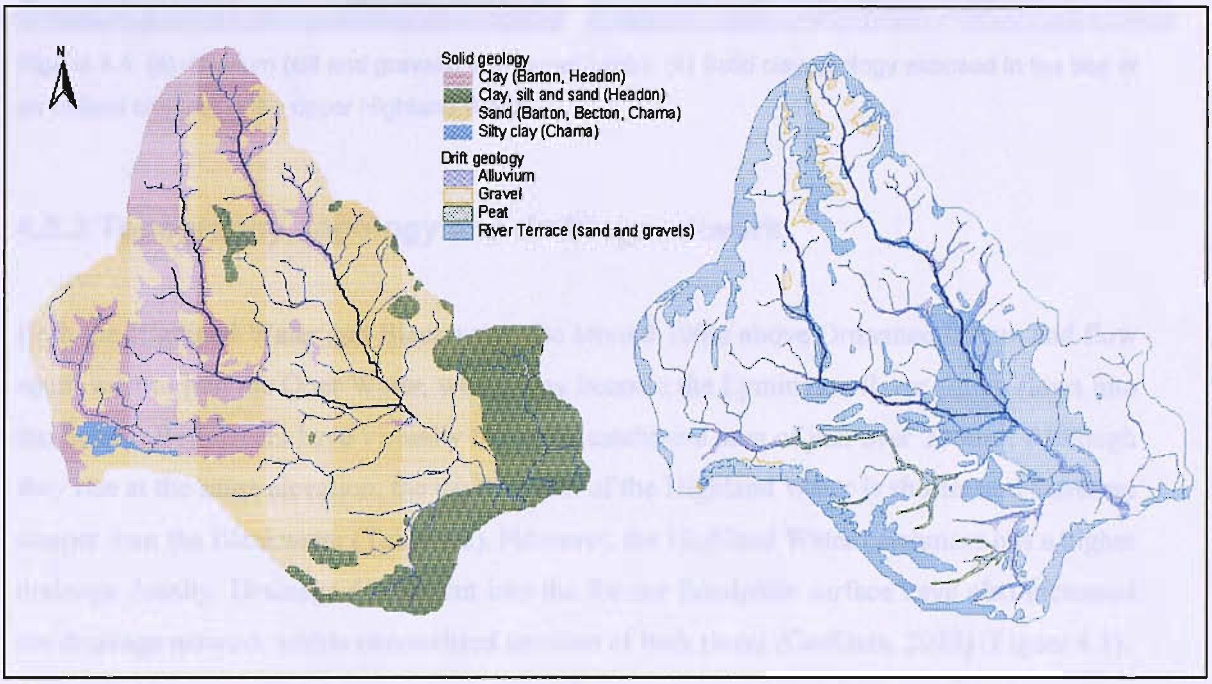


Figure 4.3 Solid and drift geology for the Lymington River catchment (from GeoData, 2003).

(a) (b)

Figure 4.4 (a) Alluvium (silt and gravels) in channel banks; (b) Solid clay geology exposed in the bed of an incised channel in the upper Highland Water.

4.5.3 Topography, topology and drainage network

Both the Highland Water and Blackwater rise around 100m above Ordnance Datum and flow south west to join the Ober Water, where they become the Lymington River which flows into the Solent. Both rivers have virtually the same catchment area of just over 25 km^2. Although they rise at the same elevation, the main stream of the Highland Water is shorter and therefore steeper than the Blackwater (Table 4.2). However, the Highland Water catchment has a higher drainage density. Drainage ditches cut into the former floodplain surface have also increased the drainage network within channelised sections of both rivers (GeoData, 2003) (Figure 4.5).

In the upper catchment the floodplains lie within shallow v-shaped valleys, and the edge of the floodplain is usually marked by a distinct break in slope. The width of the floodplains tends to increase downstream. However, there are some anomalies. In some areas there are floodplain terraces, which probably result from base level change dating from the end of the last ice age (Tubbs, 1986). These terraces locally restrict the width of the floodplain. In approximately the lowest third of each river the floodplain width increases and the break in slope at the edge of the floodplain is less obvious.

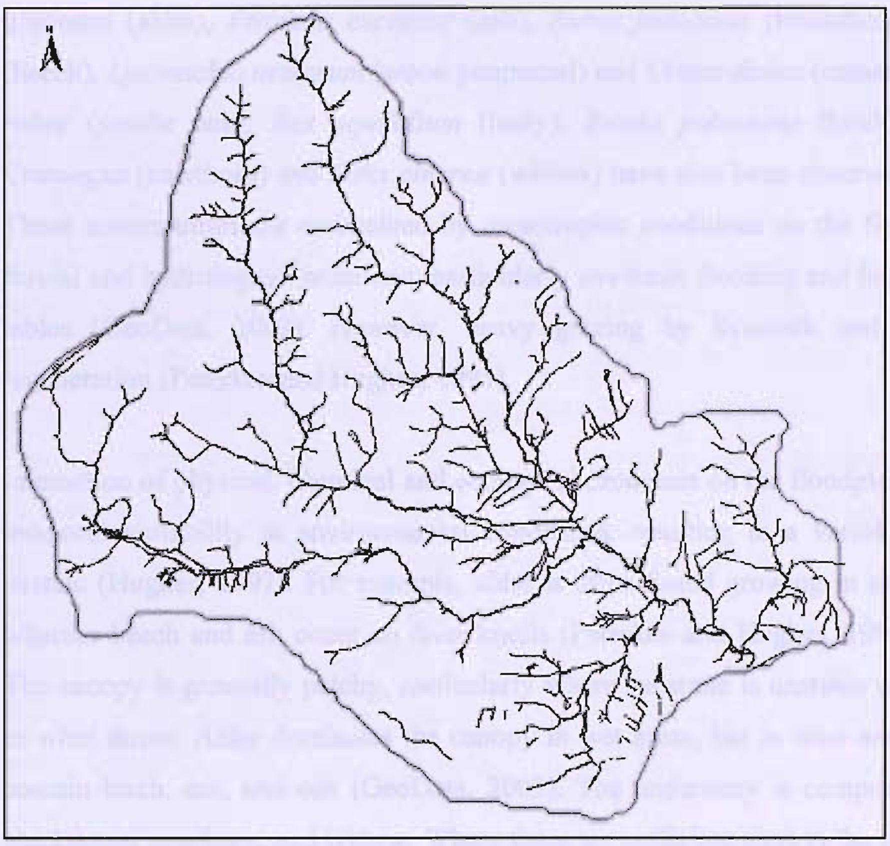


Figure 4.5 Drainage network of the Highland Water, Blackwater and Ober water basins (GeoData, 2003).

4.5.4 Land management

The land use and management in the New Forest is unique, stemming from historic Acts of Parliament that allowed individuals who live in the forest ('Commoners') rights to graze animals throughout. This has led to grazing pressure that influences the type and extent of ground vegetation, leading to grazed lawns and woodland. The New Forest is also managed for timber. Historically this was both for wood fuel, with pollarded trees being common prior to the 19th century but less so today; and for commercial forestry. The Forestry Commission presently maintains large areas of inclosure, which are fenced to prevent livestock entry and grazing. This has led to a variety of woodland management, with coniferous and mixed woodland plantations.

4.5.5 Vegetation

Streams in the New Forest are surrounded by large areas of semi-natural floodplain forest (Peterken, 1996). Peterken *et al.* (1996) identified this as NVC type W7, containing *Alnus* *glutinosa* (alder), *Fraxinus excelsior* (ash), *Rubus fruticosus* (blackthorn), *Fagus sylvatica* (beech), *Lysimachia nemorum* (wood pimpernel) and *Urtica dioica* (common nettle). *Quercus robur* (sessile oak), *Ilex aquifolium* (holly), *Betula pubescens* (birch), *Corylus* (hazel), *Crataegus* (hawthorn) and *Salix cinerea* (willow) have also been observed (GeoData, 2003). These communities are maintained by mesotrophic conditions on the floodplain created by fluvial and hydrological processes, particularly overbank flooding and high or perched water tables (GeoData, 2003). However, heavy grazing by livestock and deer limits forest regeneration (Peterken and Hughes, 1995).

Interaction of physical, chemical and ecological processes on the floodplain cause spatial and temporal variability in environmental conditions, resulting in a varied floodplain species mosaic (Hughes, 1997). For example, alder is often found growing in poorly drained areas, whereas beech and ash occur on drier knolls (Peterken and Hughes, 1995; GeoData, 2003). The canopy is generally patchy, particularly where substrate is unstable and trees are subject to wind throw. Alder dominates the canopy in wet areas, but in drier areas the canopy may contain birch, ash, and oak (GeoData, 2003). The understory is composed of holly, hazel, blackthorn, hawthorn, and willow. Where there are sufficient gaps in the canopy, willow may grow large enough to form part of it (GeoData, 2003). The ground flora is diverse with a mosaic of hydrophilic species, including *Juncus effusus* (common rush), *Carex remota* (remote sedge), *Filipendula sp.* (meadowsweet), *Cirsium palustre* (thistle), *Valeriana officianalis* (common valerian), *Eupatorium cannabinium* (hemp agimony), *Lychnis flos-cuculi* (ragged robin), *Crepis paludosa* (marsh hawksbeard), and *Chrysosplenium oppositifolium* (golden saxifrage), which may be found in particularly wet areas (GeoData, 2003).

Floodplains within the inclosures are covered by plantation woodland (either coniferous or coniferous-deciduous mix). Exclusion of livestock from these areas results in dense understory vegetation, dominated by *Pteridium aquilinium* (bracken) (e.g. see Figure 4.20)

4.5.6 Conservation status

The New Forest National Park is owned by the State, but managed by the Forestry Commission. It has SSSI (Site of Special Scientific Interest), SPA (Special Protection Area) and cSAC (candidate Special Area of Conservation) status, and the SSSI is also a Ramsar site due to the plant and invertebrate species associated with the wetland areas.

4.6 LIFE 3 Restoration implementation

4.6.1 Restoration works

Based on results from the baseline geomorphological audit (GeoData, 2003), the LIFE 3 project initiated a set of restoration measures to increase the extent of wet woodland and bog woodland within the New Forest. This was principally done by increasing channel-floodplain connectivity within the Blackwater and Highland Water catchments. Four restoration methods were used: (i) re-occupation of the former meandering course of the channel and infilling the channelised reach; (ii) creation of a new sinuous course where former channels had been destroyed; (iii) raising channel bed levels using locally sourced clay and gravels; and (iv) re-introducing wood into channelised reaches (Sear *et al.*, 2006). The geomorphological baseline survey (GeoData, 2003) was used to identify the most suitable reaches for each form of restoration. In addition to the channel works, conifers were removed from the floodplain before restoration works began. Details of the restoration works are given in Table 4.3 and shown on Figure 4.6.

Table 4.3 Summary of channel and floodplain restoration works undertaken during the LIFE 3 project. (Snagging = minor adjustments to previous restoration work)

Site	Restoration dates (inclusive of site set-up)	Restoration type	NGR
Rhinefield	28/7/03 – 12/8/03	Reconnection plus wood jam work at upstream end.	Wood jam work from SU25400 04780 to SU25993 04590
	17/8/05 – 2/9/05	Snagging plus reconnection of meander omitted in previous year due to rare snail.	Reconnection (plus some bed-level raising towards downstream end) from SU25993 04590 to SU26763 04566
	5-21/6/06	Snagging plus bed level raising down channelised section just upstream of bridge to downstream end	Bed level raising from SU26763 04566 to SU26844 04500
Highland Water	13/8/04 – 20/10/04	Bed level raising on open forest, reconnection within Inclosure plus wood jam work in Holmhill	Bed level raising on open forest from SU24684 10075 to SU24782 09860
	6-24/6/05	Snagging plus reconnection for approx 350m at down-stream end	Reconnection (plus some bed level raising & new channel cutting) from SU24782 09860 to SU25239 08895
	1&2/12/05	Revetment work	Wood jam work from SU25239 08895 to SU26543 08099
	15-22/5/06	Snagging	
Blackensford	27/6/05 – 16/8/05	Bed level raising on open forest, reconnection within inclosure	Bed-level raising on open forest to inclosure boundary Western trib: from SU22795 06916 to SU23017 06980 Eastern trib: from SU23024 07291 to SU 23081 07044
	30/11/05	Wood jam work within inclosure	
	22-31/5/06	Snagging	Reconnection & wood jam work from inclosure boundary on 2 tribs to SU23660 06603
	23-24/6/06	Snagging	
Dames Slough	9/5/05 – 3/6/05	Reconnection	Reconnection (minimal bed-level raising) from SU24067 05097 to SU25331 04823
	1-2 /6/06	Snagging	
	22/6/06	Snagging	

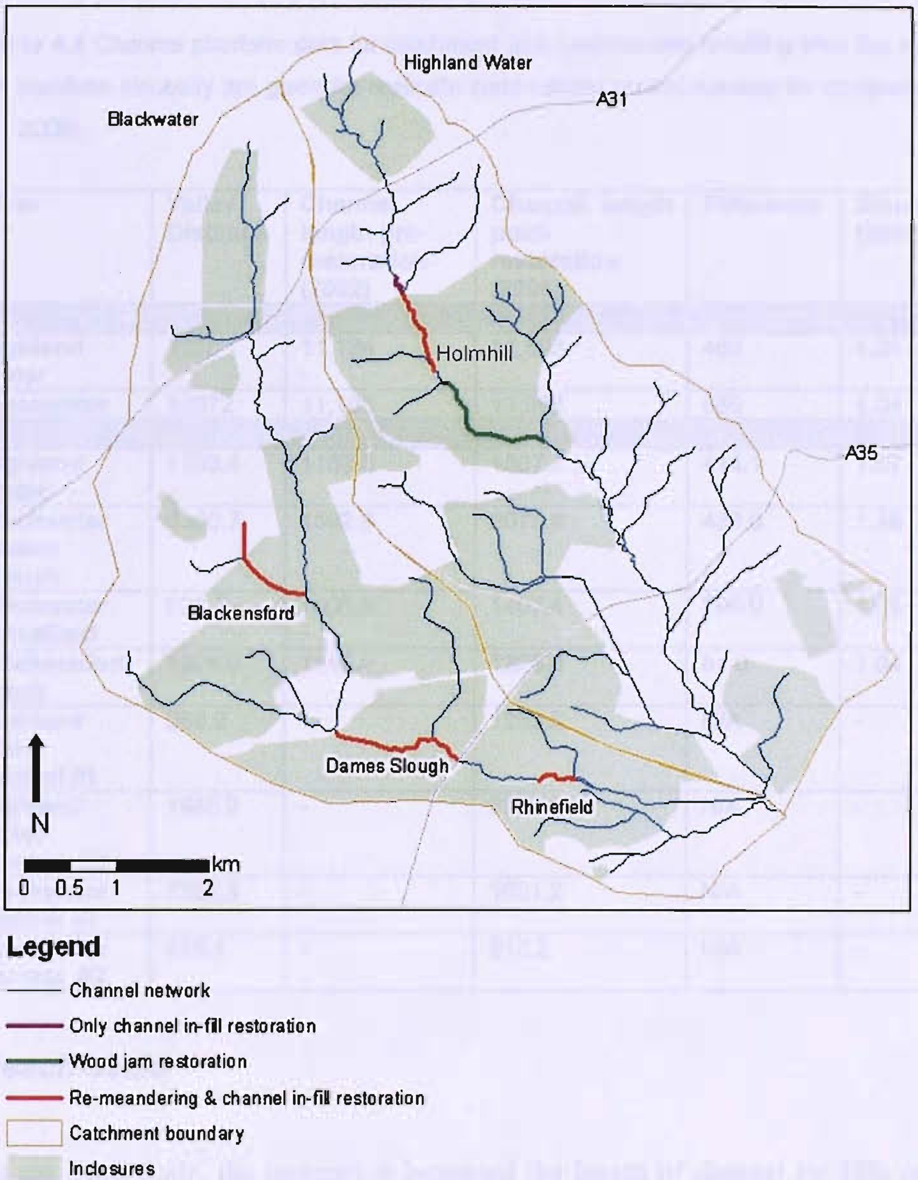


Figure 4.6 Location of different forms of restoration during LIFE 3 in the Lymington catchment.

4.6.2 Changes in channel planform

Catchment-scale

The restoration resulted in major changes to channel planform and length. The restored channels were surveyed in 2006. Re-occupation of meander bends (abandoned due to earlier modification) and creation of new channels increased stream length by a combined total of 1435 m (for both rivers). At the catchment scale the average sinuosity of the Highland Water has increased by 4%, and the Blackwater by 8% (Table 4.4).

Table 4.4 Channel planform data for catchment and reach-scales resulting from the restoration. Values for planform sinuosity are given for replicate semi-natural control reaches for comparison (from Sear *et al.*, 2006).

River	Valley Distance	Channel length pre-restoration (2002)	Channel length post-restoration (2006)	Difference	Sinuosity (2002)	Sinuosity (2006)
			CATCHMENT- SCALE			
Highland Water	8525	11,124	11,593	469	1.31	1.36
Blackwater	10672	11,103	11,968	966	1.04	1.12
			REACH- SCALE			
Highland Water	1103.4	1183.5	1597.6	414.1	1.07	1.45
Blackwater Dames Slough	1350.7	1592.9	2078.9	486.0	1.18	1.54
Blackwater Rhinefield	936.7	1008.4	1407.4	399.0	1.08	1.50
Blackensford Brook	1098.9	1145.0	1226.0	81.0	1.04	1.12
Highland Water Control #1	969.9	-	1288.2	N/A	-	1.33
Highland Water Control #2	1946.2	-	2779.1	N/A	-	1.43
Blackwater Control #1	1226.8	-	1631.2	N/A	-	1.33
Blackwater Control #2	618.4	-	913.2	N/A	-	1.48

Reach-scale

At the reach-scale, the restoration increased the length of channel by 35% on the Highland Water (Holmhill), 30.5% at Dames Slough, 42.5% at Rhinefield and 7.4% at Blackensford Bottom (Figure 4.7). Channel sinuosity has increased, and values are now similar to those at semi-natural sites (Table 4.4). Thus the restoration has had a significant local affect on channel planform at the reach-scale, with resulting planform morphologies similar to the target semi-natural reaches (Sear *et al.*, 2006).

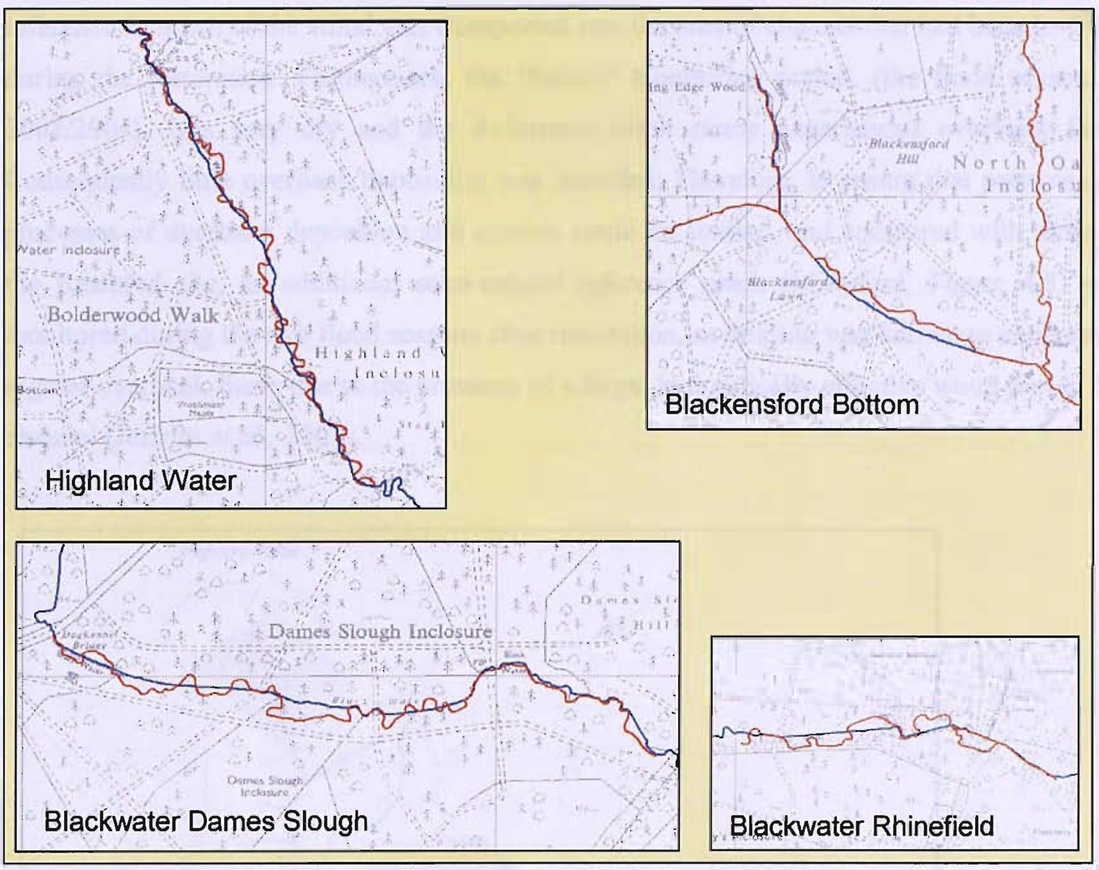


Figure 4.7 Reach-scale planform changes arising from the restoration. Red is the 2006 post-restoration planform, blue is the 2002 pre-restoration planform.

4.7 Research methodology and study sites

4.7.1 Research methodology

At the outset of the monitoring programme, the intention was to use the BACI framework to monitor an 'Impacted' and a 'Control' site, and also to monitor a semi-natural 'Reference' site. Therefore, 'Before' monitoring was conducted on a channelised reach that was going to be restored (Impacted), a channelised reach that was unaffected by the restoration (Control), and a semi-natural ('Reference') reach that was also unaffected by the restoration (Figure 4.8). However, during the course of the restoration, wood jams were added to the Control reach, rendering it no longer a true control. Nevertheless, it was still possible to ascertain the impacts of the restoration, as the Restored reach could be compared with the un-changed, Reference reach. Channel in-filling took place during the restoration immediately downstream of the Reference reach (Figure 4.6). This did not affect the ability of the reach to function as a reference for some of the variables monitored, e.g. fine sediment transport, but it did affect the monitoring of small wood dynamics. For this variable, the site could not function as a reference as much of the wood was transported into the area of channel that had been in-filled during the restoration. Furthermore, the 'Before' monitoring period, (the flood season of 2003/2004), was very dry and the Reference reach rarely experienced overbank flow. Consequently little overbank deposition was recorded. Therefore, to ensure that patterns and processes of overbank deposition and erosion could be studied, and compared with those at the Restored site, an additional semi-natural reference reach (Millyford, Figure 4.8) was monitored during the two flood seasons after restoration, as this site was known to experience regular overbank flows due to the presence of a large, hydraulically effective wood jam in the channel (Jeffries *et al.*, 2003).

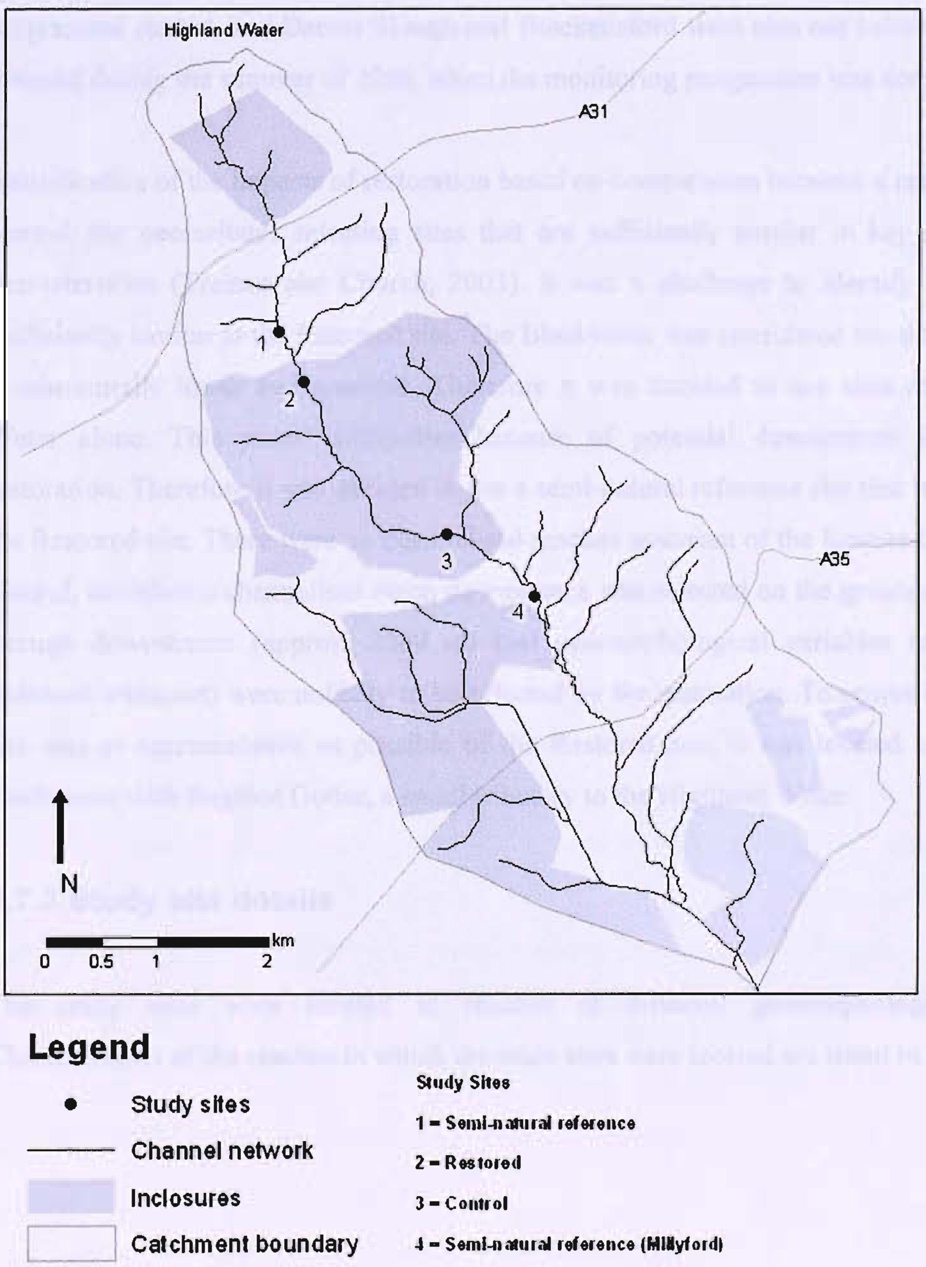


Figure 4.8 Location of study sites on the Highland Water.

4.7.2 Study site selection

The Restored site on the Highland Water (in Holmhill inclosure) was selected for two main reasons. Firstly, because it was scheduled for restoration during the first summer after monitoring began (2004), therefore there was potentially an opportunity to monitor geomorphological processes at the site both before and after the restoration (although in practice the restoration works took longer than planned and the downstream section of the restoration on the Highland Water was only completed in 2006 (Table 4.3)). The second reason for selecting this site was the long standing data record for the Highland Water. The Rhinefield site was not suitable as it was restored during the summer before the monitoring programme started, and Dames Slough and Blackensford were also not suitable as they were restored during the summer of 2006, when the monitoring programme was coming to an end.

Identification of the impacts of restoration based on comparisons between a restored site and a control site necessitates selecting sites that are sufficiently similar in key stream channel characteristics (Trainor and Church, 2003). It was a challenge to identify sites that were sufficiently similar to the Restored site. The Blackwater was considered too different as it had a substantially lower bed gradient. Therefore it was decided to use sites on the Highland Water alone. This posed difficulties because of potential downstream impacts of the restoration. Therefore it was decided to use a semi-natural reference site that was upstream of the Restored site. There were no channelised reaches upstream of the Restored site to use as a control, therefore a channelised reach downstream was selected on the grounds that it was far enough downstream (approx. 2000 m) that geomorphological variables (except for fine sediment transport) were unlikely to be affected by the restoration. To ensure that the control site was as representative as possible of the Restored site, it was located upstream of the confluence with Bagshot Gutter, a small tributary to the Highland Water.

4.7.3 Study site details

The study sites were located in reaches of different geomorphological character. Characteristics of the reaches in which the main sites were located are listed in Table 4.5.

Table 4.5 Characteristics of reaches within which each study site was located.

	Before Restoration			After restoration		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Catchment area upstream of reach (km^2)	5	7	11	5	7	11
Reach length (m)	410	1183	452	410	1598	452
Mean bankfull width (m)	1.88	5.91	3.73	1.88	4	3.73
Mean bankfull depth (m)	1.2	1.7	1.1	0.73	0.78	1.1
Q_{bf} ($m^3 s^{-1}$)	1.61	7.35	4.1	0.9	0.56	4.1
Sinuosity	1.45	1.07	1.01	1.45	1.45	1.01
Bed slope	0.0078	0.008	0.0057	0.006	0.005	0.0057
Unit stream power (using Q_{bf}) (W m^{-2})	65.53	97.60	61.46	28.18	6.87	61.46
Hydraulically effective & Complete jams/100m	1.95	0.17	0.00	0.98	0.31	0.66
Partial jams/100m	0.24	0.76	0.22	0.98	1.00	0.44
High water jams/100m	0.00	0.68	0.66	0.24	0.31	0.44
Floodplain vegetation	Deciduous open woodland	Coniferous inclosure woodland	Coniferous inclosure woodland	Deciduous open woodland	Coniferous inclosure woodland (some conifers felled)	Coniferous inclosure woodland
Floodplain slope	0.0113	0.0067	0.01	0.0113	0.0067	0.01
Floodplain width	30	45	50	30	45	50
Bed material (mm):						
D84	62.00	65.00	55.00	64.00	46.00	60.00
D50	39.00	44.00	37.00	36.00	26.00	32.00
D16	22.00	28.00	20.00	18.00	16.00	16.00

*NB Reaches are defined as the length of channel of a specific geomorphological character. See Figure 4.8 for definitions and locations of sites.

Site 1: Semi-natural reference site

Site 1 was located in open deciduous woodland (Figures 4.10 and 4.11.). Monitoring was focused in the vicinity of a hydraulically effective wood jam (Figure 4.10). A contour map showing the location of monitoring equipment is presented in Figure 4.9. The map was created in ArcGIS from topographic data collected using an electronic total station. Data points were collected approximately every 4 m^2, although a higher density of data points were collected in and around the channel where changes of slope occurred more frequently, and a lower density was collected towards the outer margins of the floodplain where the change of slope was minimal.

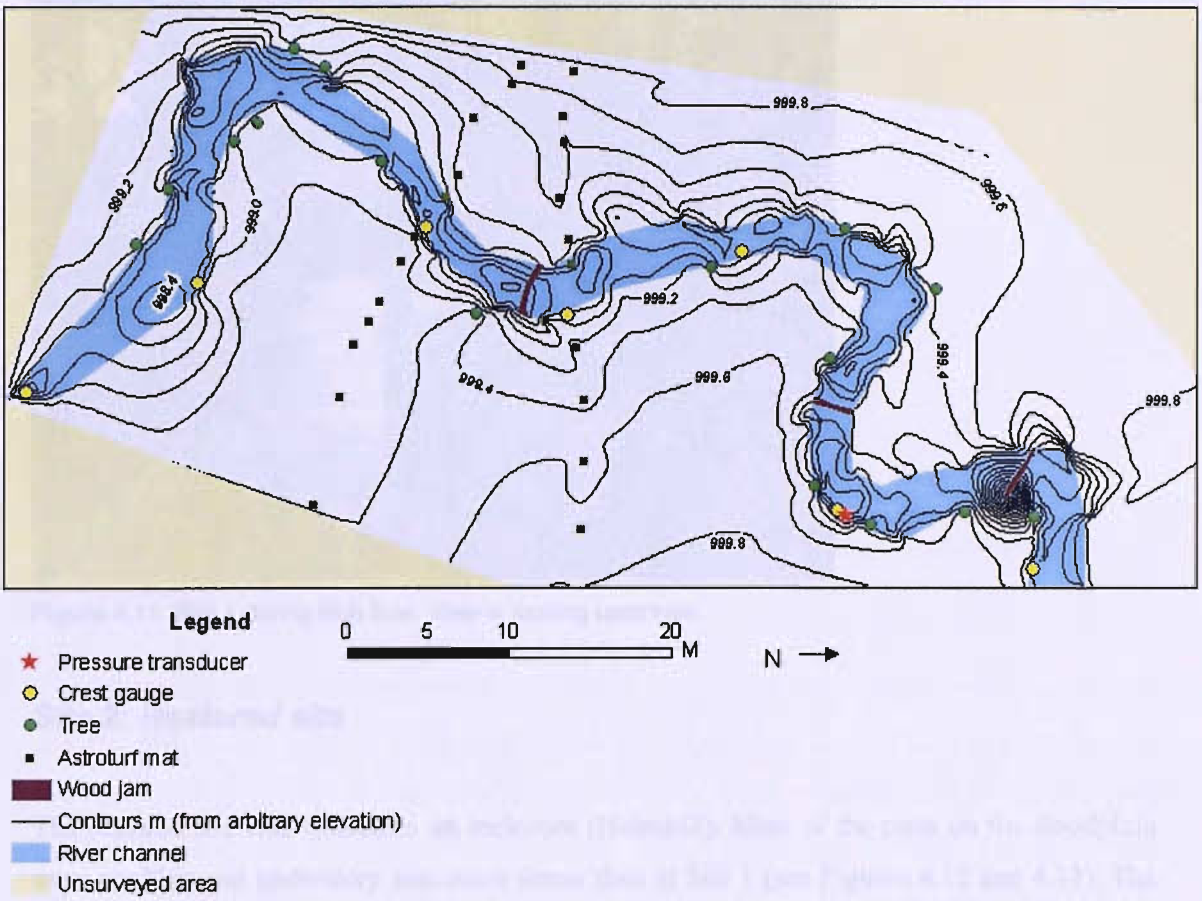


Figure 4.9 Contour map of Site 1. Flow is from right to left of page.

Figure 4.10 Wood jam at Site 1. The photograph was taken during high flow.
Flow is from right to left of page.

Figure 4.11 Site 1 during high flow. View is looking upstream.

Site 2: Restored site

The restored site was located in an inclosure (Holmhill). Most of the trees on the floodplain were conifers and understory was more dense than at Site 1 (see Figures 4.12 and 4.13). The channel was straightened and deepened between 1960 and 1970 and had further incised, resulting in a very deep (nearly 2 m) and straight channel (Figures 4.12 and 4.13). Spoil from the channelisation was present on both sides of the channel. Consequently the channel was disconnected from its floodplain.

Figure 4.12 Restored site before restoration looking upstream. Note the straight, deep channel with spoil heaps on both sides.

Figure 4.13 Restored site before restoration looking downstream. The person provides a sense of channel depth.

The restoration at this site principally involved re-occupation of the former meandering channel and in-filling of the channelised reaches (Figures 4.14 and 4.15). Consequently the channel dimensions were smaller (see Table 4.5) which led to re-coupling of the channel and floodplain. This is illustrated by the presence of flood waters on the floodplain (Figures 4.16 and 4.17). The inclosure was also opened up to grazing by New Forest ponies after the restoration.

Figure 4.14 Channel infilling during restoration at the Restored site.

Figure 4.15 Re-occupied meandering channel at the Restored site. Flow is away from the camera.

Figure 4.16 Ponded overbank flow at the Restored site post restoration. Flow is from right to left of page. The main channel is discernable by the area of rippled water surface.

Figure 4.17 Overbank flow creating floodplain channels at the Restored site post restoration. Flow is toward the camera.

Detailed topographic surveys were undertaken of the Restored site before and after restoration using an electronic total station, at a resolution of approximately one point every 0.25 m^2. Digital elevation models (DEMs) were then created using ArcGIS (Figures 4.18 a and b).

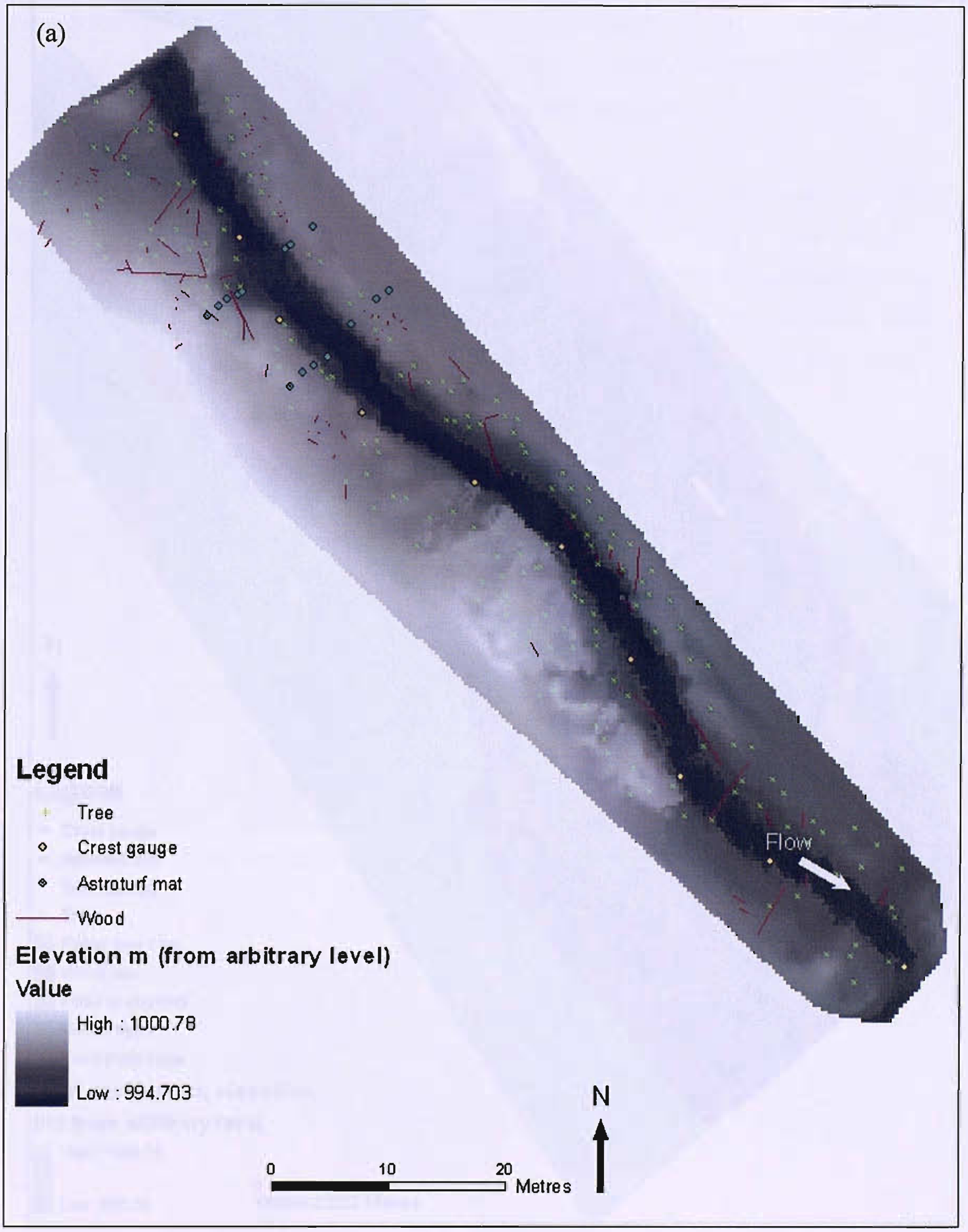
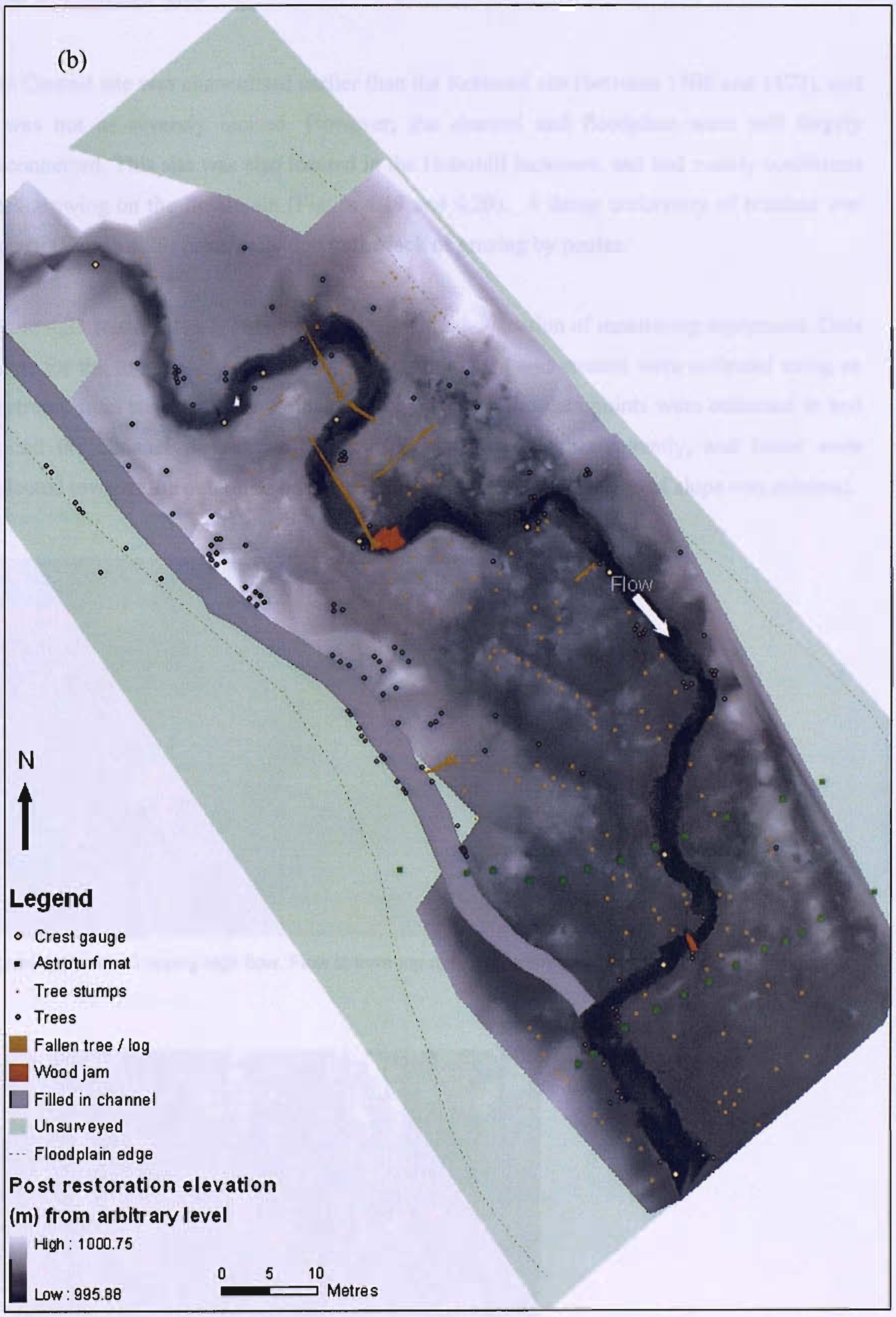


Figure 4.18 Digital elevation models of the re-meandered reach (a) before and (b) after restoration.


(b)
Flow
N
Legend
Crest gauge
Astroturf mat
Tree stumps
Trees
Fallen tree / log
Wood jam
Filled in channel
Unsurveyed
Floodplain edge
Post restoration elevation
(m) from arbitrary level
High : 1000.75
Low : 995.88
0 5 10
Metres

Site 3: Control site

The Control site was channelised earlier than the Restored site (between 1806 and 1872), and it was not as severely incised. However, the channel and floodplain were still largely disconnected. This site was also located in the Holmhill inclosure, and had mainly coniferous trees growing on the floodplain (Figure 4.19 and 4.20). A dense understory of bracken was present (Figure 4.20) principally due to the lack of grazing by ponies.

Figure 4.21 represents a DEM of the site showing the location of monitoring equipment. Data points for the topographic survey from which the DEM was created were collected using an electronic total station at approximately every 1 m^2. More data points were collected in and around the channel where changes of slope occurred more frequently, and fewer were collected towards the outer margins of the floodplain where the change of slope was minimal.

Figure 4.19 Site 3 during high flow. Flow is from top right to bottom left of photograph.

Figure 4.20 Bracken and conifers on the floodplain at Site 3.

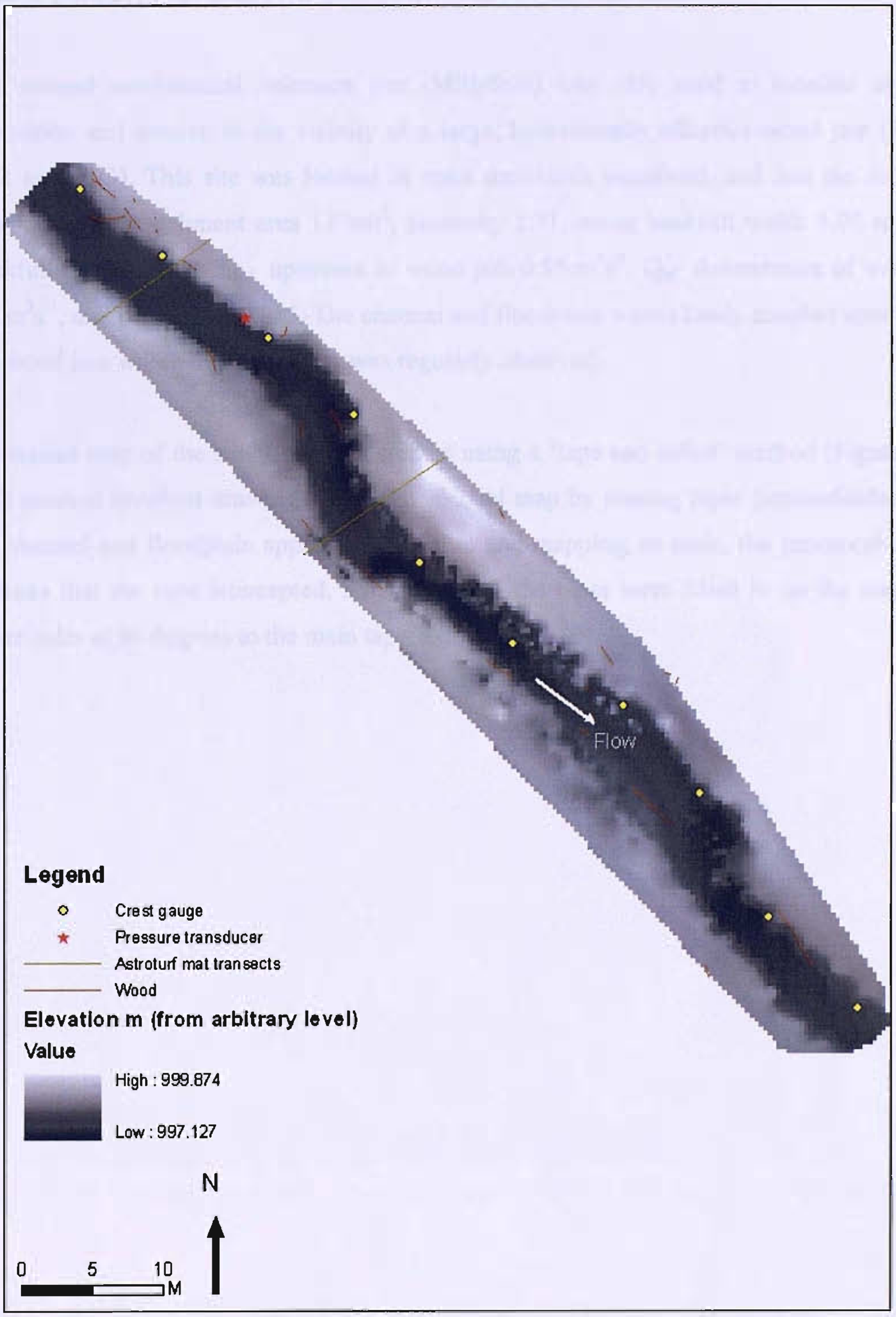


Figure 4.21 Digital elevation model of Site 3 (Control).

Site 4 (Millyford): Second semi-natural reference site

The second semi-natural reference site (Millyford) was only used to monitor overbank deposition and erosion in the vicinity of a large, hydraulically effective wood jam (Figures 4.22 and 4.23). This site was located in open deciduous woodland, and had the following characteristics: catchment area 13 km^2, sinuosity 1.71, mean bankfull width 5.05 m, mean bankfull depth 0.89 m, Q_{bf} upstream of wood jam 0.55 m^{3}s^{-1}, Q_{bf} downstream of wood jam 2.2 m^{3}s^{-1}, and bed slope 0.0085. The channel and floodplain were closely coupled upstream of the wood jam where overbank flow was regularly observed.

A detailed map of the study site was created using a 'tape and offset' method (Figure 4.24). This method involved drawing a two dimensional map by placing tapes perpendicular across the channel and floodplain approx. every 10 m and mapping, to scale, the geomorphological features that the tape intercepted. Areas between the tapes were filled in on the map using meter rules at 90 degrees to the main tape.

Figure 4.22 Flooding upstream of the wood jam at Site 4.

Figure 4.23 Ponding upstream of the wood jam at Site 4 displaying high channel-floodplain connectivity.

Figure 4.24 (below) Tape and offset map of Site 4 displaying complex networks of floodplain channels. In order to show the variability in floodplain channel depth, the floodplain channels were assigned a number between 1 and 5 as shown below:
Floodplain channel 1: very shallow (<10 cm)
Floodplain channel 2: deep (>10 cm)
Floodplain channel 3: deep and wet
Floodplain channel 4: flowing
Floodplain channel 5: flowing with characteristics of main channel, e.g. permanent flow

Flow is down the page

Figure 4.24 Tape and offset map of Site 4.

4.8 Timeline of monitoring and restoration

As discussed in Section 4.5, the initial intention of using the BACI framework for monitoring the effects of the restoration was not possible for all variables due to the addition of wood jams at the Control site. However, Table 4.6 shows how the monitoring programme was designed around the restoration work on the Highland Water to ensure that both before and after monitoring was carried out at the Restored site as well as at a variety of other sites (including a control and semi-natural reference sites) against which to compare the impacts of the restoration.

Table 4.6 Dates of variables monitored at each site and dates of restoration on the Highland Water

Dates	Variables monitored	Site 1	Site 2	Site 3	Site 4
First flood season monitored: Oct 2003 - April/May 2004	Fine sediment transport (in-channel and supply to floodplain)	✓	✓	✓	x
	Overbank deposition (Astroturf mats)	✓	✓	✓	x
	Small wood dynamics	✓	✓	✓	x
Dry season: August 2004 - October 2004	RESTORATION	No restoration at the actual site, but channel bed levels raised immediately downstream	Re-occupation of former meander bends and infilling of straightened channel	Addition of wood jams	x
Second flood season monitored: Oct 2004 - April/May 2005	Fine sediment transport (in-channel and supply to floodplain)	✓	✓	✓	x
	Overbank deposition (Astroturf mats)	✓	✓	✓	✓
	Overbank deposition (Vegetation mats)	x	✓	x	✓
	Small wood dynamics	✓	✓	✓	x
	Floodplain erosion	✓	✓	x	✓
Dry season: June 2005	RESTORATION	x	Completion of restoration work that began in 2004 downstream of monitoring site	x	x
Third flood season monitored: October 2005 - April/May 2006	Fine sediment transport (in-channel and supply to floodplain)	✓	✓	✓	x
	Overbank deposition (Astroturf mats)	✓	✓	✓	✓
	Overbank deposition (Vegetation mats)	x	✓	x	✓
	Small wood dynamics	✓	✓	✓	x
	Floodplain erosion	✓	✓	x	✓

4.9 Summary

This chapter has described details of the LIFE 3 restoration project that was undertaken in the New Forest between 2002 and 2006. Characteristics of the study area (the Highland Water and Blackwater catchments) and specific study sites (Restored site, Control site and two Reference sites) have been provided. The overall methodological approach (BACI) and monitoring techniques used in the thesis have also been discussed, and a time-line of variables monitored has been provided.

Chapter 5. Defining reference conditions and targets (2): semi-natural forested floodplains in the New Forest

5.1 Introduction

This chapter uses field based observations of geomorphological features (and inferred processes) from semi-natural forested floodplains in the New Forest to refine the general reference conditions for floodplain forests identified from the literature (Chapter 3). One of the geomorphological features frequently observed were floodplain channels; in order to gain a greater understanding of the processes forming floodplain channels, their distribution, morphology and evolution was investigated. This knowledge of the specific geomorphological features (and inferred processes) found in semi-natural forested floodplains in the New Forest was subsequently used to identify variables to monitor in order to assess the impacts of the restoration on floodplain geomorphological dynamics.

5.2 Overview of New Forest floodplains

Floodplains in the New Forest are composed of fluvially deposited clays, silts, sands and gravels (GeoData, 2003). Floodplain width (defined as the width of the relatively flat valley floor, terminating at the break of slope with the adjacent hillslopes) increases downstream (Jeffries, 2002), from only a few metres in the headwaters to more than 150 m at the confluence between the Highland Water and the Blackwater. The floodplain surface is topographically variable, with a range of geomorphological features (Table 5.1, Figure 5.5).

As discussed in Chapter 4, two landuse practices dominate: commoning in the open forest and plantation forestry in the inclosures. Floodplains in the open forest are semi-natural, with assemblages of NVC type W7 woodland communities (Peterken *et al.*, 1996) (Chapter 4). Grazing by livestock and deer limits forest regeneration (Peterken and Hughes, 1995) and the development of dense understory vegetation (see Figure 5.1 (a)). However, exclusion of livestock from the inclosures, which are covered by plantation woodland (either coniferous or coniferous-deciduous mix), results in dense understory vegetation in these areas of floodplain, frequently dominated by bracken (see Figure 5.1 (b)).

(a) (b)

Figure 5.1 (a) Lawn on the floodplain in the open forest (Ober Water); (b) Dense surface vegetation on the floodplain in an inclosure (Blackwater).

A survey for the Environment Agency undertaken by GeoData (2003) identified semi-natural and modified reaches along the Highland Water and Blackwater (Figure 5.3). Evidence of modification included the presence of conifers on the floodplain, drains cut into the floodplain, spoil heaps bordering the channel (e.g. Figure 5.2 (a)), deeply incised channels (e.g. Figure 4.13, Chapter 4), and channel planforms with low sinuosity (e.g. Figure 5.2 (b)). Reaches with no evidence of modification were classified as semi-natural by default (e.g. Figure 5.2 (c)).

(a)

(b)

(c)

Figure 5.2

(a) Example of a modified stretch of river with spoil along the channel bank (centre-left of photograph) (Blackwater); **(b)** Example of a modified stretch of river with very low sinuosity (Blackwater); **(c)** Example of a typical semi-natural stretch of river with low banks, meandering planform and wood in the channel (Highland Water) (photograph from GeoData, 2003).

Although not included in the GeoData (2003) survey, a third tributary of the Lymington River with areas of semi-natural forested floodplain, the Ober Water, was included in the identification of semi-natural reference conditions. The Ober Water joins the Lymington River from the west at SU 291 041. It has an average slope of 0.003, its sinuosity is 1.33, and it drains a catchment of 16.3 km^2. Sections of the Ober Water were also channelised before 1850 (Brookes, 1983). Modified reaches on the Ober Water were identified initially through Brookes (1983) and verified through field observations (Figure 5.3).

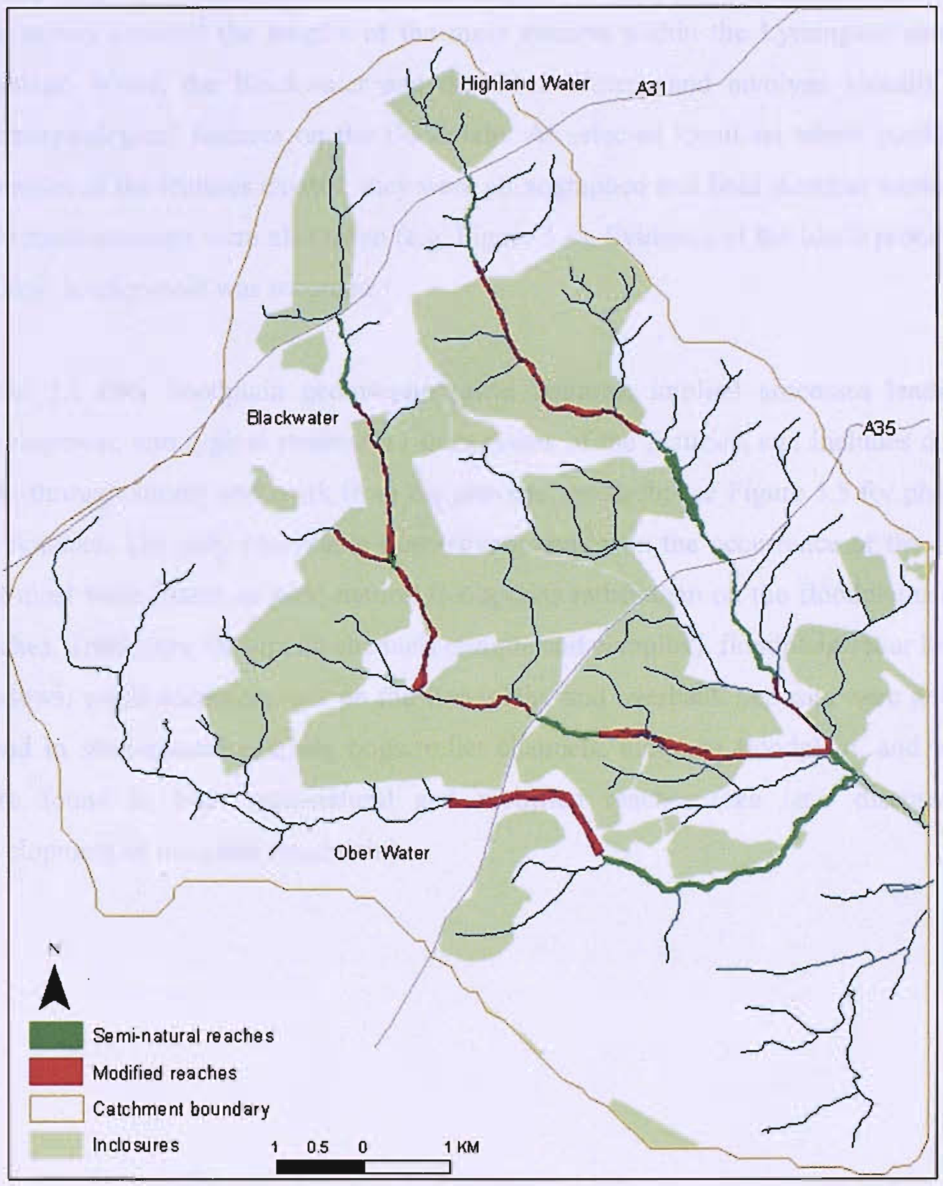


Figure 5.3 Modified and semi-natural reaches along the Highland Water, Blackwater and Ober Water (identified from GeoData, 2003, Brookes, 1983, and field observations).

The floodplain within semi-natural reaches was topographically variable, with diverse floodplain geomorphology (GeoData, 2003). Table 5.1 lists geomorphological features identified by GeoData (2003), Jeffries (2002), and Jeffries *et al.* (2003). In addition, in order to gain a broad understanding of floodplain processes and features, a rapid walk through survey was undertaken in September 2004. This was aimed at obtaining an overview of: (i) the geomorphological features that existed on semi-natural floodplains, (ii) the locations of the features on the floodplain and within the catchment, (iii) approximate dimensions of the different features, and (iv) evidence of processes creating the features, e.g. erosion and deposition.

The survey covered the lengths of the main streams within the Lymington catchment (the Highland Water, the Blackwater and the Ober Water), and involved visually identifying geomorphological features on the floodplain. At selected locations where particularly clear examples of the features existed, they were photographed and field sketches were made; rapid field measurements were also taken (e.g. Figure 5.4). Evidence of the likely processes leading to their development was recorded.

Table 5.1 lists floodplain geomorphological features, implied processes leading to their development, and typical structures / dimensions of the features, and includes data from the walk-through survey and work from the previous research; see Figure 5.5 for photographs of the features. The only observable downstream pattern in the occurrence of the features was that most were found on semi-natural floodplains rather than on the floodplains of modified reaches. Trashlines, floodplain channels (simple and complex), floodplain scour hollows, sand shadows, wood accumulations on the floodplain, and overbank deposits were generally only found in semi-natural reaches; bogs, relict channels, incipient floodplain, and wood pieces were found in both semi-natural and modified reaches (see later discussion on the development of incipient floodplain).

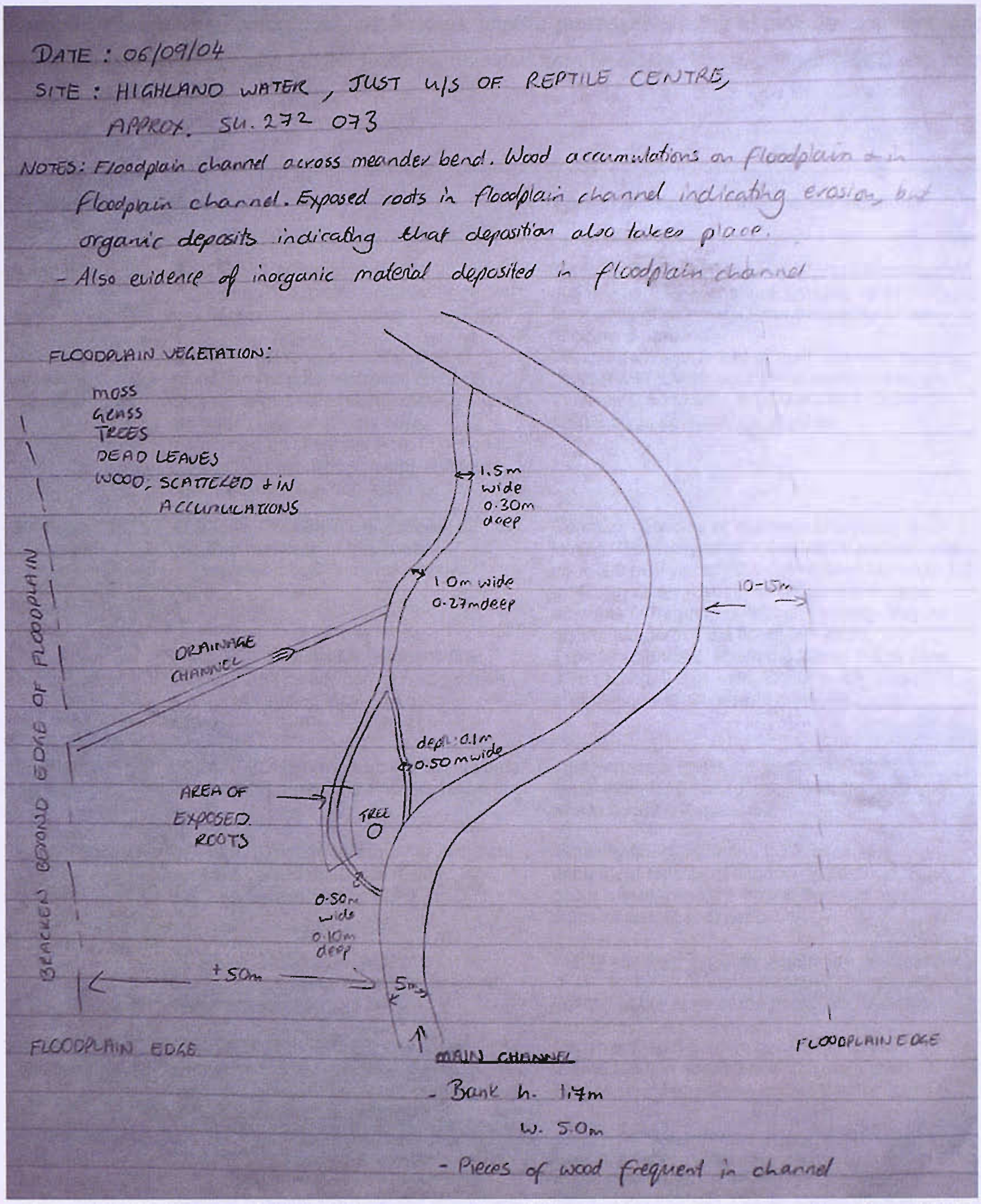


Figure 5.4 Example of a field sketch of a floodplain channel across a meander bend on the Highland Water.

Table 5.1 Floodplain geomorphological features, implied processes leading to their development, and typical structures / dimensions of the features, obtained from GeoData (2003), Jeffries (2002) and from direct field observations.

Floodplain Feature	Process	Typical structure / dimensions / location
Trashline	FLOODING: Movement of organic material on floodplain demarcating recent limit of maximum inundation.	Typically 0.10 - 0.50 m width of trash accumulated in a line parallel to channel; typically up to 10 m from edge of channel. Occur frequently where flooding is present.
Floodplain channels (simple)	UNCERTAIN: one or combination of (i) scour into floodplain surface; (ii) linear deposition to create intermediate low-lying areas; (iii) relict channels being maintained by overbank flow. Function to confine flow resulting in areas of faster flow & floodplain scour.	Typically within a few m of main channel; roughly parallel with it, with occasional lateral branches. Typically 0.50 m wide & 0.20 m deep. Occur frequently in semi-natural reaches.
Floodplain channels (complex)	As above. Possibly more complex due to complex networks of tree roots concentrating flow more frequently.	Complex networks of channels bifurcating & re-joining. Generally up to 1.0 m width, occasionally up to 2.0 m. Typically 0.1-0.5 m deep but up to 1.0 m. Occur rarely, usually associated with large amounts of frequent overbank flooding. May be distributed across the floodplain width.
Floodplain scour hollow	UNCERTAIN: Possibly overbank flow concentrated locally between vegetation, e.g. roots causing local flow acceleration & scour.	Typically elongate, approx. 0.2 m to 0.5 m deep, 0.75 m long, 0.5 m wide. Occur rarely, usually in association with floodplain channels.
Overbank deposit	DEPOSITION: movement of material onto floodplain that remains after cessation of flood.	Thin veneer of sediment, depth: 10^{-3} to 10^{-2} m; aerial extent: 10^{-2} to 10^{0} m^2. Occur frequently where flooding is present.
Sand shadows / wake deposits	DEPOSITION: Organic and / or sediment deposits behind obstacles to flood flow e.g. trees / raised topography.	Typically 0.5 m wide and 0.75 m long but dependent on size of shadowing obstacle. Rare, occur where overbank flow is frequent and contains lots of sediment.
Bog	PONDING: impermeable layers in floodplain stratigraphy causing perched water table.	Highly variable. Typically depths are on the scale of 10^{-2} to 10^{0} m, & aerial extent of 10^{1} m^2. Usually located at the edge of the floodplain. Variable throughout the catchment.
Relict channels	CHANNEL MOVEMENT: channels abandoned either naturally (due to meander cut-off or avulsion) or as a result of human channel modification.	Variable. Depth & width generally increase downstream in accordance with main channel. May be found anywhere across the floodplain.
Incipient floodplain	ACCRETION: Lateral & vertical accretion within the confines of an incised channel. Reflects channel cross section adjustment as a response to incision.	Vegetated gallery; typically narrow (0.5 m to 10.0 m) and low (0.25 - 0.5 m); often occur on alternate sides of the channel. Length typically 1-5 m.
Wood / wood accumulation on floodplain	WOOD FROM FALLEN TREES / BRANCHES: wood may be rafted into accumulations by overbank flow. Causes energy dissipation through increasing resistance to flow. May cause flow to be re-routed around it.	Wood sizes vary from small branches (10^{-2} m) to whole trees (10^{1} m). Wood accumulations vary but are generally on the scale of 10^{0}m; depth typically < 0.02 m. Accumulations generally only occur where flooding is present.

Figure 5.5 (below) Geomorphological features observed on New Forest floodplains: (a) Trashlines; (b) Simple floodplain channel parallel to main channel; (c) Complex floodplain channels and trees; (d) Floodplain scour hollow; (e) Fine sediment deposited overbank; (f) Wake deposit (organic material) downstream of a tree; (g) Sand shadow (fine sediment deposit) behind hummock (centre of photograph); (h) Relict channel; (i) Vegetated incipient floodplain (left-centre); (j) Wood accumulation on floodplain.

(a)

(b)

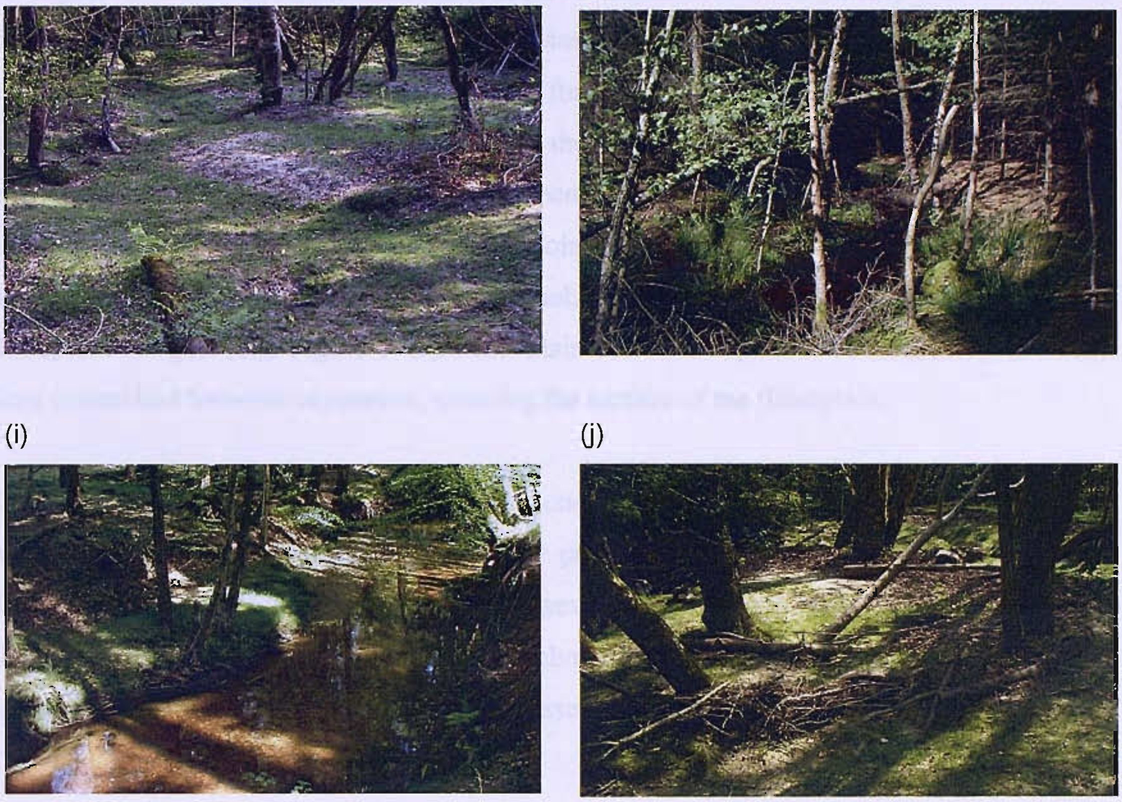
(c)

(d)

(e)

(f)

(g) (h) (i) (j)



5.3 Morphology and evolution of floodplain channels in forested floodplain rivers

5.3.1 Floodplain channels

One of the most widespread geomorphological features observed on floodplains in the New Forest were floodplain channels (e.g. Figure 5.5 (b)). These were studied in more detail, partly because they were widespread, but also because of their apparent importance for floodplain function. Floodplain channels frequently appeared to control the direction of flood water and movement of flood-borne material. After the main channel, they were the most coherent and continuous of natural (or semi-natural) features, often several tens of metres in length and connected to the main channel or to other floodplain channels. They were, in short, the most dominant morphological feature on the floodplain surface, expressing a topology that appeared to be intrinsically linked to overbank hydraulics and therefore to the functioning of the floodplain. As such they are key hydrogeomorphological elements in semi-natural reaches.

Floodplain channels are shallow channels scoured into the floodplain surface that usually only flow during floods (the equivalent of 'flood channels' observed on floodplains in the Gearagh, e.g. Brown *et al.* (1995)). They vary in width from 0.1 m to 1.5 m and depth from 0.05 m to 1.0 m. Floodplain channels occur mainly on the floodplain adjacent to large, hydraulically effective wood jams, or across tight meander bends. They exist as single, distinct channels, or as networks of channels bifurcating and re-joining; single floodplain channels are usually located within a few metres of the main channel, but networks of channels may extend to the floodplain margins (e.g. Figure 5.12). Floodplain channels appear to be formed by overbank flow channelled between vegetation, scouring the surface of the floodplain.

The structure of riverine ecosystems can be understood at a number of hierarchical scales, ranging from the catchment-scale down to the patch-scale (Frissell *et al.*, 1986) (see Section 4.4.1). Therefore, to understand the processes leading to floodplain channel formation, floodplain channels were examined at the catchment-scale (Section 5.3.2), reach and feature-scales (Section 5.3.3), and patch-scale (processes of deposition and erosion, Chapters 6 and 7).

5.3.2 Catchment-scale distribution of floodplain channels

The aim of this section is to identify catchment-scale controls on the development of floodplain channels in order to explain their distribution and subsequently their formation. In order to identify potential processes leading to their development, it is necessary to understand where they occur, and why they form in these areas - what is it about the reaches where they are found that leads to their development? And what is it about reaches where they are not found that inhibits their development?

Methodology

In order to identify geomorphological characteristics that are potentially responsible for the development of floodplain channels, the following study set out to identify firstly where the floodplain channels were, and secondly, the differences in geomorphological characteristics between reaches where floodplain channels were present and reaches where they were absent.

Floodplain channels appear to be linked to overbank flow (Jeffries, 2002). Variables that were likely to influence the frequency and extent of overbank flow (identified within the literature review, Chapter 3) were therefore surveyed through (a) a field study, and (b) a desktop study.

These variables included floodplain width (which may influence overbank flow extent, depth and velocity (Fagan and Nanson, 2004)), channel sinuosity (as sinuosity increases so too does the form resistance of the channel; and water is superelevated on the outside of meander bends (Bathurst *et al.,* 1977), both of which are likely to increase overbank flow (Chapter 3); and sinuous channels are also more likely to contain wood jams (GeoData, 2003)); floodplain connectivity (a direct measure of the likelihood of overbank flow); channel dimensions (which define channel capacity and therefore the likelihood of overbank flow (Chapter 3)); the number and type of wood jams present (another roughness element promoting overbank flow (Jeffries *et al.,* 2003)); and floodplain vegetation type (which influences floodplain roughness (Klassen and Zwaard, 1974; Tabacchi *et al.,* 2000)).

(a) Field study

The field study was undertaken to identify reaches where floodplain channels were present within the Highland Water, Blackwater and Ober Water, and to record the following variables: channel dimensions; the frequency and type of wood jams present; and the nature of floodplain vegetation. These variables were surveyed within all reaches regardless of whether or not floodplain channels were present. Although previous surveys had identified these characteristics in 1998 (Jeffries, 2002) and in 2002 (GeoData, 2003), it was deemed prudent to re-assess these variables at the time of study (2004).

A walk through survey was considered the most appropriate method for capturing this information over the catchment-scale. The survey was carried out during the winter, at a time of year when the understorey vegetation was likely to cause minimum problems in seeing the floodplain surface. The survey involved walking along the main channels and dividing them into reaches of relatively uniform geomorphological character (e.g. German, 2000; Jeffries, 2002; GeoData, 2003). The presence or absence of floodplain channels was noted from observations within each reach (Figure 5.6).

To obtain an average estimate of main channel width and bank height for each reach, these variables were estimated (to the nearest 0.1 m) approximately five times throughout each reach and then averaged (bank height is defined here as the distance from the channel bed to the level of greatest change in slope in the channel bank). From these estimated measurements average channel capacity was obtained for each reach. The number of wood jams of different types were counted for each reach. Type of wood jam was determined using an adaptation from the typology of Gregory *et al.* (1985), whereby 'partial jams' block a portion of the channel but do not span the entire width; 'high water jams' are raised above the channel bed and therefore only function as dams during high flow, 'complete jams' span the entire width of the channel, on the channel bed, but do not cause a step in flow, and 'hydraulically effective jams' ('active' according Gregory *et al.* (1985)) block the entire width of the channel and cause a hydraulic step in the flow. Floodplain vegetation was classified as deciduous, coniferous, or mixed.

Survey error

The visual estimates of channel dimensions were subject to observer error. In order to assess this error (survey error), seven measurements of bank height and channel width were both estimated and made using a metre rule, to the nearest 0.1 m (Table 5.2 and 5.3). The average difference between estimated and measured values of channel width was 0.21 m, with a standard deviation of 0.23. The average difference divided by the average channel width was 0.08. This demonstrates that the technique is precise to within 8%. The average difference between estimated and measured values of bank height was 0.12 m, with a standard deviation of 0.23. The average difference divided by the average bank height was 0.13, demonstrating that the technique used for estimating bank height is precise within 13%. Although these levels of precision do not guarantee that the estimates are accurate, they do show that the estimates will highlight real changes in channel width and bank height.

Table 5.2 Estimated and measured values of channel width.

Estimated (m)	Measured (m)	Difference (Measured - Estimated)
3.0	3.2	0.2
2.5	2.4	-0.1
2.5	2.8	0.3
2.0	2.4	0.4
2.5	2.5	0
2.0	2.0	0
2.0	2.5	0.5
Average channel width		2.54 m
Average difference		0.21 m
S.D.		0.23
Average difference / Average channel width		0.08

Table 5.3 Estimated and measured values of bank height.

Estimated (m)	Measured (m)	Difference (Measured - Estimated)
1	1.1	0.1
1	0.9	-0.1
1.5	1	-0.5
0.7	0.6	-0.1
1	1	0
1	1.1	0.1
0.6	0.6	0
Average bank height		0.9
Average difference		0.12
S.D.		0.21
Average difference / average bank height		0.13

(b) Desktop study

The desktop study obtained the following geomorphological data from reaches where floodplain channels were present and where they were absent:

1. Channel sinuosity. Ordnance Survey Landline data were used to calculate channel sinuosity by dividing channel length by valley length.

2. Floodplain width. This was calculated from LIDAR (LIght Detection And Ranging) data (the edge of the floodplain was depicted by a break in slope between the relatively flat valley floor and the edge of the adjacent hillslope).

3. Floodplain connectivity. The floodplain was considered to be connected to the channel where there was evidence of overbank flow on the floodplain (e.g. trashlines). Reaches on the Highland Water and Blackwater where the channel and floodplain were connected were identified from the GeoData (2003) survey - floodplain connectivity was determined for the Ober Water through field observations.

Results

Floodplain channels were generally present in semi-natural reaches and absent from modified reaches. Figure 5.6 re-classifies the geomorphological reaches according to whether or not floodplain channels were present and whether the reaches were semi-natural or modified.

Figure 5.6 and Table 5.4 show that floodplain channels predominantly occurred in semi-natural reaches, but were also present in some modified reaches (HW5, BW2, BW4 and

BW7). Furthermore, there were no semi-natural reaches where floodplain channels are absent. Table 5.4 also shows that floodplain channels only occurred in reaches in which the channel and floodplain were connected (i.e. in reaches where overbank flow reached the floodplain). The type of floodplain vegetation (deciduous, coniferous or mixed) did not seem to be associated with the presence or absence of floodplain channels, as floodplain channels were found in reaches with all three types of vegetation. Similarly, floodplain width did not appear to influence the development of floodplain channels as floodplain channels were observed on floodplains ranging in width from 30-155 m, and there was little difference in the average floodplain width (89 m) for reaches where floodplain channels were observed compared with the average for reaches where they were absent (88 m). The standard deviations in floodplain width were high both for reaches where floodplain channels were present (44.47) and where they were absent (39.17). Compared with reaches where floodplain channels were absent, reaches where floodplain channels were present had a higher average channel sinuosity (1.32 compared with 1.08), lower average channel width (4.1 m compared with 4.3 m), lower bank height (0.9 m compared with 1.2 m), and smaller channel capacity (3.6 m^2 compared with 5.4 m^2), and more wood jams of all types (Table 5.4).

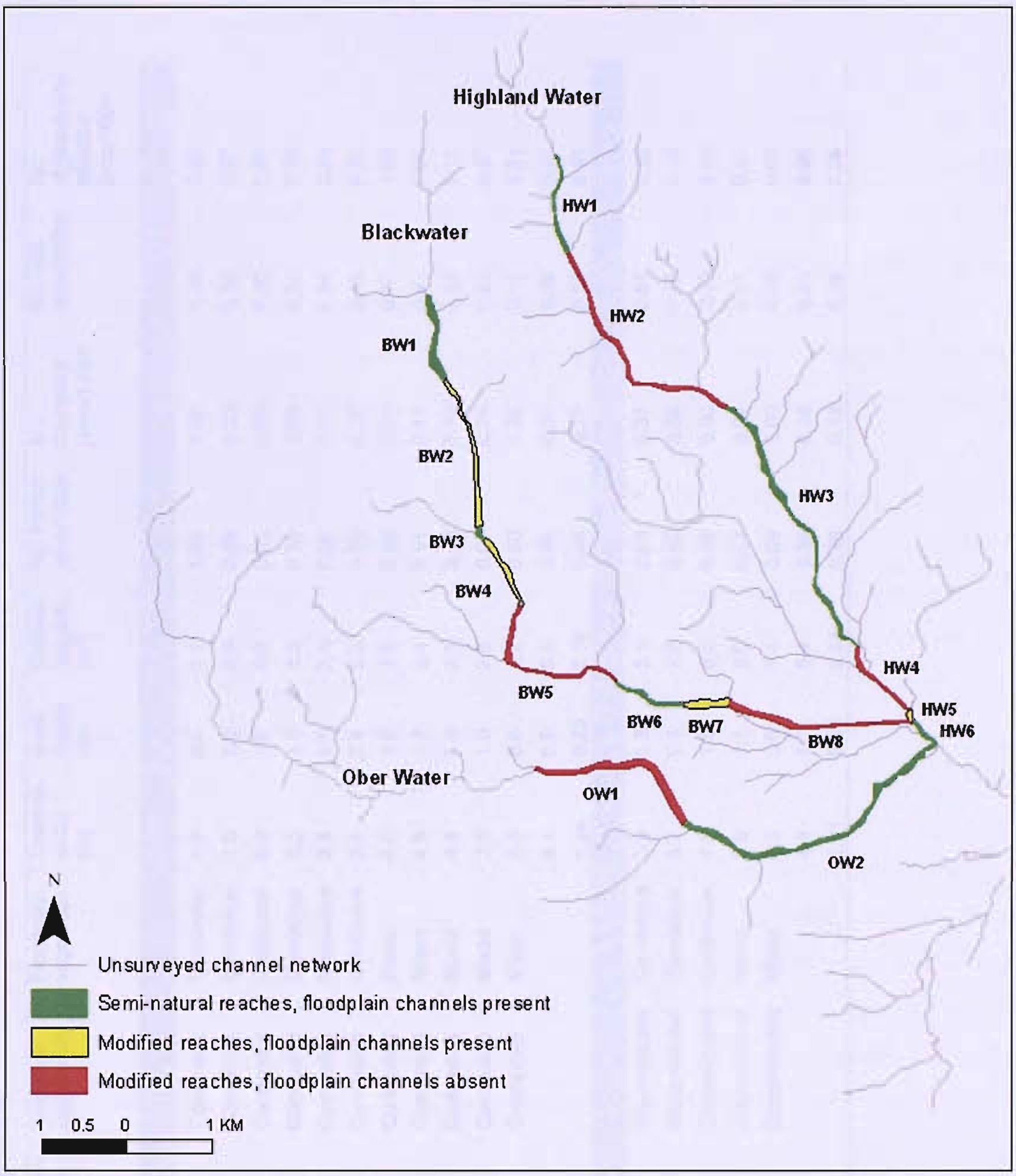


Figure 5.6 Classification of channels into reaches according to whether or not floodplain channels were present and whether the reaches were semi-natural or modified.

Table 5.4 Characteristics of reaches identified in Figure 5.6.

Reach identifier	Semi-natural (SN) or modified (MOD)	Channel length (m)	Channel sinuosity	Floodplain width (m)	Floodplain connectivity	Floodplain vegetation	Channel width (m)	Bank height (m)	Channel capacity (m^2)	No. Partial jams/100m	No. Complete jams/100m	No. HW jams/100m	No. Hydraulically effective jams/100m
Reaches where floodplain channels were present													
HW1	SN	1296	1.43	30	Connected	Deciduous	1.9	0.6	1.1	1.39	1.00	1.16	0.23
HW3	SN	3728	1.37	120	Connected	Deciduous	4.5	1.0	4.5	0.89	0.32	0.75	0.27
HW5	MOD	180	1.22	155	Connected	Deciduous	6.0	1.0	6.0	0.00	0.00	0.00	0.56
HW6	SN	378	1.16	155	Connected	Deciduous	8.3	1.0	8.3	0.79	1.06	0.53	0.00
BW1	SN	1183	1.35	52	Connected	Deciduous	2.3	1.1	2.4	0.08	0.17	0.34	0.25
BW2	MOD	1960	1.21	40	Connected	Coniferous	2.8	0.8	2.3	0.56	0.26	0.15	0.20
BW3	SN	183	1.22	54	Connected	Mixed	4.0	0.6	2.3	0.55	0.00	0.00	1.09
BW4	MOD	938	1.26	60	Connected	Mixed	4.6	1.2	5.4	0.11	0.11	0.43	0.00
BW6	SN	947	1.38	102	Connected	Mixed	4.5	0.6	2.5	0.00	0.53	0.53	0.11
BW7	MOD	1407	1.50	105	Connected	Mixed	2.8	1.0	2.8	0.07	0.14	0.21	0.07
OW2	SN	3880	1.43	108	Connected	Mixed	3.6	0.6	2.2	0.80	0.39	0.18	0.21
Average			**1.32**	**89**			**4.1**	**0.9**	**3.6**	**0.48**	**0.36**	**0.39**	**0.27**
S.D			**0.11**	**44.47**			**1.84**	**0.23**	**2.16**	**0.46**	**0.37**	**0.35**	**0.31**
Reaches where floodplain channels were absent													
HW2	MOD	3062	1.10	53	Disconnected	Coniferous	3.9	1.3	5.1	0.69	0.33	0.56	0.16
HW4	MOD	1052	1.02	150	Disconnected	Deciduous	5.2	1.4	7.2	0.57	0.38	0.19	0.10
BW5	MOD	2155	1.12	74	Disconnected	Coniferous	4.5	1.5	6.8	0.19	0.00	0.09	0.00
BW8	MOD	2232	1.04	100	Disconnected	Mixed	5.8	1.1	6.6	0.27	0.04	0.31	0.13
OW1	MOD	2269	1.10	61	Disconnected	Mixed	2.3	0.6	1.4	0.09	0.00	0.00	0.00
Average			**1.08**	**88**			**4.3**	**1.2**	**5.4**	**0.36**	**0.15**	**0.23**	**0.08**
S.D.			**0.04**	**39.17**			**1.31**	**0.35**	**2.37**	**0.26**	**0.19**	**0.22**	**0.08**

Modified reaches where floodplain channels were present

The above results provide an overview of geomorphological characteristics that were generally associated with reaches where floodplain channels were present and where they were absent. In order to gain a greater understanding of the relative importance of the different variables for the formation of floodplain channels, geomorphological characteristics of specific reaches that were modified but where floodplain channels were still present were further explored. What was it about the geomorphology of these modified reaches that has led to the development of floodplain channels, when they do not occur in other modified reaches?

Firstly, it can be seen from Table 5.4 that the channel and floodplain were connected in modified reaches where floodplain channels were present, whereas they were disconnected in reaches where floodplain channels were absent. Therefore it is sensible to argue that floodplain connectivity is needed for floodplain channels to develop. In order to understand what it was about these reaches that made them connected, when other modified reaches were disconnected, modified reaches with floodplain channels are examined individually.

HW5

This short reach (180 m) at the downstream end of the Highland Water was close to the confluence with the Blackwater (Figure 5.6). The reach was modified, and had large channel dimensions (channel capacity 6.0 m^2), but it had retained a sinuous planform (sinuosity 1.22). The reach had a high frequency of hydraulically effective wood jams (0.56 / 100 m). This could have been a result of the sinuous planform, as GeoData (2003) identified that wood jams frequently formed at 'jam points', for example on a meander inflection confined by trees. It is therefore likely that the high channel sinuosity and the high frequency of hydraulically effective wood jams promoted overbank flow, despite the large channel capacity, achieving floodplain connectivity and consequently the development of floodplain channels.

BW2

This reach was on the Blackwater and was approx. 1960 m long (Figure 5.6). The presence of incipient floodplain (e.g. Figure 5.5 (h)) suggests that, although the reach was modified before 1960, the channel was recovering post-modification (GeoData, 2003) by reducing channel capacity through lateral (and vertical) accretion (see Figure 5.7). Channel sinuosity was high for a modified reach (1.21), and channel dimensions were small – the channel capacity (2.3 m^2) was similar to the semi-natural reach immediately upstream (2.4 m^2). Furthermore, wood jams were present, and there were more hydraulically effective wood jams / 100 m (0.2) than in reaches where floodplain channels were absent (average 0.08). It is therefore suggested that floodplain connectivity had been re-established post modification through reduced channel capacity, increased sinuosity and the establishment of wood jams (particularly hydraulically effective wood jams).

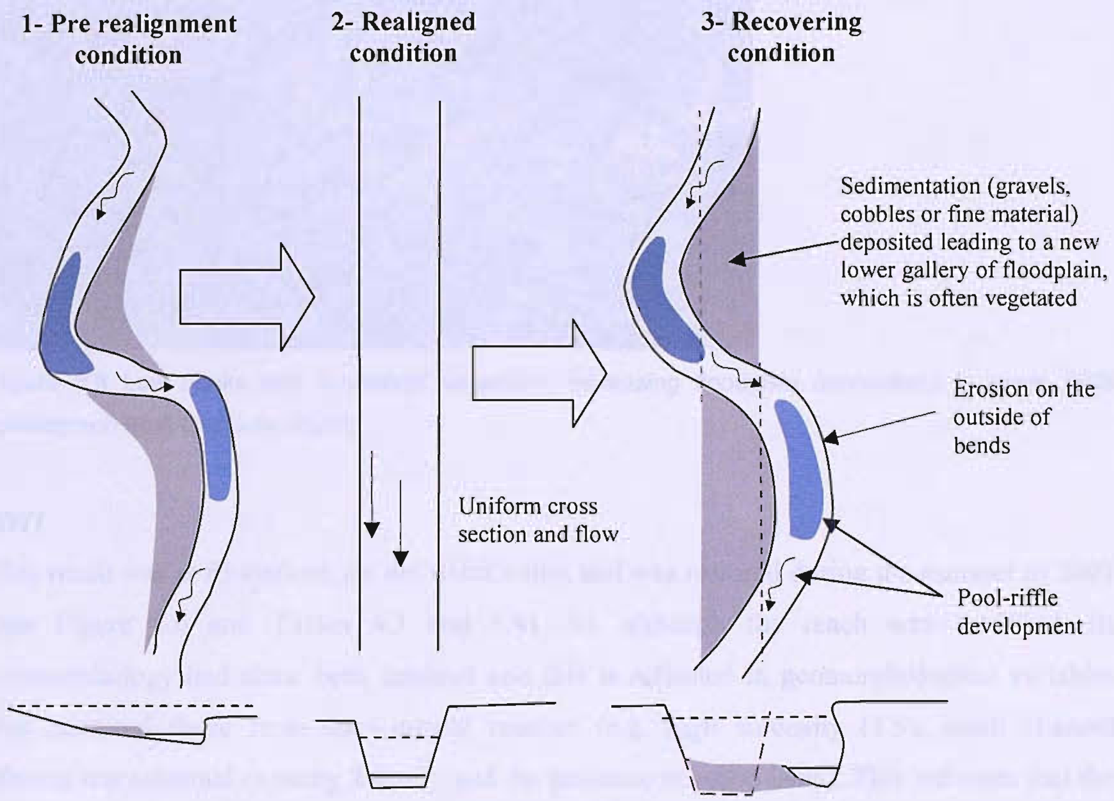


Figure 5.7 Channel recovery through the development of incipient floodplain.

BW4

BW4 was approximately 938 m in length, and was located further downstream on the Blackwater. The floodplain connectivity in this reach was more difficult to explain as channel dimensions were large (channel capacity 5.4 m^2) and there were no hydraulically effective wood jams present. However, channel sinuosity was high (1.26), possibly promoting floodplain connectivity. Furthermore, although average bank height and channel width were large (1.2 m and 4.6 m respectively), they were also variable throughout the reach; bank height ranged from 0.8 m to 2.0 m, and channel width ranged from 3.0 m to 6.0 m. Riparian vegetation also helped reduce channel capacity and increase floodplain connectivity, which was a particularly effective process where the banks were low (Figure 5.8).

Figure 5.8 Low banks and in-channel vegetation increasing floodplain connectivity in reach BW4 (photograph from GeoData, 2003).

BW7

This reach was at Rhinefield, on the Blackwater, and was restored during the summer of 2003 (see Figure 4.6 and Tables 4.3 and 4.4). So, although the reach was modified, its geomorphology had since been restored and this is reflected in geomorphological variables that mirrored those from semi-natural reaches (e.g. high sinuosity (1.5), small channel dimensions (channel capacity 2.8 m^2), and the presence of wood jams). This indicates that the restoration was successful at re-connecting the floodplain, facilitating the development of floodplain channels.

These results suggest that floodplain connectivity and the development of floodplain channels was particularly related to high channel sinuosity, small channel capacity, and the presence of hydraulically effective wood jams. Compared with modified reaches where floodplain channels were absent, modified reaches where floodplain channels were present had higher channel sinuosity (average 1.03 compared with 1.08), lower channel capacities (4.1 m^2 compared with 5.4 m^2), and more hydraulically effective wood jams / 100m (0.20 compared with 0.08).

In order to verify if the observed differences in characteristics between reaches where floodplain channels were present and where they were absent are significantly different, Student's t-tests were run. Table 5.5 shows that, at the 0.05 level, for reaches where floodplain channels were present compared with those where they were absent: channel sinuosity was significantly higher, channel depth was significantly lower, and there were significantly more hydraulically effective wood jams / 100 m.

Table 5.5 Student's t-test results for reaches where floodplain channels were present and where they were absent.

Variable	Hypothesis	t-stat	t-critical at the 0.05 level	Accept or reject H_o
Channel sinuosity	H_1: $\mu_{present} > \mu_{absent}$ H_0: no significant difference	4.66	1.76	*Reject H_o, accept H_1
Channel width (m)	H_1: $\mu_{absent} > \mu_{present}$ H_0: no significant difference	0.24	1.76	Accept H_o
Channel depth (m)	H_1: $\mu_{absent} > \mu_{present}$ H_0: no significant difference	2.29	1.76	*Reject H_o, accept H_1
Channel capacity (m^2)	H_1: $\mu_{absent} > \mu_{present}$ H_0: no significant difference	1.49	1.76	Accept H_o
No. Partial jams/100m	H_1: $\mu_{present} > \mu_{absent}$ H_0: no significant difference	0.57	1.76	Accept H_o
No. Complete jams/100m	H_1: $\mu_{present} > \mu_{absent}$ H_0: no significant difference	1.33	1.76	Accept H_o
No. HW jams/100m	H_1: $\mu_{present} > \mu_{absent}$ H_0: no significant difference	1.11	1.76	Accept H_o
No. Hydraulically effective jams/100m	H_1: $\mu_{present} > \mu_{absent}$ H_0: no significant difference	2.05	1.76	*Reject H_o, accept H_1

$\mu_{present}$ is the mean of the reaches where floodplain channels were present; μ_{absent} is the mean of the reaches where floodplain channels were absent; * Indicates significant difference.

The t-tests generally confirm the earlier observations identifying which geomorphological variables were important for the development of floodplain channels based on details of modified reaches where floodplain channels were present. However, they also indicate that bank height was more important than channel capacity in promoting floodplain connectivity and the development of floodplain channels. This could be because low banks maximise the chance of any increase in channel roughness causing overbank flow (e.g. wood in a shallow, wide channel is likely to form more of an obstruction to flow than wood in a deep, narrow channel). Alternatively, the absence of a significant difference in channel capacity between reaches where floodplain channels were present and where they were absent could be due to the compound survey error associated with the calculation of channel capacity.

Discussion

The results of the catchment-scale survey of floodplain channels have demonstrated that overbank flow (expressed as 'floodplain connectivity') was a requirement for floodplain channel development. This is consistent with observations of floodplain channels in other countries, e.g. in the Gearagh, southwest Ireland (Brown *et al.*, 1995) and in Cooper Creek, Australia (Fagan and Nanson, 2004). However, contrary to the findings by Fagan and Nanson (2004), floodplain width was not related to floodplain channel development. Fagan and Nanson (2004) argue that floodplain width is important through its control on the distribution and energy of overbank flows. This may be the case in Cooper Creek, where floodplain channels were observed across the width of the floodplain; however, in the New Forest, floodplain channels were predominantly (although not exclusively) found bordering the main channel, where in-channel and floodplain vegetation were more important controls than floodplain width on the distribution and energy of overbank flows.

Significantly more hydraulically effective wood jams were observed in reaches where floodplain channels were present than where they were absent, indicating that they may play an important role in promoting the development of floodplain channels. This is supported by other research that identifies in-channel wood jams promoting overbank flow (e.g. Gregory *et al.,* 1985; Brown, 1997; Jeffries *et al.,* 2003; Brummer *et al.,* 2006), particularly hydraulically effective wood jams (Jeffries *et al.,* 2003).

Reaches where floodplain channels were present generally had smaller channel dimensions than reaches where they were absent. This is likely to be due to a smaller channel capacity promoting overbank flow (see Chapter 3) and hence floodplain channel development. However, bank height was found to be more important than channel capacity for floodplain channel development; this could either reflect the fact that low banks maximise the chance of any increase in channel roughness causing overbank flow, or it could be due to the compound survey error associated with the calculation of channel capacity (as already discussed).

High channel sinuosity was associated with the presence of floodplain channels. This is likely to be due to (i) high sinuosity promoting overbank flow (particularly across meander bends (e.g. Howard, 1996; Warner, 1997; Gay *et al.,* 1998)) and (ii) high sinuosity creating jam points and consequently promoting the development of wood jams (GeoData, 2003), further promoting overbank flow and the development of floodplain channels.

Other studies have suggested that floodplain vegetation plays a key role in concentrating overbank flow (e.g. Piégay, 1997; Brown, 1997; Jeffries *et al.,* 2003), leading to the development of floodplain channels. However, this study has demonstrated that the *type* of forest vegetation (deciduous, coniferous or mixed woodland) on the floodplain is not important, as floodplain channels were observed under all three types of woodland.

The catchment-scale survey of floodplain channels has identified floodplain connectivity, channel sinuosity, bank height, and the presence of hydraulically effective wood jams as important controlling factors for floodplain channel development; floodplain width and floodplain forest type were not found to be important.

5.3.3 Reach-scale distribution and morphology of floodplain channels

To further understand the development of floodplain channels, this section examines their distribution and morphology at the reach-scale.

Method

The catchment-scale survey identified reaches on the Highland Water, the Blackwater, and the Ober Water where floodplain channels were present. These reaches were re-visited and the floodplain channels were mapped at the reach-scale (10^0 – 10^2 m). Two types of mapping techniques were used: the most complex networks of floodplain channels were mapped using a 'tape and offset' method, and less complex floodplain channels were mapped through levelling, taking field measurements, and through field sketches.

The 'tape and offset method' involved drawing a scaled map of an area of floodplain and channel by placing tapes perpendicularly across the channel and floodplain every 10 m and mapping, to scale, the geomorphological features that the tape intercepted (see Figure 5.9). Areas between the tapes were mapped using measured offsets at 90 degrees to the main tape. The maps were then digitised using MapInfo and ArcGIS (see Figures 5.10, 5.11 and 5.12). This method was preferred over topographic surveying as the presence of vegetation rendered the use of a DGPS (Differential Global Positioning System) or a total station impractical. Field sketches were deemed inappropriate for these areas of complex floodplain channel networks as a higher level of precision was needed to accurately represent them. However, field sketches (in conjunction with field measurements) were thought acceptable for less complex areas where the structure of floodplain channels could more easily be identified and sketched.

A purposive sampling strategy was employed to select floodplain channels to survey to ensure that the range of 'types' of floodplain channels that occurred throughout the catchments were represented (see Patton, 1990 for a full discussion of this sampling methodology). In total, 15 areas with floodplain channels were sketched. The field sketches were digitised onto a background 1:10,000 landline map of the catchment; the field measurements were used to aid in the accuracy of the map reproductions.

In addition to the 'tape and offset' maps and the field sketches, levelling was used to record floodplain channel slopes and cross-sections. This method was preferred over topographic surveys using a total station because only a relatively small number of data points were required, and levelling captured this information to an acceptable level of precision more rapidly.

(a) 

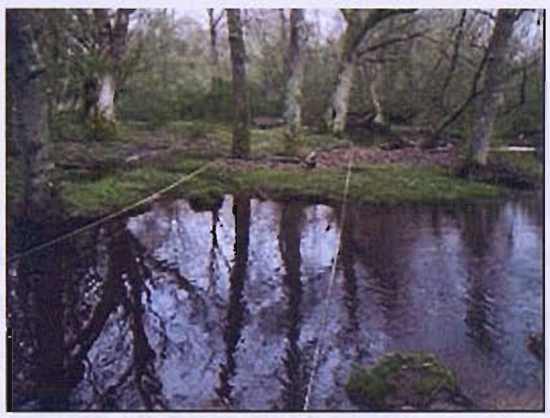
(b) 

Figure 5.9 (a) and (b) Tape and offset method for mapping reaches with complex networks of floodplain channels.

Data analysis

The following quantitative variables describing the observed floodplain channel distributions (in approx. 100 m long reaches) were calculated from the tape and offset maps and from the field sketches (Table 5.6) in order to develop a typology of floodplain channels in the New Forest:

- Floodplain channel width / main channel width
- Main channel sinuosity: length of the main channel / valley (reach) length

- Floodplain channel sinuosity: total floodplain channel length / reach length
- Total sinuosity (after Richards, 1982): sum of all channel lengths / valley length
- Braiding index (i) (after Brice, 1960,1964): 2 x (sum of the lengths of bars or islands in a reach) / centre line reach length
- Braiding index (ii) (after Howard *et al.,* 1970): Average number of channels (including floodplain channels) in several transects (in this work 5 transects were used).
- Average (mean) island length for the reach (m)
- Average (mean) island width for the reach (m)

In order to contextualise the results, and position reaches of New Forest streams with floodplain channels within a global context, the same variables were also calculated for a selection of multiple channel rivers reported within the literature (Table 5.7).

Results

Floodplain channel distribution

(i) Tape and offset maps

Tape and offset maps were created from three sites, located on the Highland Water (Millyford wood jam SU 270 077, Figure 5.10), on the Blackwater (SU 257 046, Figure 5.11) and on the Ober Water (SU 287 039, Figure 5.12). Variable networks of floodplain channels of different depths were observed at the three sites. In order to show on the maps how the depths varied, the floodplain channels were assigned a number between 1 and 5 as shown below:

Floodplain channel 1: very shallow (< 10 cm)
Floodplain channel 2: deep (>10 cm)
Floodplain channel 3: deep with water
Floodplain channel 4: flowing
Floodplain channel 5: flowing with characteristics of main channel, e.g. bars
LWD: large wood (diameter > 0.10 m; length > 1.0 m).

Figure 5.10 Tape and offset map of Millyford, flow is down the page.

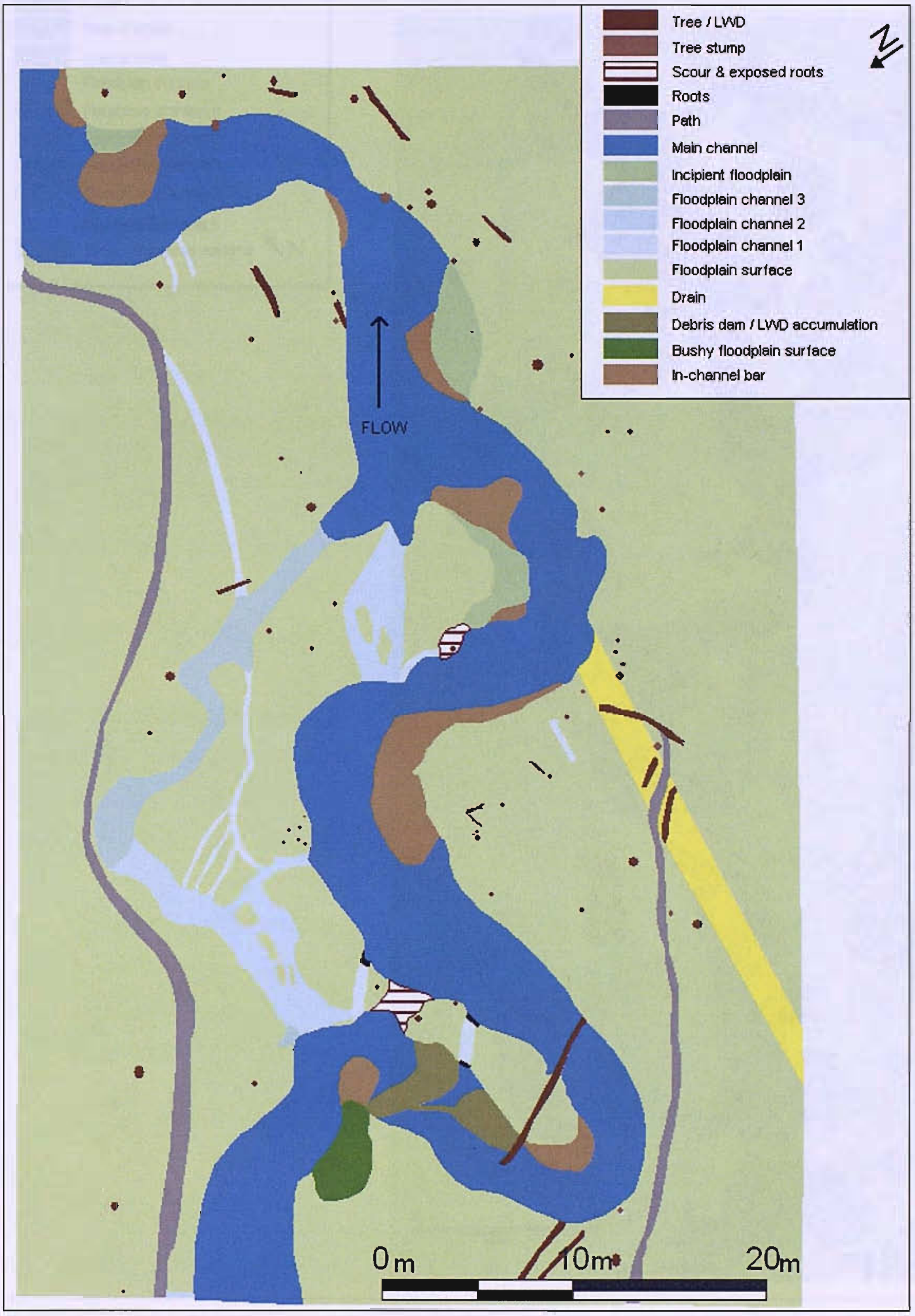


Figure 5.11 Tape and offset map of a reach on the Black Water (floodplain margins are approx. 50 m either side of the channel).

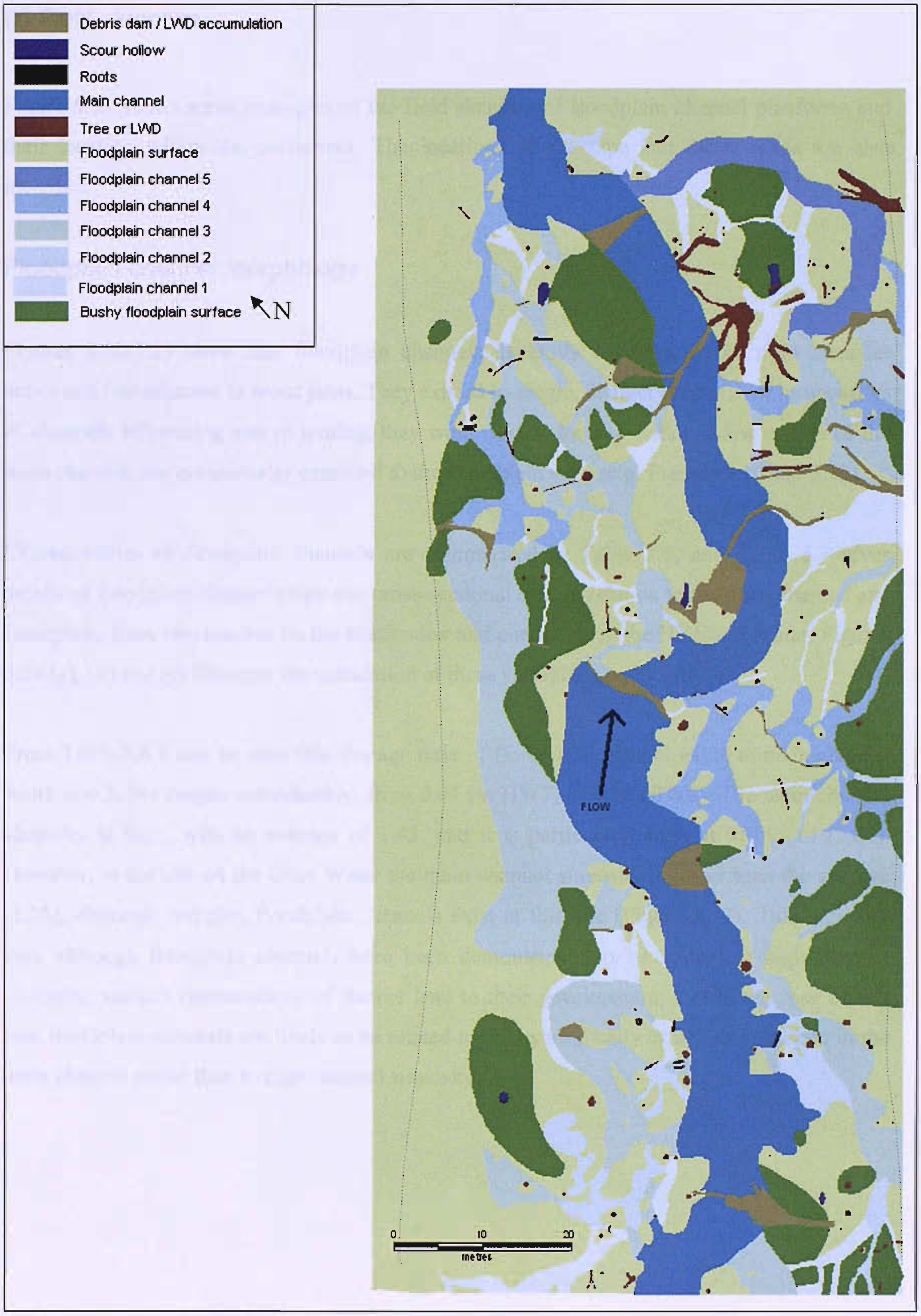


Figure 5.12 Tape and offset map of a reach on the Ober Water (dashed lines represent floodplain margins).

(ii) Field sketches

Figure 5.13 shows some examples of the field sketches of floodplain channel planforms and their location within the catchment. The locations of the tape and offset maps are also included.

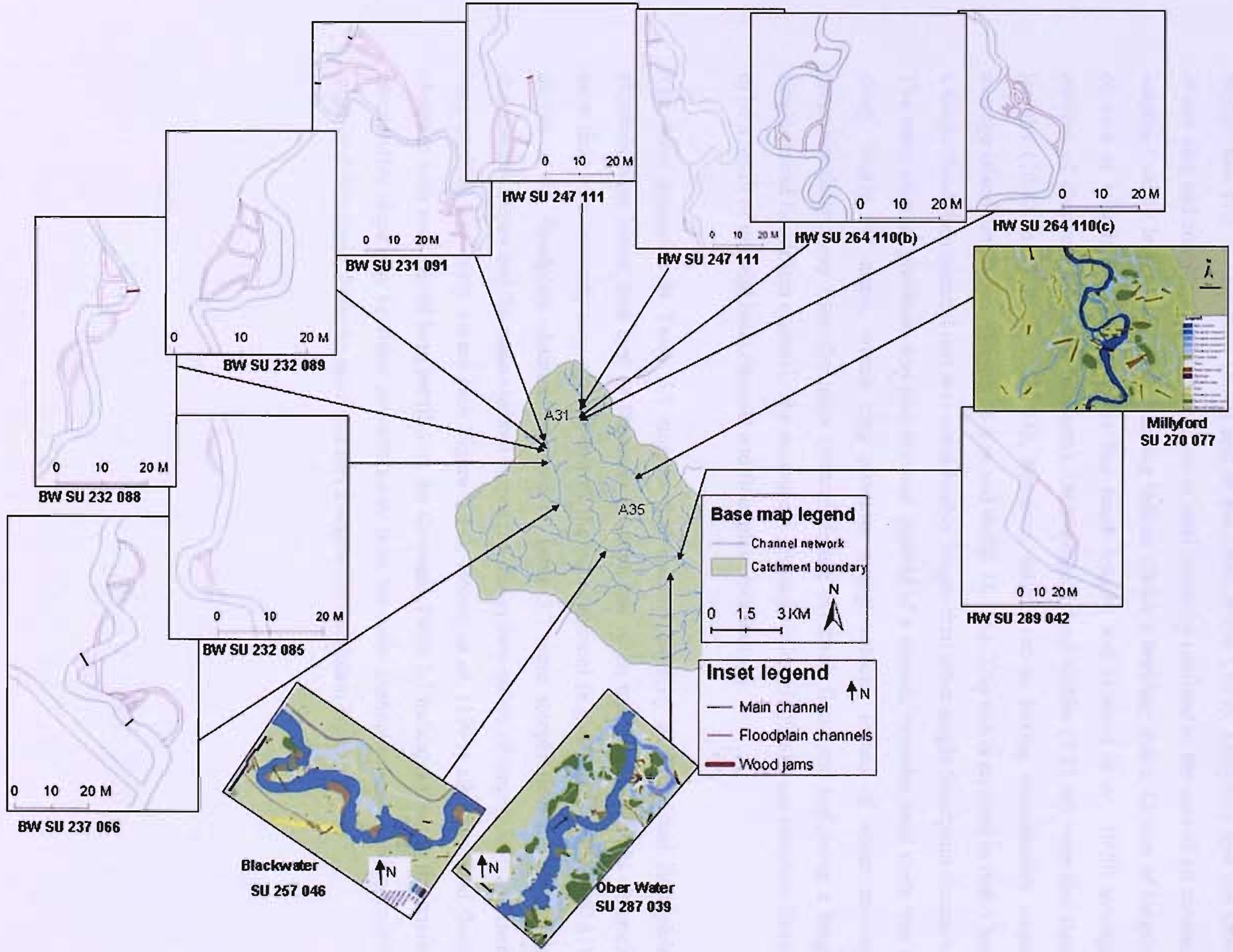
Floodplain channel morphology

Figures 5.10-5.13 show that floodplain channels generally occurred across tight meander bends and / or adjacent to wood jams. They existed as single, distinct channels, or as networks of channels bifurcating and re-joining; they were usually located within a few metres of the main channel, but occasionally extended to the floodplain edge (e.g. Figures 5.10 and 5.12).

Characteristics of floodplain channels are summarised in Table 5.6, and Table 5.7 gives details of floodplain channel slope and cross-sectional area in relation to the main channel and floodplain, from two reaches on the Blackwater and one reach on the Highland Water. Figures 5.14 (a), (b) and (c) illustrate the calculation of these variables graphically.

From Table 5.6 it can be seen that average ratio of floodplain channel width to main channel width is 0.3, but ranges considerably, from 0.07 (in HW7) to 0.50 (BW6). The main channel sinuosity is high, with an average of 1.45, and it is particularly high at Millyford (2.01). However, at the site on the Ober Water the main channel sinuosity is lower than the average (1.16), although complex floodplain channels exist at this site (Figure 5.12). This indicates that, although floodplain channels have been demonstrated to be related to high channel sinuosity, various combinations of factors lead to their development, and in the case of this site, floodplain channels are likely to be related to the hydraulically effective wood jam in the main channel rather than to high channel sinuosity.

Figure 5.13 Examples of reach-scale morphology of floodplain channels in relation to the main channel.



The floodplain channel sinuosity (defined as total floodplain channel length / reach length) was generally higher than the main channel sinuosity (average 2.07), but it was considerably higher than this at Millyford (6.37) and at the Ober Water (7.57). Millyford and the Ober Water also had considerably higher values of total sinuosity (defined as the sum of all channel lengths / valley length), and both braiding indices (Brice's braiding index: (2(sum of lengths of bars or islands in a reach)/centre line reach length) and Howard *et al.,* 1970: average number of channels in several transects). On average, island widths (5.01 m) were half their lengths (10.62 m). HW SU 289 042, however, stands out as having considerably larger average island dimensions (length 46.8 m and width 24.1 m). This site is atypical in that it had a single floodplain channel that was considerably longer than other single floodplain channels. The main channel planform was also unusual: instead of a smooth meander bend there was a sharp, nearly 90° angle, which may promote a high-velocity thread of water moving perpendicularly away from the main channel during overbank flow, and sustaining a long, single-thread floodplain channel. The anomalous characteristics of this site are therefore likely to be a result of unusual local channel and floodplain morphology.

The three examples in Table 5.7 suggest that channel capacity of individual floodplain channels were lower than that of the main channel, but when multiple floodplain channels exist their total capacity may exceed that of the main channel (e.g. BW SU 23133 09181). Slopes of the floodplain channels reported in Table 5.7 were steeper than the floodplain downvalley slopes and the main channel slopes (by one or two orders of magnitude), and their long profiles were very varied (see Figure 5.14); Brown *et al.* (1995) also observed flood channels with very varied long profiles on the Gearagh. Table 5.7 indicates that the floodplain cross-valley slope may be either upwards away from the main channel towards the floodplain edge, or downwards, from the main channel towards the floodplain edge.

Table 5.6 Characteristics of floodplain channels in relation to the main channel obtained from planform maps.

Location	Source	Catchment area (km^2)	Floodplain channel width / main channel width	Main channel sinuosity	Floodplain channel sinuosity (total floodplain channel length / reach length)	Total sinuosity (Richards, 1982): sum channel lengths / valley length	Braiding index (Brice, 1960,1964): 2(sum of lengths of bars or islands in a reach)/centre line reach length	Braiding index (Howard et al., 1970): Average number of channels (including floodplain channels) in several transects	Average Island length (m)	Average island width (m)
Millyford (SU 270 077)	T&O	12.7	0.25	2.01	6.39	8.41	6.89	7	5.7	2.2
Ober Water (SU 287 039)	T&O	20.73	0.27	1.16	7.57	8.72	6.29	9	10.2	2.8
Blackwater (SU 257 046)	T&O	20.3	0.21	1.82	1.84	3.67	2.15	2	8.6	2.0
HW SU 246 111	DFS	2.18	0.24	1.39	1.22	2.61	0.65	2	5.0	9.0
HW SU 247 111	DFS	2.5	0.20	1.83	1.06	2.89	2.12	2	12.9	6.6
HW SU 246 110(a)	DFS	3.05	0.43	1.73	1.56	3.29	2.17	2	7.1	2.4
HW SU 246 110(b)	DFS	3.25	0.41	1.35	0.55	1.90	0.79	2	8.5	3.5
HW SU 246 110(c)	DFS	3.50	0.41	1.28	2.00	3.28	2.52	2	6.1	2.8
HW SU 287 044	DFS	47.25	0.07	1.52	0.85	2.37	1.22	2	5.1	1.5
HW SU 289 042	DFS	50.02	0.21	1.08	0.87	1.95	1.53	2	46.8	24.1
BW SU 231 091	DFS	4.29	0.47	1.86	2.53	4.39	4.00	3	21.9	10.0
BW SU 232 091	DFS	4.58	0.29	1.35	1.86	3.21	2.08	3	4.8	3.9
BW SU 232 089	DFS	4.79	0.40	1.30	1.44	2.74	1.58	3	6.2	2.7
BW SU 232 088	DFS	4.97	0.43	1.33	1.15	2.49	1.22	2	8.7	3.4
BW SU 232 085	DFS	5.97	0.25	1.44	1.14	2.58	1.33	2	4.9	2.3
BW SU 235 081	DFS	6.97	0.50	1.05	1.72	2.77	2.42	2	14.3	3.8
BW SU 237 066	DFS	11.83	0.20	1.24	1.43	2.67	1.46	2	7.4	4.5
BW SU 256 046	DFS	20.21	0.10	1.38	2.09	3.47	1.94	4	6.9	2.8
Average			**0.30**	**1.45**	**2.07**	**3.52**	**2.35**	**3**	**10.6**	**5.0**

T&O: Tape and offset maps; DFS: Digitised field sketches; HW: Highland Water; BW: Blackwater

Table 5.7 Characteristics of floodplain channels in relation to the main channel and floodplain, obtained from the cross-section survey.

Location	Main channel cross-section area m^2	Floodplain channel cross-section area (total if > 1 floodplain channel) m^2	Main channel slope (m/m)	Floodplain channel slope (m/m)	Floodplain downvalley slope (m/m)	Floodplain cross-section slope (m/m)
BW SU 231 091	0.959	1.17	0.0086	0.796	0.016	0.002
BW SU 237 066	2.37	1.03	0.0068	0.035	0.015	0.007
HW SU 289 042	6.88	0.21	0.0018	0.013	0.007	*0.008

* slope is downwards, away from main channel towards floodplain edge

Figures 5.14 (below) Illustrations of how floodplain channel characteristics were calculated for different locations: (a) HW SU 289 042; (b) BW SU 237 066; (c) BW SU 231 091.

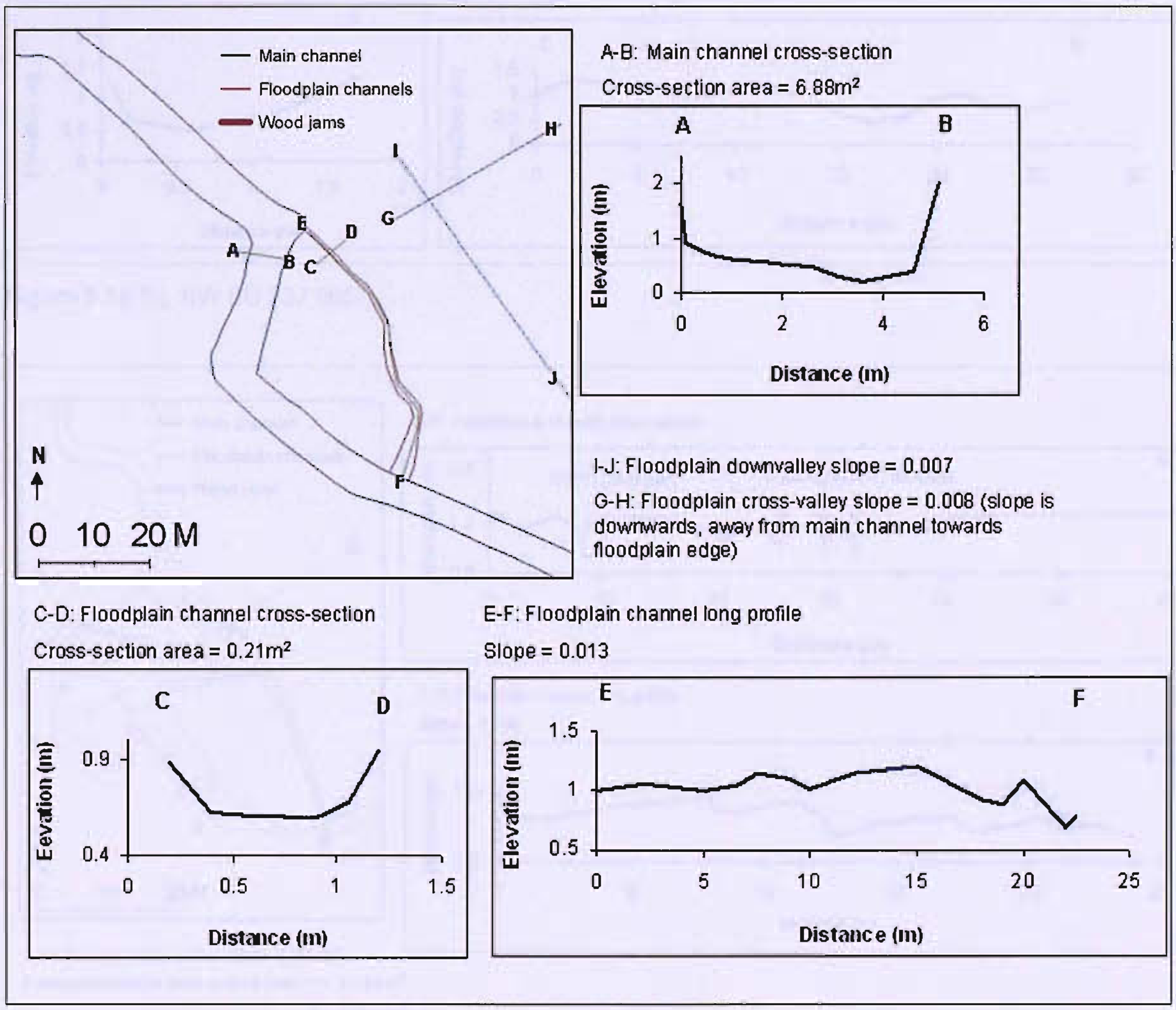


Figure 5.14 (a) HW SU 289 042.

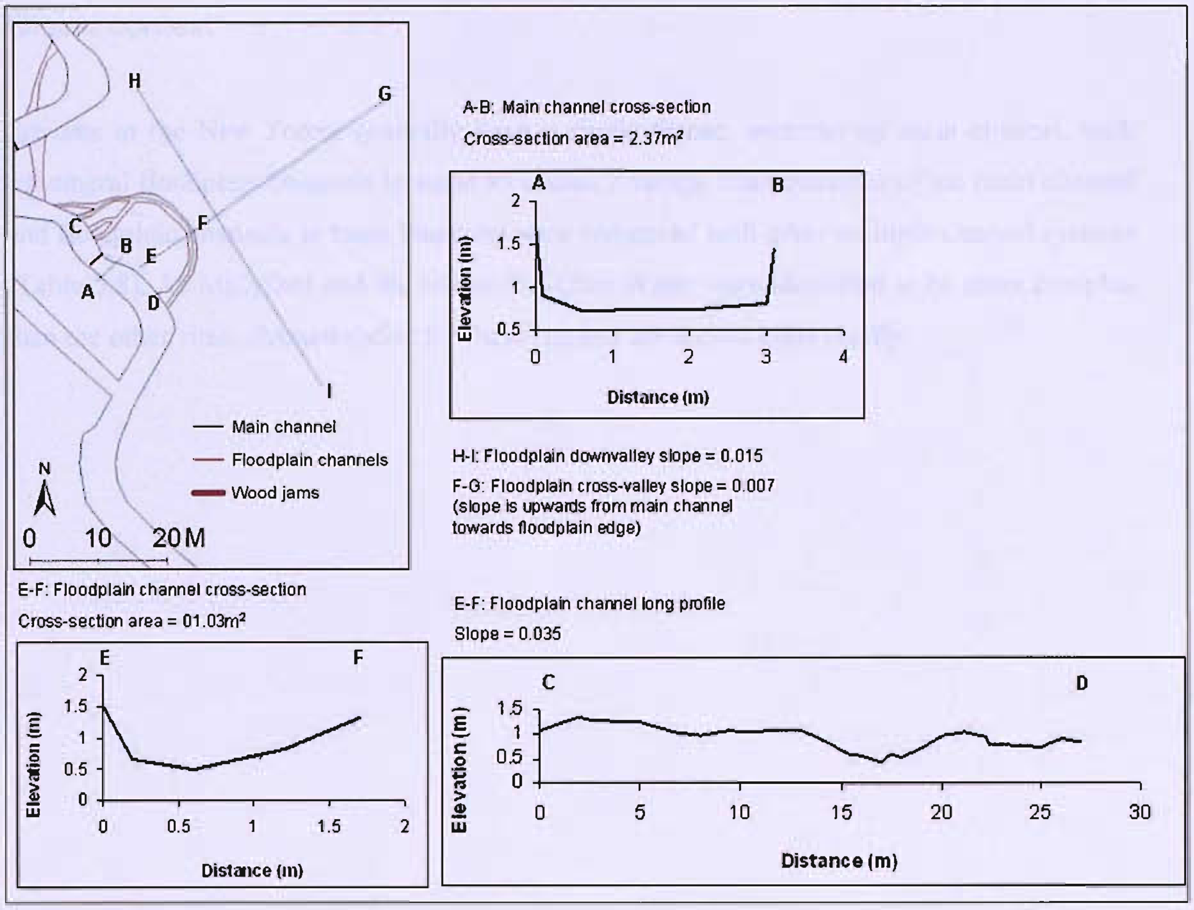


Figure 5.14 (b) BW SU 237 066.

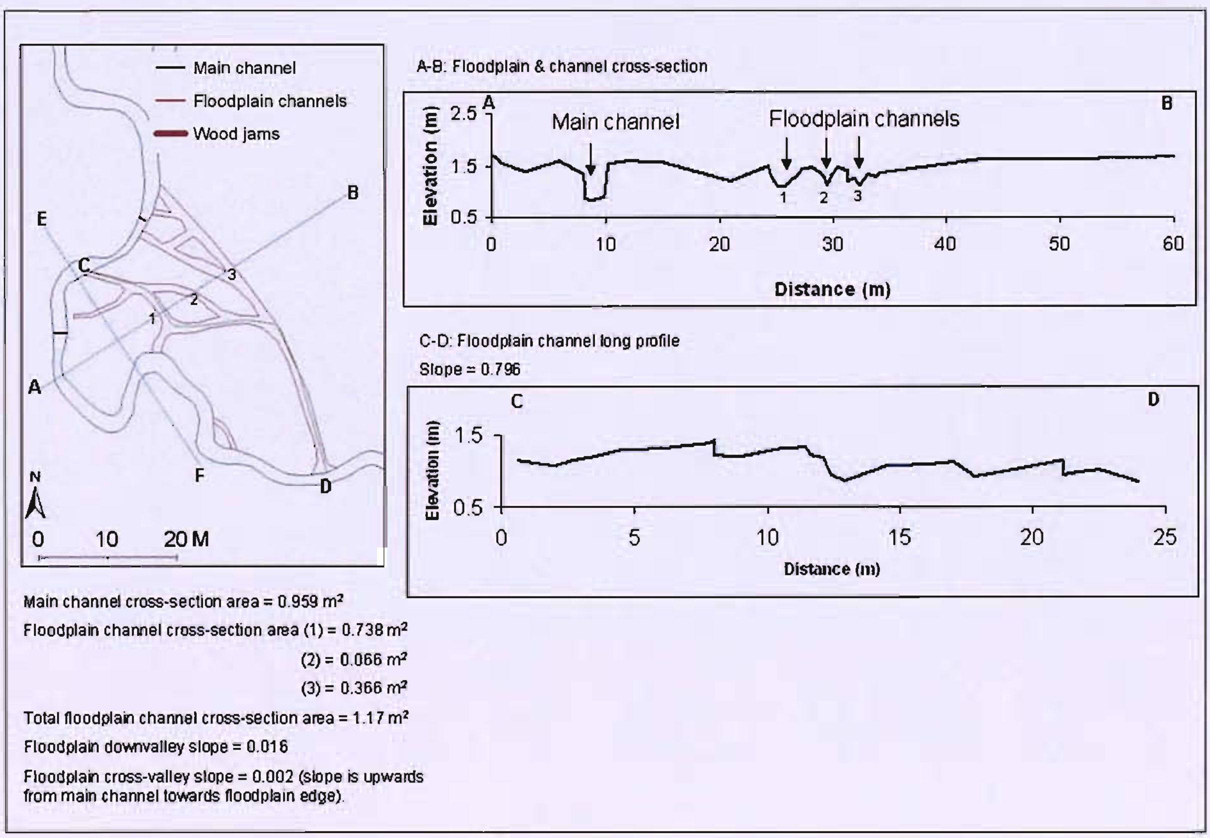


Figure 5.14 (c) BW SU 231 091.

Global context

Streams in the New Forest generally have a single thread, meandering main channel, with ephemeral floodplain channels in some locations. Average characteristics of the main channel and floodplain channels in these locations were compared with other multiple channel systems (Table 5.8). As Millyford and the site on the Ober Water were identified to be more complex than the other sites, characteristics for these reaches are shown individually.

Table 5.8 Characteristics of areas with floodplain channels in the New Forest and other multiple channel systems (for definitions see Table 5.6).

Location	River 'type'	Source	Floodplain channel width / main channel width	Floodplain channel sinuosity	Total sinuosity	Braiding index (Brice, 1960,1964)	Braiding index (Howard et al., 1970)	Average Island length (m)	Average island width (m)
New Forest: average for locations with floodplain channels (excluding the site on the Ober Water and Millyford)	Single thread, meandering main channel, with ephemeral floodplain channels in some locations	T&O & DFS	0.30	1.46	2.89	1.82	2.31	10.95	5.33
New Forest: Millyford, one of the most complex areas of floodplain channels	As above	T&O	0.25	6.39	8.41	6.89	7	5.7	2.2
New Forest: Ober Water, one of the most complex areas of floodplain channels	As above	T&O	0.27	7.57	8.72	6.29	9	10.2	2.8
Gearagh on the River Lee, southwestern Ireland.	Anastomosing	A reproduction of islands & channels from a 1:2,500 map (Fig. 34 from Brown et al., 1995, p61).	0.5075	0.70	12.00	13.00	13	39.50	Approx. 20m
Zaire	Anastomosing	Summerfield (1991)			13.00	13.00	12		
Rakaia, New Zealand	Braided	Warburton, pers comm. cited in Brown et al. (1995)			12.00	14.00	12		
Waimakariri, New Zealand	Braided	Warburton, pers comm. cited in Brown et al. (1995)			5.00	4.00	6		
Flume study	Flume	Young, 1989, cited in Brown et al. (1995)			4	6.00	5		
Nisqually, in the Puget Lowlands, Pacific Northwest	Anastomosing	* An orthophotograph (Fig. 10 from Collins & Montgomery, 2002 p243). Includes perennial floodplain channels			5.1	4.61	4	443	130.00
Cooper Creek, Australia	Anastomosing	Fagan and Nanson (2004)						400-3500	90-630

*unclear Figure, so an estimate

From Table 5.8 it can be seen that in most areas in the New Forest where floodplain channels were present, channel characteristics were generally very different to those observed in other multiple-channel river systems (braided and anastomosed). In particular, braiding indices were much lower in the New Forest (e.g. Brice's braiding index of 1.82 compared with 13 for the Gearagh and the Zaire). However, characteristics from the most complex sites in the New Forest (Millyford and the Ober Water) were comparable with other multiple-channel systems. For example, Millyford had a Brice's braiding index of 6.89 and the Ober Water of 6.29, and Brice's index from other studies of anastomosed and braided channels ranged from 5.1 (Nisqually) to 14 (Rakaia). Islands were generally smaller in the New Forest than in other studies, reflecting the overall smaller scale of the river system, but the proportions were similar to those in the Gearagh, with the length of islands being approximately twice the width (Brown *et al.,* 1995).

It is therefore interpreted that, in general, single-thread, meandering streams in the New Forest have very different characteristics to multiple-channel systems, even in areas where floodplain channels are present. However, in certain locations, complex networks of floodplain channels exist (e.g. Millyford and the site on the Ober Water), where characteristics (e.g. braiding indices) are similar to those in other multiple-channel systems. This may indicate that these complex areas could develop into anastomosed reaches, with multiple permanent channels (anastomosed rather than braided, as the islands were made up of floodplain rather than mobile bars, as found in braided river, see Brown *et al.* (1995)). However, other than at Millyford and at the site on the Ober Water, there is no evidence of multiple permanent channels, and even at these sites where the floodplain channels display characteristics of the main channel (e.g. bars and bedload), the main channel is clearly distinguishable from the floodplain channels (see Section 5.3.6 for a discussion on the evolution of floodplain channels).

5.3.4 Floodplain channel typology

From the previous sections it is apparent that considerable variability exists in the reach-scale distribution and morphology of floodplain channels in the New Forest. In order to understand the mechanisms of their formation, it was useful to simplify the variability into distinct 'types' of floodplain channel. Based on data from Section 5.3.3, a 'typology' of floodplain channels observed in the New Forest is presented in Figure 5.15, ranging from Type 1 to Type 3.

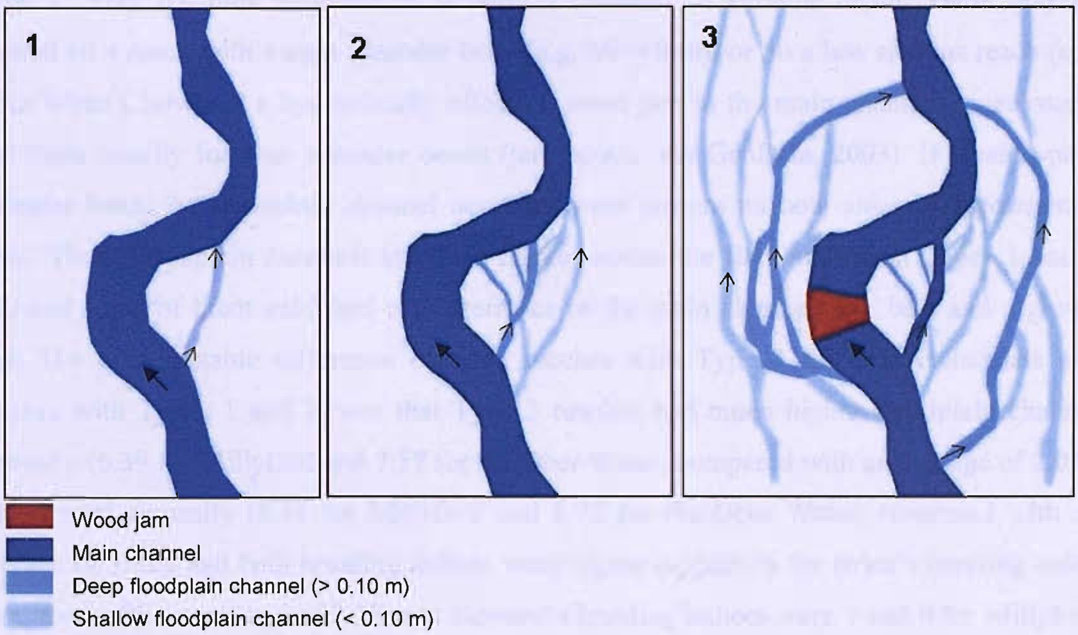


Figure 5.15 Floodplain channel typology from Type 1 to Type 3; arrows indicate flow direction.

Type 1: A single floodplain channel across the inside of a meander bend, usually shallow (< 0.10 m). There may or may not be a wood jam in the main channel. The floodplain channel is usually located within a few metres of the main channel e.g. HW SU 289 042, HW SU 287 044, BW SU 232 085 (Figure 5.13). These reaches had fairly low floodplain channel width to main channel width ratios, ranging from 0.07 to 0.25 (compared with an average of 0.30 for all reaches); the range of the main channel sinuosity (1.08 to 1.52) was similar to the average (1.45); floodplain channel sinuosity was low (0.85 to 1.84, compared with an average of 2.07); total sinuosity was low (1.95 to 2.58 compared with an average of 3.52); both braiding indices were low (Brice's: 1.22 to 1.53, compared with an average of 2.35, and Howard's: 2 compared with an average of 3); and island lengths and widths were very variable (lengths range from 4.9 to 46.8m and width from 1.5 m to 24.1 m compared with an average length of 10.6 m and average width of 5.0 m; however, this large range is due to the large dimensions of the island in HW SU 289 042, already discussed).

Type 2: A more complex network of floodplain channels across the inside of a meander bend. Some may be deep (> 0.10 m). There may or may not be a wood jam in the main channel. The floodplain channels were usually located within a few metres of the main channel. Type 2 were the dominant type of floodplain channels observed in the New Forest, e.g. BW SU 232 089 and BW SU 231 091 (Figure 5.13), and hence had reach characteristics that approximate to the average (Table 5.6).

Type 3: Very complex networks of floodplain channels of variable depth. These may be located on a reach with a tight meander bend (e.g. Millyford), or on a less sinuous reach (e.g. Ober Water), however a hydraulically effective wood jam in the main channel is necessary, and these usually form on meander bends (jam points, see GeoData, 2003). If located on a meander bend, the floodplain channel networks were present on both sides of the meander bend. These floodplain channels extended further across the floodplain than Types 1 and 2 did, and some of them exhibited characteristics of the main channel, e.g. bars and a gravel bed. The most notable difference between reaches with Type 3 floodplain channels and reaches with Types 1 and 2, was that Type 3 reaches had much higher floodplain channel sinuosity (6.39 for Millyford and 7.57 for the Ober Water, compared with an average of 2.07), higher total sinuosity (8.41 for Millyford and 8.72 for the Ober Water, compared with an average of 3.52), and both braiding indices were higher (approx. 6 for Brice's braiding index compared with an average of 2.35, and Howard's braiding indices were 7 and 9 for Millyford and the Ober Water respectively, compared with an average of 3). The values of these variables were similar to those observed in anastomosed systems, e.g. the Gearagh (Table 5.8).

5.3.5 Mechanisms of floodplain channel formation

Global scale

To identify the mechanisms that form the three types of floodplain channel observed in the New Forest, mechanisms forming floodplain channels reported in the literature (and discussed in the Literature Review, Chapter 3) are re-capped here.

1. Floodplain surface channels.

Floodplain surface channels are channels located within the floodplain that are shallower than the main channel(s) and usually only flow during periods of flooding (Brown *et al.,* 1995; Fagan and Nanson, 2004). The principal processes forming these channels are floodplain surface scour (Brown *et al.,* 1995; Piégay *et al.,* 1998; Fagan and Nanson, 2004) due to overbank flow concentration and acceleration, for example by floodplain topography (e.g. gilgai mounds, Fagan and Nanson, 2004) and vegetation (e.g. trees and wood (Harwood and Brown, 1993; Piégay *et al.*, 1998; Hupp, 2000), and headward erosion at the point of overbank flow re-entry to the main channel (Warner, 1997). These channels have been observed on Cooper Creek, Queensland, Australia (Fagan and Nanson, 2004), the River Ain, France (Piégay *et al.*, 1998) and in the Gearagh, southwestern Ireland (Brown *et al.,* 1995).

The drivers of overbank flow vary, but Brown *et al.* (1995) argue that in the Gearagh, overbank flow is promoted by in-channel wood jams ponding flow upstream.

2. Meander cut-offs.

Meander cut-offs represent a form of channel avulsion (Thompson, 2003), which is defined as "flow diversions that cause the formation of new channels on the floodplain" (Makaske, 2001 p149 see Chapter 3)). Meander cut-offs occur when a new channel develops across the neck of a meander bend and captures the flow from the main channel (Gay *et al.,* 1998; Thompson, 2003). Flow across a meander neck is promoted by tight meander bends (Howard, 1996), and reduced channel capacity through in-channel aggradation (e.g. Brooks *et al.,* 2003; Thompson, 2003) and in-channel blockages, such as ice or wood (e.g. Maser and Sedell, 1994; Makaske, 2001; Abbe and Montgomery, 2003; O'Conner *et al.,* 2003; Brummer *et al.,* 2006). The dominant process leading to the creation of meander cut-offs is upstream headward erosion of a knick-point at the point of re-entry to the main channel (Thompson, 2003). The high slope increases the erosive power of overbank flow, causing the knick point to migrate upstream, leaving a channel in its wake (Gay *et al.,* 1998; Thompson, 2003). This is the process suggested to be responsible for the creation of meander cut-offs on the Powder River, Montana (Gay *et al.,* 1998), and on the Blackledge River in central Connecticut, USA (Thompson, 2003).

3. Chute channels

Chute channels are shallow channels formed by scour across coarse point bar deposits – they are common in rivers with a low supply of cohesive overbank deposits (Howard, 1996). Chutes typically form on rivers which experience infrequent but extreme discharges (Lewin, 1978).

As discussed in Chapter 3, there is limited literature concerning processes of floodplain channel formation. The main processes leading to different types of floodplain channel identified within the literature have been mentioned above; however, there may be other important processes that have received less investigation. For example, preferential retardation of floodplain deposition in floodplain channels (e.g. Jeffries, 2002; Fagan and Nanson, 2004), re-activation of old channels, and re-enforcement / initiation of floodplain channels through trampling by people or livestock.

New Forest

The three types of floodplain channel identified in the New Forest (Figure 5.15) appear to be formed by various combinations of the processes that form floodplain channels in other systems, as already discussed. A conceptual model for their formation, based on an understanding of the processes that occur in other systems in conjunction with field observations and measurements from New Forest floodplain channels, follow:

Type 3 Floodplain channels

Type 3 floodplain channels were identified in Section 5.3.4 as very complex networks of floodplain channels of variable depth, with some exhibiting characteristics of the main channel, e.g. bars and a gravel bed. These floodplain channels were associated with hydraulically effective wood jams in the main channel, which are thought to be the most important driver of these channels, causing flow ponding upstream (e.g. Brown *et al.,* 1995; Jeffries *et al.,* 2003), resulting in increased frequency and depth of overbank flow, and subsequently energy (through high shear stresses) to scour the floodplain surface. The main-channel and floodplain topography and roughness (e.g. from vegetation such as trees and wood) controls the distribution of overbank flow and hence the location of floodplain channels (Figures 5.16 (a)-(e)). The depth of scour in floodplain channels is likely to be a function of a combination of variables, including overbank flow shear stress, overbank flow frequency, and the erodibility of the floodplain material. The shear stress of overbank flow is dependent upon overbank flow depth and slope (see Figure 5.17); overbank flow frequency is related to the longevity of wood jams (see Section 5.3.6), rainfall, and channel capacity; and the erodibility of the floodplain material is dependent upon characteristics such as texture (e.g. clay or gravel), soil water content, organic content (Carling *et al.,* 1997) and the presence of roots (Figure 5.16 (f)). The floodplains within the New Forest are generally clay, underlain by a layer of coarse gravel (Figure 5.16 (g)). The clay may be fairly difficult to erode, particularly where networks of roots exist (Church, 2005 pers. Comm.; Gurnell, 2006 pers. comm.), as has been demonstrated within the soil erosion literature (see Section 3.5.3) (e.g. Moss and Walker, 1978; Davenport *et al.,* 1998). However, if scour is able to penetrate the gravel layer, this may be fairly easily eroded, possibly resulting in scour hollows and / or large floodplain channels, with characteristics of the main channel (e.g. Figure 5.16 (h)).

Floodplain channels may result in channel cut-offs (e.g. Figure 5.16 (i)) if the wood jams are in place for sufficient time (Section 5.3.6). However, the fundamental process forming them is unlikely to be headward erosion of a knickpoint, as described by Thompson (2003), as there is little evidence of headward erosion within the floodplain channels in the New Forest. Rather, as discussed earlier, it is likely to be the result of progressive vertical scour within the floodplain channels.

Figure 5.16 (below) (a), (b), (c) Overbank flow controlled by trees; **(d), (e)** Floodplain channels where overbank flow is constricted between trees; **(f)** Tree roots binding the floodplain surface and reducing its erodibility; **(g)** Floodplain material consisting of clay underlain by a layer of coarse gravel; **(h)** Floodplain channel and scour hollow eroded into gravels; **(i)** Meander neck cut-off.

(a)

(b)

(c)

(d)

(e)

(f)

(g) (h) (i)

Type 2 Floodplain channels

Type 2 floodplain channels are less complex and shallower networks of floodplain channels than Type 3, but they are more complex than Type 1. They form across the inside of meander bends and there may or may not be a wood jam present in the main channel. These channels are formed by the same fundamental processes as Type 3 (scour of the floodplain surface), although overbank flow may be induced by factors other than in-channel wood jams, for example a sinuous channel planform, small channel capacity, or trees constricting the channel. The overbank flow in these instances is likely to be less widespread, less frequent, shallower, with less erosive power than for Type 3 floodplain channels, hence fewer and shallower floodplain channels develop (Figure 5.17).

Type 1 Floodplain channels

Type 1 floodplain channels consist of a single, shallow, floodplain channel across the inside of a meander bend. As is the case with Type 2 floodplain channels, there may or may not be a wood jam in the main channel. Again, the same fundamental process of floodplain scour is likely to form Type 1 channels, however, the erosive power of overbank flow is even lower than for Type 2 channels.

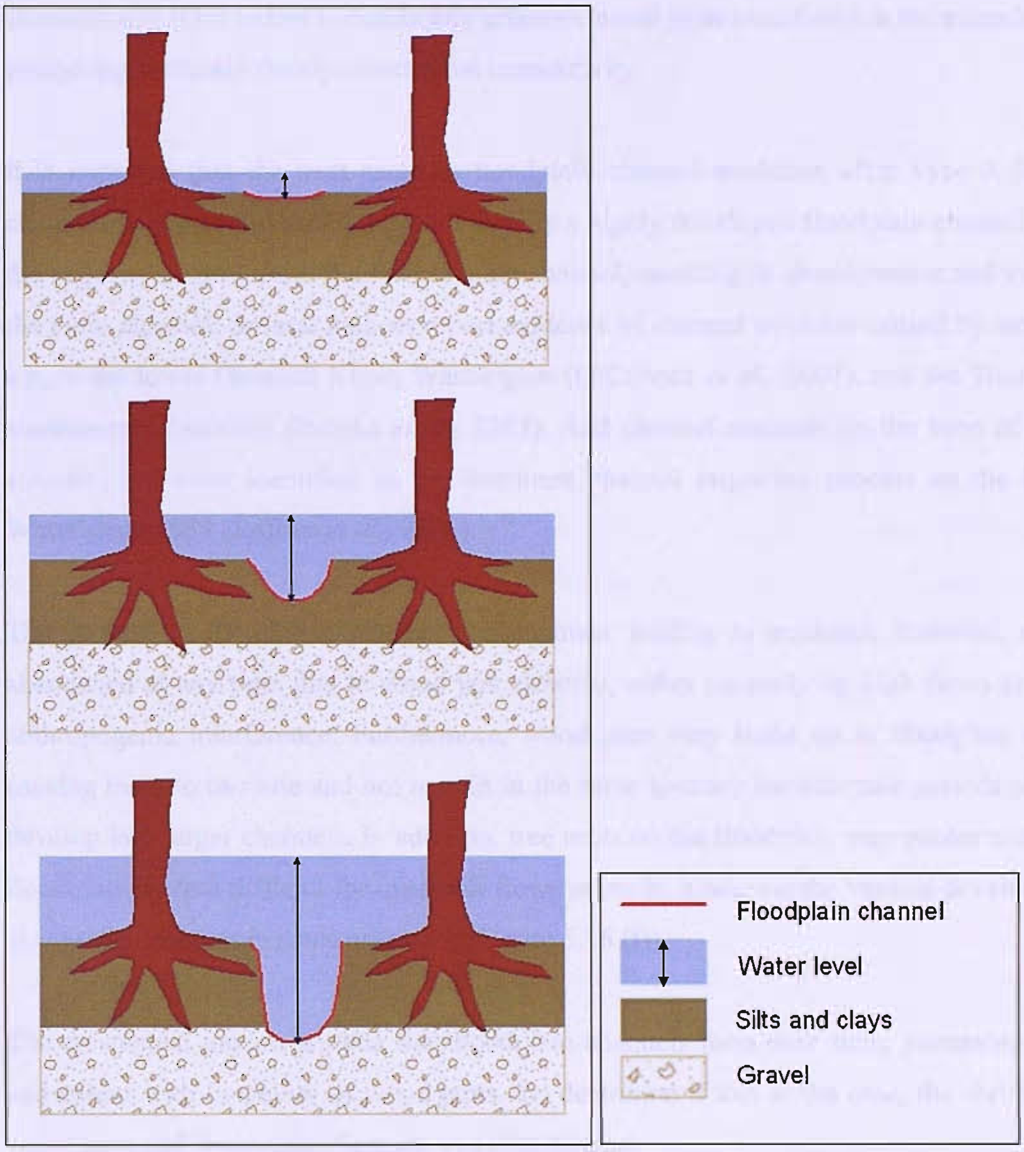


Figure 5.17 Increased depth of floodplain channels resulting from increased overbank flow depth.

Whether Type 1 or Type 2 channels form is likely to be due to local factors controlling the amount and frequency of overbank flow; Type 3 channels, however, require a hydraulically effective wood jam to be present in the main channel. Thus floodplain channel type is fundamentally controlled by the degree of floodplain-channel connectivity, which integrates time and water volume available for floodplain scour.

5.3.6 Evolution of floodplain channels

The conceptual models of the formation of the three types of floodplain channels assume that channels increase in extent, depth and number over time, as more overbank flows provide energy for floodplain scour. Therefore, given sufficient time, Type 1 channels may develop into Type 2 channels and then into Type 3 channels, however, it is unlikely that Type 3 channels will form unless hydraulically effective wood jams establishes in the meander bends, promoting sufficient floodplain-channel connectivity.

It is expected that the next stage in floodplain channel evolution after Type 3 floodplain channels would be channel avulsion, whereby a highly developed floodplain channel captures the majority of flow from the former main channel, resulting in abandonment and infilling of the main channel. Several authors report evidence of channel avulsion caused by wood jams, e.g. in the lower Quinault River, Washington (O'Connor *et al.,* 2003), and the Thurra River, southeastern Australia (Brooks *et al.,* 2003). And channel avulsion (in the form of meander cut-offs) has been identified as the dominant channel migration process on the Highland Water since 1953 (Jeffries *et al.,* 2003).

The process of floodplain channel development leading to avulsion, however, could be abandoned at any time due to wood jam removal, either naturally by high flows or through anthropogenic interference. Furthermore, wood jams may build up in floodplain channels causing them to re-route and not remain in the same location for adequate periods of time to develop into larger channels. In addition, tree roots on the floodplain may render areas of the floodplain surface difficult for overbank flows to erode, hindering the vertical development of floodplain channels in some areas (e.g. Figure 5.16 (f)).

The conceptual models assume that floodplain channels form over time, increasing in depth and extent with longevity of wood jams. To determine if this is the case, the chronology of wood jams and floodplain channels was investigated.

Methods

The chronology of wood jams with different types of associated floodplain channels was investigated using past wood jam surveys undertaken in 1983 (Gregory *et al.,* 1985); 1991 (Gregory *et al.,* 1993); 1998 (Jeffries, 2002); and in 2006 (Sear *et al.,* 2006 & field observations undertaken during this study) (Table 5.9), and through dating tilt sprouts from key living elements in wood jams (an example of dendrochronology (e.g. Hupp and Bornette, 2003)). Tilt sprouts were dated from six locations that were considered to be representative of the different floodplain channel types. Tilt sprouts (also termed adventitious sprouts (e.g. Hupp and Bornette, 2003)) are vertical branches that may grow from a horizontal tree trunk when a tree falls but remains living - the age of the tilt sprouts (the number of growth rings at the base) represents the minimum length of time during which the tree has been horizontal. Therefore, if tilt sprouts are found on trees within wood jams, the minimum age of the wood jam can be estimated.

In order to identify if floodplain channel initiation coincided with wood jam establishment, tree roots exposed in floodplain channels (from the same six sites) were analysed to establish when they were first exposed, and therefore a minimum period since the floodplain channels first started to form (an example of dendrogeomorphology (e.g. Carrara and Carroll, 1979; Hupp, 1990; Strunk, 1997; Vandekerckhove *et al.*, 2001; Bodoque *et al.*, 2005; Friedman *et al.*, 2005; Malik, 2006, Mizugaki *et al.*, 2006; Gärtner, 2007)) (Table 5.9).

Dendrogeomorphological analysis of tree stems and roots has been widely used to date both erosion and aggradation (e.g. Strunk, 1997; Vandekerckhove *et al.*, 2001; Bodoque *et al.*, 2005; Friedman *et al.*, 2005; Malik, 2006; Gärtner, 2007; Mizugaki *et al.*, 2006). Bodoque *et al.* (2005), for example, estimated sheet erosion rates using dendrogeomorphological analysis of exposed tree roots on the Guadarrama Mountains, Central Spain. They observed that growth rings changed from concentric to eccentric, and that 'reaction wood' formed when roots were first exposed (Figure 5.18).

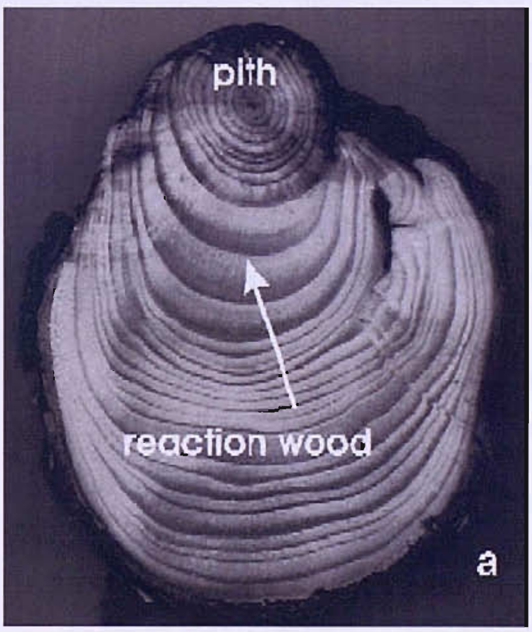


Figure 5.18 Cross section through a Scots Pine (*Pinus sylvestris*) root, showing eccentric growth rings and reaction wood, from Bodoque *et al.* (2005 p87).

Although dating tree root exposure is generally easier for conifers than for deciduous trees (Bodoque *et al.*, 2005; Gärtner, 2007), in this research it was not possible to select the roots by type, as they needed to be located in floodplain channels. The methodology employed was as follows:

1. Six locations where floodplain channels of different types were present were selected (six locations were used as this was thought to be sufficient to characterise the different floodplain channel types). Ten-cm long samples were taken using a hand saw (Malik, 2006); (a) from roots exposed in floodplain channels; and (b) from the same root where it was buried (Figure 5.19). Buried roots were sampled to ensure that any anatomical changes observed in exposed roots were not also present in the associated buried root, and so to be confident that the anatomical changes were indeed due to exposure. In order to identify the earliest date of floodplain channel initiation, exposed roots were selected from the largest floodplain channel present at each site. The number of root samples obtained per floodplain channel varied between sites depending on the availability of exposed roots: three exposed and buried root pairs were obtained at Millyford, at the downstream wood jam site on the Ober Water, and at the Blackwater site located just downstream of the A31; it was only possible to obtain two sample-pairs from the other three locations due to limited numbers of exposed roots in the floodplain channels.
2. When possible, the species of tree from which a root was obtained was identified (when direct identification was not possible, e.g. because of multiple trees in close proximity to a root, roots were identified later by comparison with other roots of known identity).
3. Roots were returned to the laboratory, cleanly sectioned, described, photographed and observed through a hand magnifying lens.
4. Attempts were then made to estimate the number of years since exposure by counting the rings since an obvious change in the patterns of growth rings (thus giving a *minimum* time since floodplain channel initiation, as the method identifies when a root was exposed which does not necessarily coincide with the initiation of floodplain channel development).

Figure 5.19 Example of an exposed and damaged section of root (5H, centre-right of photograph) and a buried section (5I, centre-left of photograph).

Results

Morphological differences were not observed between the patterns of growth rings from buried samples and those from undamaged exposed roots (Figure 5.20 (b) and (c)). This could be due the difficulties already mentioned using roots from deciduous trees rather than from conifers (Bodoque *et al.*, 2005; Gärtner, 2007). However, a clear change in growth rings was often visible if an exposed root had some obvious damage on its surface – it was then possible to count the growth rings since the damage (Figure 5.20 (a) and (d)). Cross sections from exposed roots with damage closely resemble Figure 5.18 which is of a root that has lost the upper part of its bark. Growth rings from *Quercus* spp. (Oak) samples were difficult to differentiate (as reported by Bodoque *et al.*, 2005), and therefore it was sometimes not possible to count the growth rings since damage on these samples.

This methodology, therefore, assumes that damage was caused to roots after they were exposed, and that the number of growth rings since damage gives a minimum period of root exposure, and consequently the start of erosion and floodplain channel development. It is important to note, however, that occasionally buried roots also showed damage. This could be because they were previously exposed and had since become buried by sedimentation, or roots may have become damaged whilst buried, e.g. by burrowing animals. Two other important assumptions were made in this methodology: firstly, it was assumed that the start of erosion equates to the start of floodplain channel development, however, other mechanisms also cause erosion on the floodplain, for example trampling by animals and people. Secondly, roots sometimes display 'false' and 'missing' rings (Bodoque *et al.*, 2005), which were not accounted for by this methodology.

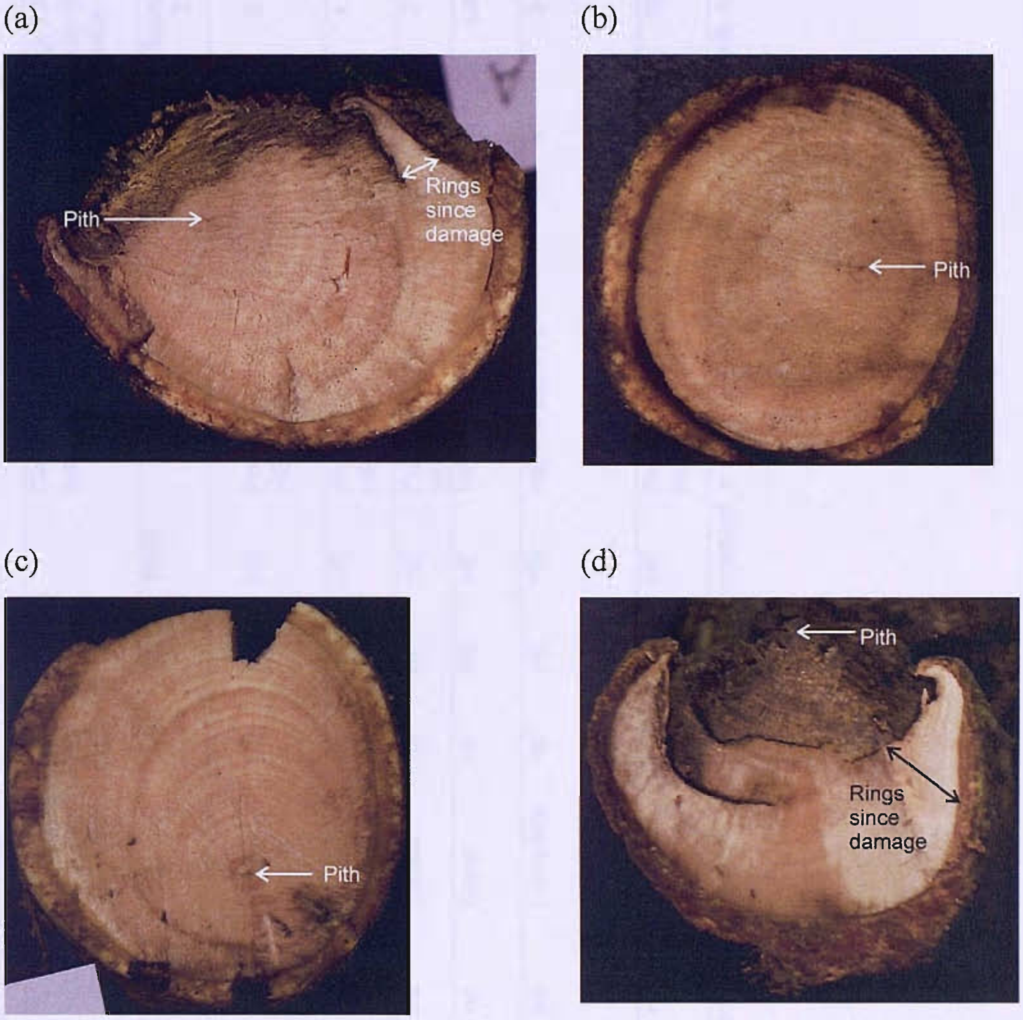


Figure 5.20 Sections through roots. (a) Exposed and damaged *Fraxinus* spp. (ash); (b) Exposed but not damaged *Fraxinus* spp.; (c) Buried *Fraxinus* spp. (NB damage on upper surface was caused during sectioning); (d) Exposed and damaged *Betula* spp. (birch).

Table 5.9 Chronology of wood jams and associated floodplain channels.

Location	Floodplain channel distribution type	Age of tilt sprouts (yrs)	Wood jams present in surveys					Chronology of jams (yrs)	Minimum age of floodplain channels from exposed, damaged roots		
			1983	1991	1998	2002	2006		Sample 1	Sample 2	Sample 3
Highland Water, Millyford wood jam SU 270 077	3	15	Partial	Partial	HE	HE	HE	Present > 23 HE > 8 but <15	11	8	6
Ober Water d/s jam SU 287 039	3	6	ns	Partial	ns	ns	HE	Present > 6 HE < 15	8	x	5
Ober Water u/s jam SU 287 039	2	5	ns	Partial	ns	ns	HE	Present > 5 HE< 15	2	2	n/a
River Blackwater u/s Rhinefield SU 257 046	2	n/a	ns	None	ns	HE	HE	HE > 4 but <15	ud	ud	n/a
River Blackwater by confluence with Blackensford Brook SU 237 066	1 or 2	n/a	ns	Complete	ns	HE	HE	HE > 4 but <15	x	3	n/a
Blackwater just d/s A31 SU 231 091	2	23	ns	Complete	ns	HE	HE	Present > 23 HE> 4 but <15	8	15	7

HE = Hydraulically effective wood jam; ns = not surveyed; ud = only undamaged exposed roots present; x = not possible to identify individual growth rings

Table 5.9 Continued

Location	**Floodplain channel distribution type**	**Age of tilt sprouts (yrs)**	**Wood jams present in surveys**					**Chronology of jams (yrs)**	**Minimum age of floodplain channels from exposed, damaged roots**
			1983	**1991**	**1998**	**2002**	**2006**		
HW SU 246 111	1	ns	None	None	None	Complete	None	None present	ns
HW SU 247 111	1		None	Partial	None	None	Partial	Partial < 4	
HW SU 246 110(a)	1		None	None	None	None	Complete	Complete < 4	
HW SU 246 110(b)	1		HE	Partial	None	None	None	None present	
HW SU 246 110(c)	2		None	None	None	None	Complete	Complete < 4	
HW SU 287 044	1		None	None	None	None	None	None present	
HW SU 289 042	1		None	None	None	Complete	None	None present	
BW SU 232 091	2		ns	Complete	None	None	None	None present	
BW SU 232 089	2		ns	None	None	Partial	Partial	Partial > 4 but < 8	
BW SU 232 088	1		ns	None	None	Partial	Complete	Present > 8 but < 15 Complete < 4	
BW SU 232 085	1		ns	Complete	None	None	Partial	Partial < 4	
BW SU 235 081	2		ns	Partial	None	None	Partial	Partial < 4	
BW SU 256 046	2	↓	ns	None	None	HE	Complete	Present > 4 but < 8 Complete < 4	↓

HE = Hydraulically effective wood jam; ns = not surveyed; ud = only undamaged exposed roots present; x = not possible to identify individual growth rings.

Table 5.9 assimilates the results from wood jam ageing and from dating exposed roots in floodplain channels. Other research (e.g. Kitts, in prep) has shown that it is only when wood jams are hydraulically effective (or 'active', using the classification of Gregory *et al.,* 1985) that they play a significant role in forcing water onto the floodplain, hence promoting floodplain channel development. Tilt sprouts, however, grow after a tree becomes horizontal but remains alive – they therefore give a minimum age of a jam, but not necessarily when it started to function as a 'hydraulically effective' jam. Therefore, jams built around living trees could be 'partial', 'high water' or 'complete' jams for a period before becoming 'hydraulically effective'. Consequently, tilt sprouts are used to identify the minimum age of the jams, but past wood jam surveys are used to identify date bands for when the jams could have been 'hydraulically effective' (assuming that the surveys refer to the same jam each year).

Table 5.9 indicates that, although floodplain channels of Types 1 and 2 formed in the absence of wood jams, they were more frequently associated with wood jams (of any type). The development of Type 1 or Type 2 floodplain channels does not appear to be related to the type or the longevity of wood jams. However, Type 3 floodplain channels occurred in association with hydraulically effective wood jams, and developed relatively rapidly (<15 yrs) (see Chapter 7). The length of time since root exposure (damage) roughly corresponded with wood jam age bands, and roots that had been exposed for longer tended to be associated with Type 3 floodplain channels, whereas more recently exposed roots were associated with Types 1 or 2 (although note the large variability in the period of root exposure from different root samples within the same floodplain channel, Table 5.9). From the data it is not possible to determine how long a jam needs to remain in the same location in order for floodplain channels to develop, however, the data do indicate that Type 3 floodplain channels only developed where hydraulically effective wood jams had been present in the main channel for more than 6 years.

These results confirm that hydraulically effective wood jams are a requirement for Type 3 floodplain channels but not necessarily for Types 1 and 2 (see Section 5.3.2). Type 2 floodplain channels were present at the site on the Blackwater downstream of the A31 (SU 231 091). A wood jam had been present at this site for more than 23 years, although it had only been hydraulically effective for between 4 to 15 years, and roots had been exposed in floodplain channels for between 7 to 15 years. This indicates that the floodplain channel may have initially developed when the jam was 'complete' rather than 'hydraulically effective'. Furthermore, it highlights the point that factors other than just the presence of hydraulically effective wood jams are required for Type 3 floodplain channels to develop (e.g. the erodibility of the floodplain surface is also important).

The hydraulic effectiveness of wood jams is important in forcing water onto the floodplain leading to the development of networks of floodplain channels (although wood jam age is also important as floodplain channels are likely to become more developed if they are inundated over many years - this may explain why only Millyford and the downstream wood jam site on the Ober Water have developed Type 3 floodplain channels, when hydraulically effective wood jams are present in the other sites). Thus, where hydraulically effective wood jams are present in the main channel, Types 1, 2 and 3 floodplain channels may indeed exist as a temporal continuum, with one type developing into the next over time. Furthermore, the hydraulic effectiveness of wood jams is likely to increase with jam age as more organic material is trapped - however, it may eventually decrease if jams break down under high flows. This highlights the importance of living trees forming key elements in jams as these are unlikely to be dislodged even during very high flows. All of the jams associated with the most significant floodplain channels in this study area are dependent upon living trees (usually *Salix* spp. (willow)) forming the key element in the wood jam structure.

Other than hydraulic effectiveness and wood jam age, the development of Type 3 floodplain channels is also likely to be related to the erodibility of the floodplain material. Tree roots play an important role in binding the floodplain material together, reducing its erodibility, as already discussed (Figure 5.16 (f)). Furthermore, the type of floodplain material is also likely to influence its erodibility. The depth of fine material above the gravels in the floodplain varied throughout the catchment. In some places it was shallow (+/- 0.30 m), so floodplain channels could scour down to gravel, creating deep floodplain channels; in other places fine material was deeper (+/- 1.0 m), rendering floodplain scour more difficult (Figure 5.21). Obviously, the ease with which floodplain scour can penetrate to gravel also depends upon characteristics of the main channel (e.g. discharge, bed slope, channel width and depth). Furthermore, fine deposits may build up from overbank flow, instigating positive feedback, whereby it becomes increasingly difficult for flows to scour into gravels as the depth of fines increases.

(a)

(b)

Figure 5.21 (a) Approximately 0.2 m; (b) Approximately 0.5 m of fine material above gravel in the floodplain.

5.4 Processes to monitor in order to assess the effects of the restoration on floodplain geomorphology

This chapter has identified floodplain channels as the principal meso-scale (10^1) geomorphological feature observed on semi-natural floodplains within the New Forest. Therefore, floodplain channel development would be a good indication of the performance of the restoration, and results from this chapter suggest that they may start to develop over the time period available for monitoring (one flood season before restoration, 2003/2004, and two flood seasons after restoration, 2004/2005, and 2005/2006 – see Chapter 4). Additionally, factors that have been identified as promoting floodplain channel development can be monitored to gain greater understanding of the processes involved in floodplain channel development.

Therefore, in order to determine the effects of the restoration on floodplain geomorphology, the following processes were monitored before and after the restoration: (i) changes in channel sinuosity (already discussed in **Chapter 4**); (ii) channel capacity and overbank flow frequency (Section 6.3.4 **Chapter 6**); (iii) fine sediment transport, hence the potential *supply* of fine sediment to the floodplain (**Chapter 6**); (iv) patterns and rates of overbank sediment deposition (**Chapter 6**); (v) patterns and rates of overbank sediment erosion (**Chapter 7**); and (vi) retention of wood, as accumulations of wood in the form of wood jams are important in promoting overbank flow, hence the potential for dynamic floodplain geomorphology (**Chapter 8**).

Chapter 6. Monitoring restoration (1): fine sediment load and overbank deposition

6.1 Introduction

In order to determine the effects of the restoration on floodplain geomorphology, Chapter 5 identified processes to monitor before and after the restoration (channel sinuosity; channel capacity and frequency of overbank flow; fine sediment load and patterns and rates of overbank sediment deposition; floodplain erosion processes; wood dynamics and retention). This is the first chapter of three that report on the monitoring results, and it focuses on monitoring fine sediment load and overbank deposition - for the overall monitoring methodology see Chapter 4.

6.2 Fine sediment load

Monitoring fine sediment transport is important in understanding floodplain geomorphological processes as it enables the potential supply of suspended sediment to the floodplain to be quantified (further discussed in Section 6.4). Due to the input of unconsolidated material and exposed floodplain surfaces during the restoration, it was expected that the fine sediment load would increase during / immediately following restoration, and then fall back to pre-restoration levels or lower, as vegetation establishes on the floodplain and on channel banks (Sear *et al.,* 1998; Marsh *et al.,* 2004) and overbank conveyance of fine sediment onto the floodplain is facilitated (Sear *et al.,* 1998). It was important to monitor any changes in fine sediment transport brought about by the restoration as these can have downstream impacts on channel morphology (Walling and Webb, 1983; Sear *et al.,* 1998) and on the instream ecological habitat and biota (Wood and Armitage, 1997; Henley *et al.,* 2000; Owens *et al.,* 2005).

This chapter describes the methodology and instrumentation used to monitor fine sediment transport. Fine sediment was focused upon rather than gravels because gravels were not deposited on the floodplain, and lateral accretion is not a dominant mechanism for floodplain development in this system (as demonstrated by Jeffries, 2002). The chapter discusses how the data were processed, and presents graphs of some of the processed data. Relationships between total suspended sediment load and total water volumes for the three reaches, over the three years monitored, highlight an increase in fine sediment concentration during the first flood season after the restoration at the Restored site (Site 2). Concentrations then decreased during the second flood season after the restoration, indicating that the system was rapidly recovering from the disturbance caused by the restoration works.

6.2.1 Method

In order to be confident that any changes observed in fine sediment transport over the three flood seasons monitored were due to the restoration rather than to climatic conditions, sediment transport was monitored on the Highland Water at the re-meandered restored site (Site 2 Figure 6.1), but also upstream, at a semi-natural reference site (Site 1 Figure 6.1) that was not affected by the restoration. To identify the downstream impacts of the planform restoration on fine sediment transport, a site downstream of Site 2 was also monitored (Site 3 Figure 6.1).

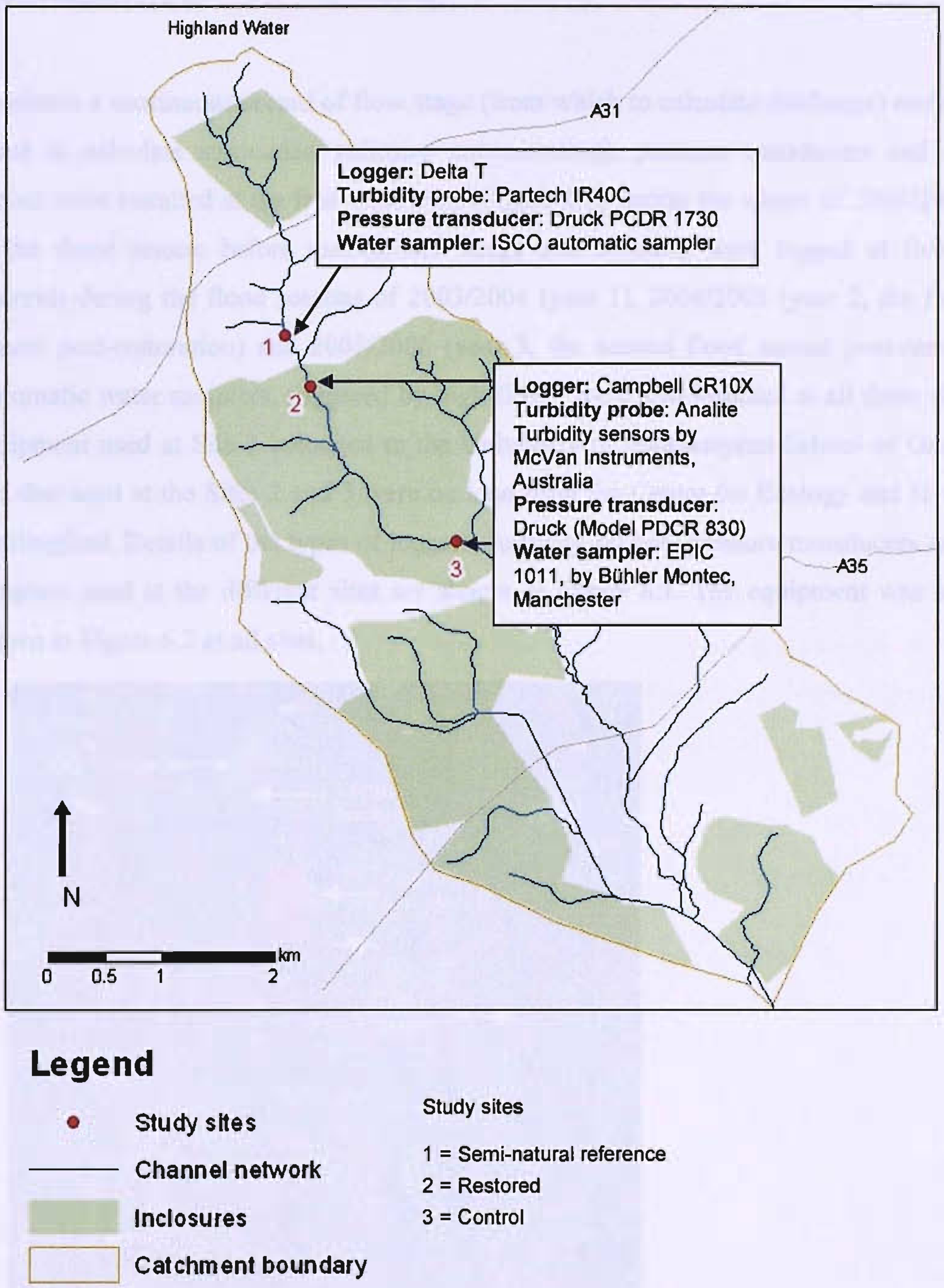


Figure 6.1 Monitoring sites and types of monitoring equipment used at each site.

Instrumentation

To obtain a continuous record of flow stage (from which to calculate discharge) and turbidity (used to calculate suspended sediment concentration), pressure transducers and turbidity probes were installed at the first three sites (Figure 6.2) during the winter of 2003/2004 (year 1, the flood season before restoration). Stage and turbidity were logged at five minute intervals during the flood seasons of 2003/2004 (year 1), 2004/2005 (year 2, the first flood season post-restoration) and 2005/2006 (year 3, the second flood season post-restoration). Automatic water samplers, triggered by high flows, were also installed at all three sites. The equipment used at Site 1 belonged to the University of Southampton School of Geography, and that used at the Sites 2 and 3 were on loan from the Centre for Ecology and Hydrology, Wallingford. Details of the types of loggers, turbidity probes, pressure transducers and water samplers used at the different sites are shown in Figure 6.1. The equipment was set up as shown in Figure 6.2 at all sites.

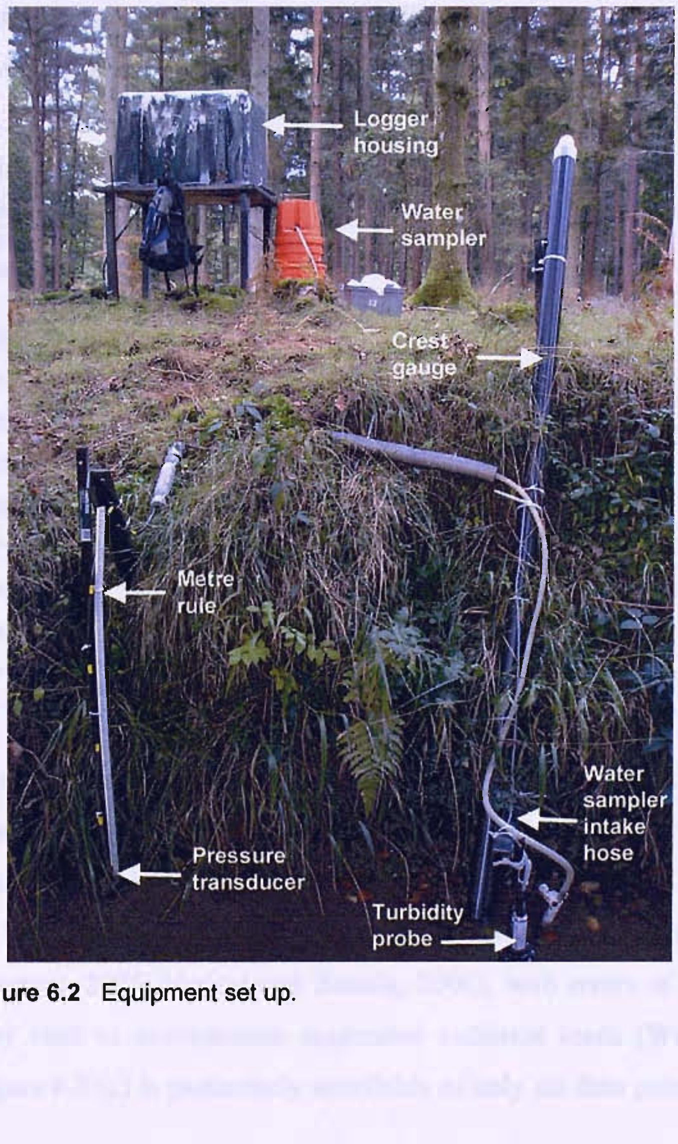


Figure 6.2 Equipment set up.

Sediment concentration analysis

Sediment concentrations were determined from 500ml water samples collected manually and automatically. Suspended sediment concentration was measured using standard filtration techniques (e.g. Lewis, 1996; Old *et al.*, 2005).

Turbidity

Turbidity probe output (mV) was logged at Sites 1, 2 and 3 (Figure 6.1). Turbidity was logged at five minute intervals due to the flashy nature of the Highland Water. To correct for instrumental drift (Old *et al.*, 2006) the probes were regularly calibrated to standard nephelometric turbidity units (NTUs) using AMCO polymer bead solutions (see Table 6.1 for dates of probe calibration). The turbidity record in mV was then calibrated to NTUs and subsequently into suspended sediment concentration (mg l^{-1}) using automatic and manual water samples (Figure 6.3) (e.g. Walling and Webb, 1987; Foster *et al.*, 1992; Gippel, 1995b; Cohen and Laronne, 2005; Old *et al.*, 2006).

Table 6.1 Dates of turbidity probe calibration.

Date of calibration	Sites
Calibrated in laboratory prior to installation in 10/2003	1,2,3
06/08/04	2,3
11/10/04	2,3
01/03/05	2,3
18/03/05	2,3
13/06/05	2,3
12/10/05	2,3
26/01/06	2,3
19/02/06	2,3
03/10/06	1,2,3

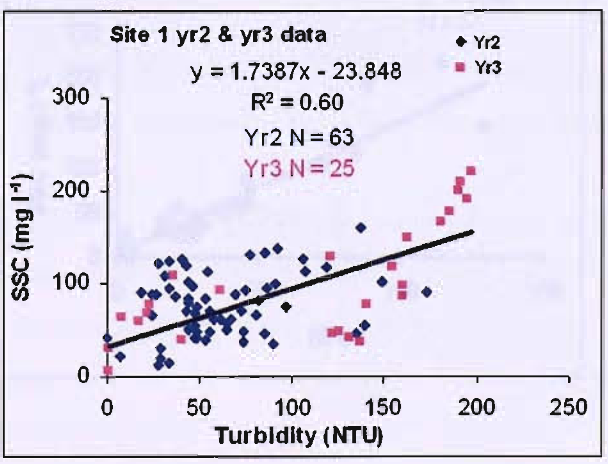
Inadequate numbers of water samples and poor turbidity data during year 1 at Site 3 meant that instead of calibrating turbidity to suspended sediment concentration, a discharge (Q) vs suspended sediment concentration rating was used (Figure 6.3 (c)). Rating curves are known to be associated with very high uncertainty (e.g. Walling and Webb, 1987; Cohen and Laronne, 2005; Vericat and Batalla, 2006), with errors of up to 280% (Walling, 1977), and they tend to overestimate suspended sediment loads (Walling, 1977). The relationship in Figure 6.3 (c) is particularly unreliable as only six data points were used. However, it was the only option available to obtain a rough estimate of fine sediment transport at Site 3 before restoration.

The calibration for Site 3 year 3 data was based on only a limited number of water samples, however the third graph in Figure 6.3 (c) shows that when year 3 data were plotted with those from year 2, they fell within the same area, hence the year 3 calibration was assumed to be robust.

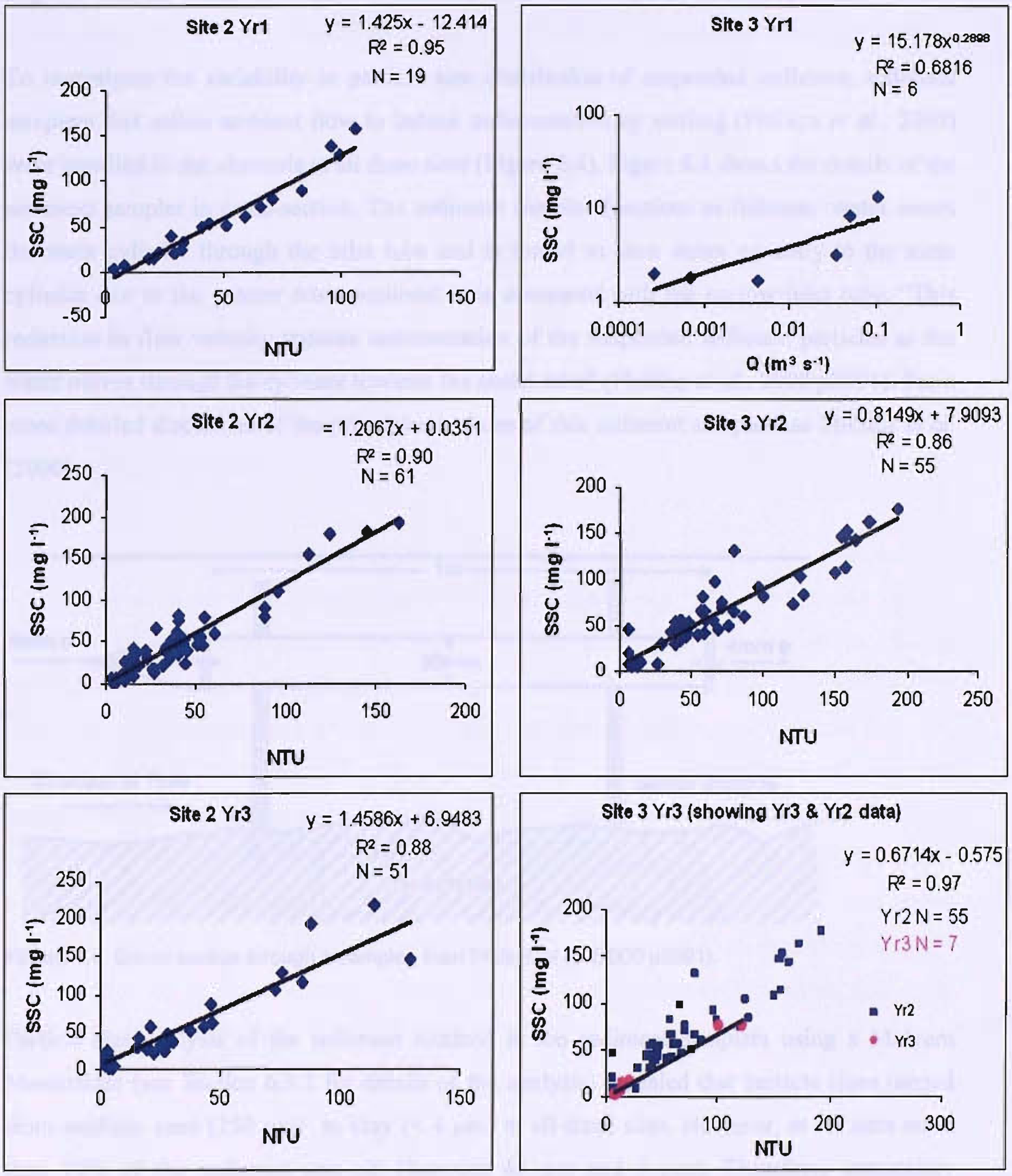
The calibration for Site 1 from year 3 data was also used to calibrate suspended sediment concentration from turbidity for years 1 and 2. During year 1, too few water samples were obtained; during year 2 many samples were obtained but the calibration did not include as high values of suspended sediment as it did for year 3, and as the plots for year 2 fell within those of year 3 (Figure 6.3 (a)) it was assumed that the relationship between turbidity and suspended sediment concentration had not changed between the years. It was also sensible to assume a constant relationship between the years as the same turbidity probe was used for all three years, and there is no reason for the nature of the fine sediment to have changed as the restoration did not extend to Site 1.

Figure 6.3 (below) Turbidity probe calibration (NTU to SSC) for (a) Site 1, (b) Site 2 and (c) Site 3. SSC: Suspended sediment concentration (mg l^{-1}).

(a) Site 1



(b) Site 2 (c) Site 3



When calibrated to suspended sediment concentration from water samples, turbidity data are assumed to represent suspended sediment concentration of water passing through a reach. Some uncertainty is associated with this methodology (Henley *et al.*, 2000). Firstly, turbidity is affected by the particle size distribution, particle shape, particle composition and water colour (Gippel, 1995b). However, in most situations turbidity is a good representation of suspended sediment concentration, as variations in particle size distribution are not generally large, or they are related to suspended sediment concentration (Gippel, 1995b; Lewis, 1996).

To investigate the variability in particle size distribution of suspended sediment, sediment samplers that utilise ambient flow to induce sedimentation by settling (Phillips *et al.*, 2000) were installed in the channels at all three sites (Figure 6.4). Figure 6.4 shows the details of the sediment sampler in cross-section. The sediment sampler functions as follows: water enters the main cylinder through the inlet tube and is forced to slow down on entry to the main cylinder due to the greater cross-sectional area compared with the narrow inlet tube. "This reduction in flow velocity induces sedimentation of the suspended sediment particles as the water moves through the cylinder towards the outlet tube" (Phillips *et al.*, 2000 p2591). For a more detailed discussion of the principles and use of this sediment sampler see Phillips *et al.* (2000).

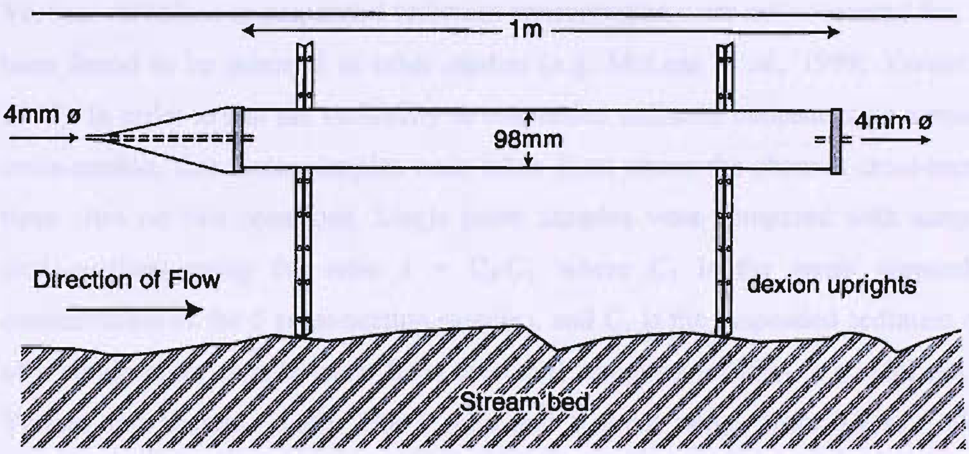


Figure 6.4 Cross-section through a sampler, from Phillips *et al.* (2000 p2591).

Particle size analysis of the sediment retained in the sediment samplers using a Malvern Mastersizer (see Section 6.3.2 for details of the analysis) revealed that particle sizes ranged from medium sand (250 μm) to clay (< 4 μm) at all three sites. However, at all sites more than 70% of the sediment was silt (between 63 μm and 4 μm). Therefore, uncertainty associated with variations in the particle size distribution of suspended sediment was considered minimal.

A second consideration when calibrating suspended sediment concentration from water samples is that the water samples should cover the range in turbidity monitored in the field (Lewis, 1996). However, the automatic water samplers often failed to trigger, and due to the inherent difficulties in obtaining water samples during storms in small catchments (Walling, 1977), suspended sediment concentration from water samples only reached a maximum of 250 mg l^{-1} (approx. 200 NTU), although during some peak flows turbidity reached 1000 NTU. It was assumed that the calibrations held true for turbidity above the range in the calibrations, but this assumption is associated with an unspecified level of uncertainty.

A third assumption in the methodology is that suspended sediment concentration from point samples is representative of suspended sediment transport through the entire vertical profile of the flow (Vericat and Batalla, 2006) as well as across the entire cross-section of the channel (Reid *et al.,* 1997; Steiger *et al.*, 2003). These assumptions are likely to be invalid in large rivers where suspended sediment may not be evenly mixed throughout the cross-section (Horowitz *et al.,* 1990; Wass *et al.,* 1997; Wass and Leeks, 1999; Amos *et al.,* 2004; Old *et al.,* 2005), but are unlikely to be a problem in a small, rough and well-mixed channel like the Highland Water (e.g. Bathurst *et al.,* 1985).

Vertical variations in suspended sediment concentration were not accounted for, as these have been found to be minimal in other studies (e.g. McLean *et al.,* 1999; Vericat and Batalla, 2006). In order to test the variability in suspended sediment concentration across the channel cross-section, five water samples were taken from across the channel cross-section from the three sites on two occasions. Single point samples were compared with samples from the cross-sections using the ratio $k = C_5/C_1$, where C_5 is the mean suspended sediment concentration of the 5 cross-section samples, and C_1 is the suspended sediment concentration of a single point sample taken from the usual sampling location (e.g. McLean *et al.,* 1999; Vericat and Batalla, 2006). The *k* ratio had a small range, from 0.7 to 1.08, and varied randomly with discharge. Therefore, suspended sediment concentration from point samples was assumed to be well representative of suspended sediment transport across the entire cross-section of the channel.

Flow stage

The pressure transducers were calibrated in the laboratory before the equipment was installed in the field so that the data output was in metres. Stage-discharge relationships were obtained from all three sites through a combination of dilution gauging (Barsby *et al.,* 1967; The Water Research Associate, 1979) and the velocity-area approach (e.g. Whiting, 2003), depending on flow stage. Logger output stage was then calibrated to discharge for the different sites (Figure 6.5). A different stage-discharge relationship was calculated for Site 2 before and after the restoration due to the substantial changes in channel dimension during the restoration; the same relationships were used over the three flood seasons at the other two sites as these channel dimensions did not change over the monitoring period. However, it needs to be kept in mind that stage-discharge relationships are notoriously unreliable in natural channels as cross-sections do fluctuate even during single floods (Cohen and Laronne, 2005). Furthermore, values of discharge used in the calibrations only reached a maximum of 1 $m^3 s^{-1}$, with an associated maximum stage of approx. 0.5 m; peak flows frequently exceeded this stage. As with the turbidity data, it was assumed that the calibrations held true for stage values above the range in the calibrations, but, together with unreliability associated with unstable channel cross sections, this introduced an unspecified level of uncertainty into the calculation of discharge.

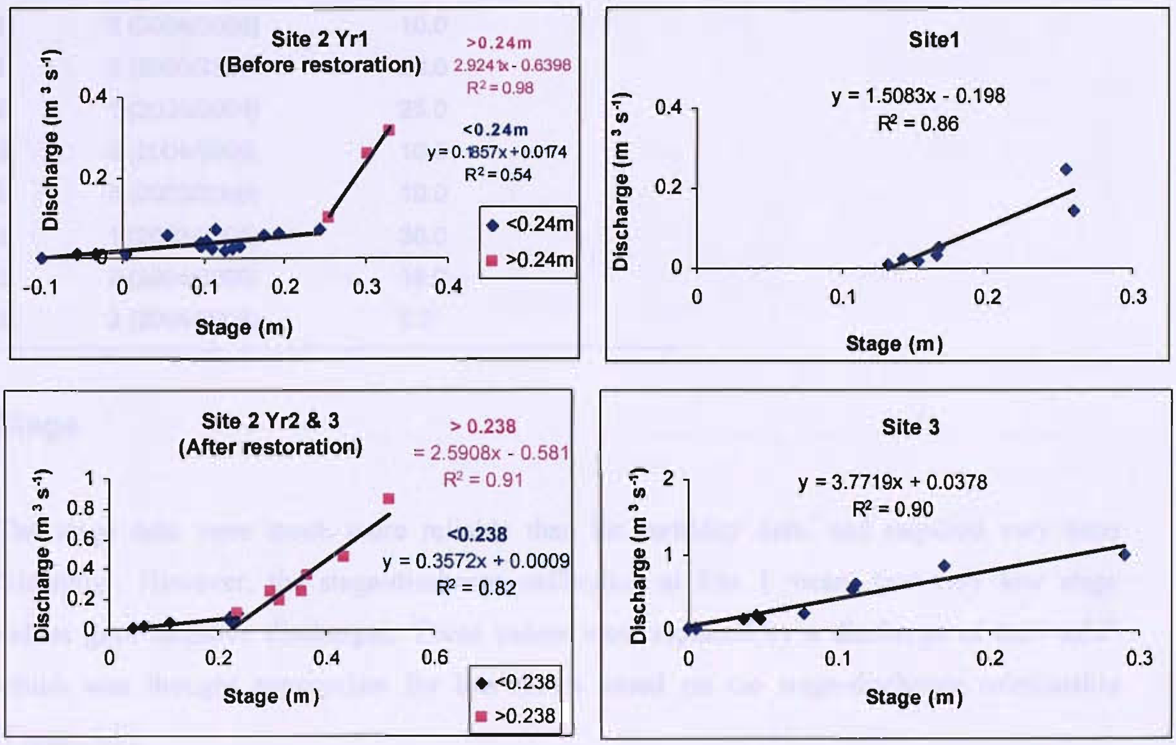


Figure 6.5 Stage-discharge relationships.

Data 'cleaning'

Turbidity

Some of the data output from the turbidity probes were unreliable (termed 'bad' data) due to the probes becoming fouled by algae growth, and sometimes being buried by sediment transport during high flows (e.g. as found by Cohen and Laronne, 2005). During much of the summer period, and on occasions during the flood seasons, flows were so low that the water level dropped below the sensors, giving unreliable turbidity data. Table 6.2 shows the percentage of 'bad' data from each site during the three flood seasons monitored. During data processing, obviously 'bad' data were deleted. Missing data for periods of less than four hours were filled in using a moving average of the previous four hours (the average time from low flow to flood peak); if data were missing for longer than four hours they were filled in using a low flow average. 'Low flows' were defined as the lowest 25% of flows at each site during the monitoring period (e.g. Old *et al.*, 2006).

Table 6.2 Percentage of 'bad' data between October and April for the three sites over the three flood seasons monitored.

Site	Year	Percentage of 'bad' data between October & April (inclusive)
1	1 (2003/2004)	35.0
1	2 (2004/2005)	10.0
1	3 (2005/2006)	29.0
2	1 (2003/2004)	25.0
2	2 (2004/2005)	10.5
2	3 (2005/2006)	10.0
3	1 (2003/2004)	38.0
3	2 (2004/2005)	18.0
3	3 (2005/2006)	5.0

Stage

The stage data were much more reliable than the turbidity data, and required very little 'cleaning'. However, the stage-discharge calibration at Site 1 meant that very low stage values gave negative discharges. These values were replaced by a discharge of 0.01 m^3s^{-1} which was thought appropriate for low flows based on the stage-discharge relationship (Figure 6.5).

6.2.2 Results

The Highland Water has a flashy flow regime with floods rising and subsiding within hours. This led to very 'peaky' hydrographs (Figure 6.6). The graphs in Figure 6.6 are examples of the suspended sediment concentration and discharge data from the three sites.

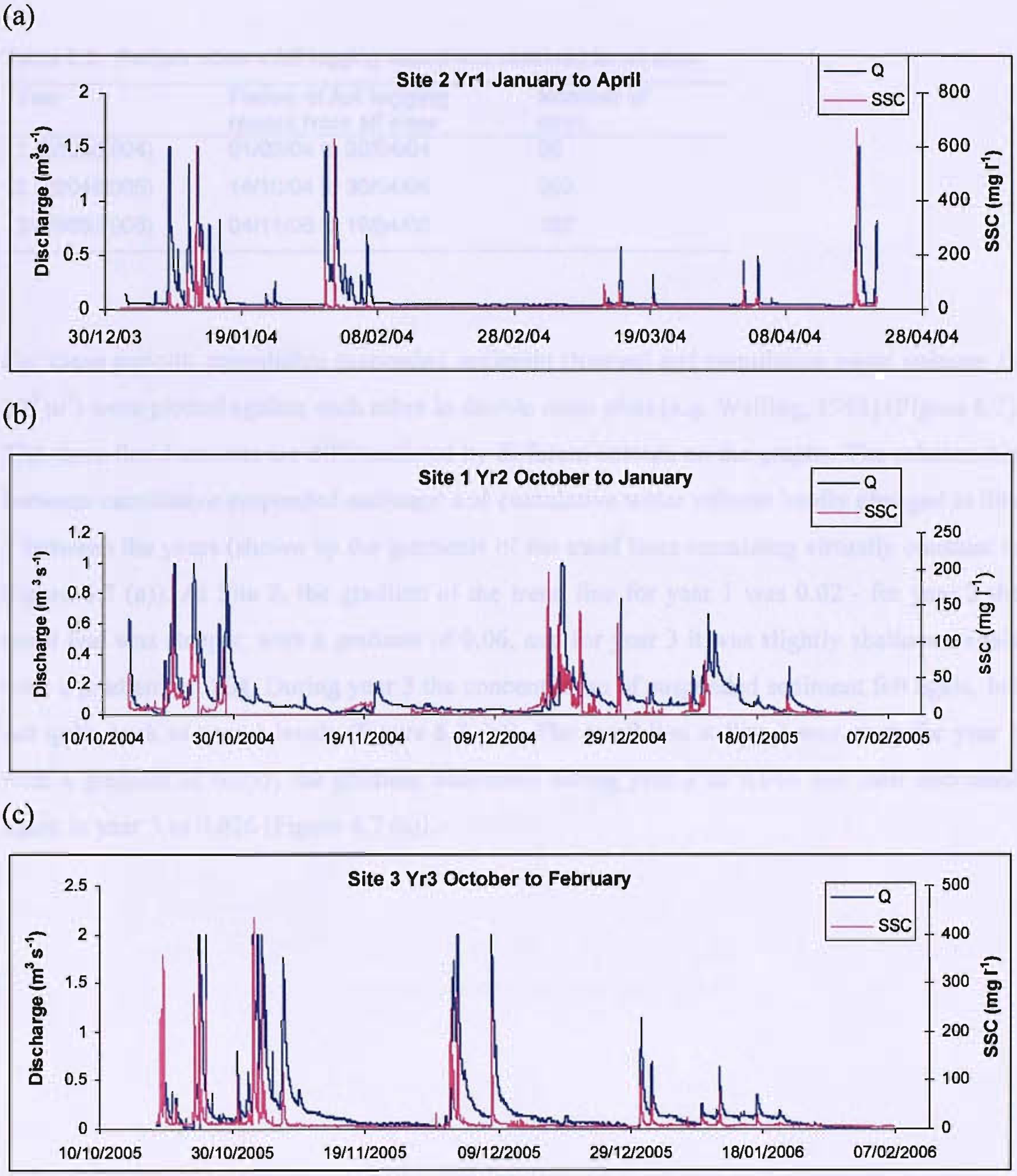


Figure 6.6 Examples of suspended sediment concentration (SSC) and discharge (Q) data from the three sites.

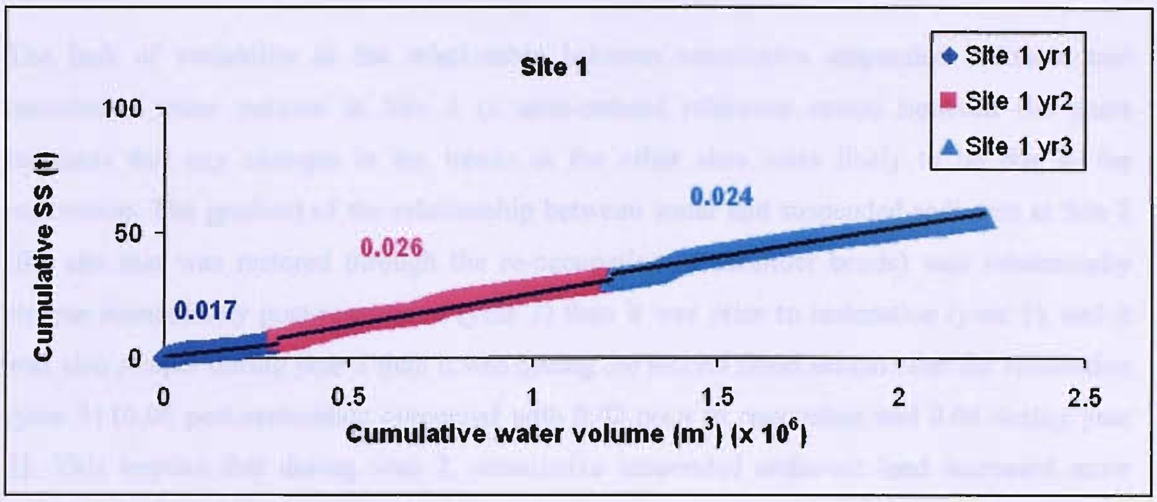
The main flood season, and therefore the main period of suspended sediment transport, was from October to April. Unfortunately it was not possible to obtain reliable logging data from all sites for all three years for this period. Table 6.3 shows the periods when a full logging record was obtained for all sites.

Table 6.3 Periods when a full logging record was obtained for all sites.

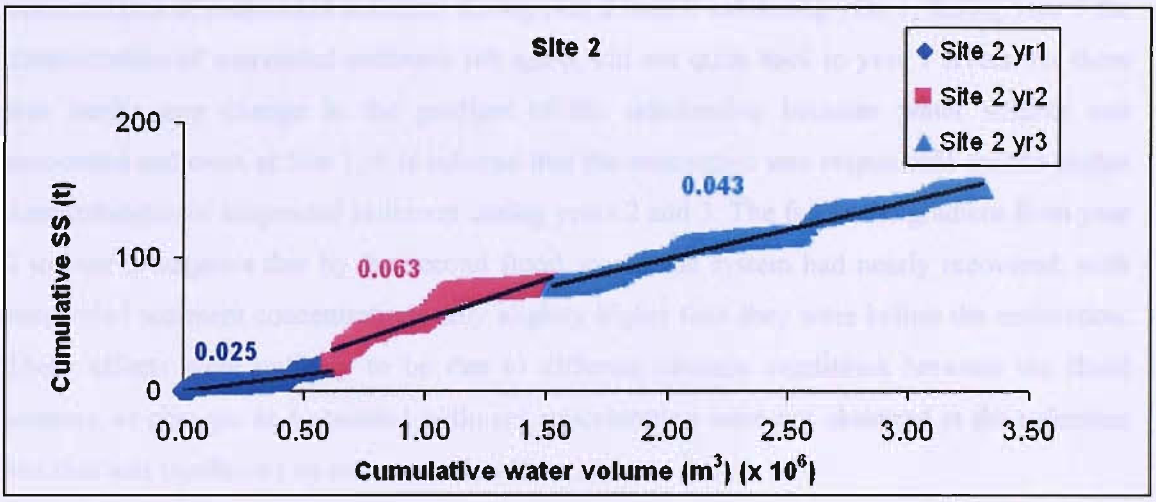
Year	Period of full logging record from all sites	Number of days
1 (2003/2004)	01/02/04 to 30/04/04	90
2 (2004/2005)	14/10/04 to 30/04/05	202
3 (2005/2006)	04/11/05 to 19/04/06	167

For these periods, cumulative suspended sediment (tonnes) and cumulative water volume (x 10^6 m^3) were plotted against each other in double mass plots (e.g. Walling, 1995) (Figure 6.7). The three flood seasons are differentiated by different colours on the graphs. The relationship between cumulative suspended sediment and cumulative water volume hardly changed at Site 1 between the years (shown by the gradients of the trend lines remaining virtually constant in Figure 6.7 (a)). At Site 2, the gradient of the trend line for year 1 was 0.02 - for year 2 the trend line was steeper, with a gradient of 0.06, and for year 3 it was slightly shallower again with a gradient of 0.04. During year 3 the concentration of suspended sediment fell again, but not quite back to year 1 levels (Figure 6.7 (b)). The trend line at Site 3 was steep for year 1 with a gradient of 0.055; the gradient decreased during year 2 to 0.046 and then decreased again in year 3 to 0.026 (Figure 6.7 (c)).

(a)



(b)



(c)

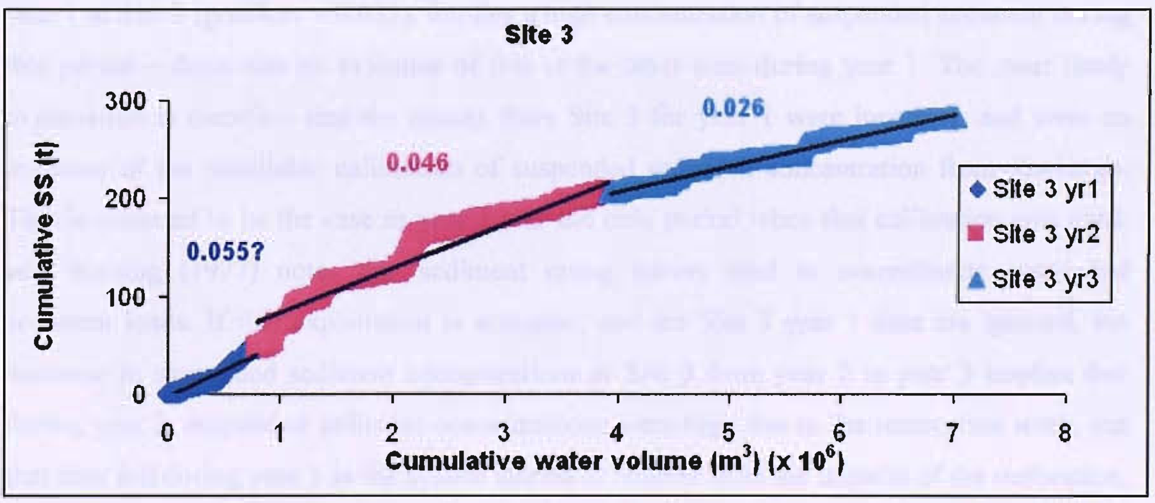


Figure 6.7 Relationship between cumulative water volume and cumulative suspended sediment (SS) for years 1, 2 and 3 at (a) Site 1, (b) Site 2 and (c) Site 3. The numbers above the curves indicate the gradient of the trend lines.

6.2.3 Discussion

The lack of variability in the relationship between cumulative suspended sediment and cumulative water volume at Site 1 (a semi-natural reference reach) between the years indicates that any changes in the trends at the other sites were likely to be due to the restoration. The gradient of the relationship between water and suspended sediment at Site 2 (the site that was restored through the re-occupation of meander bends) was substantially steeper immediately post-restoration (year 2) than it was prior to restoration (year 1), and it was also steeper during year 2 than it was during the second flood season after the restoration (year 3) (0.06 post-restoration compared with 0.02 prior to restoration and 0.04 during year 3). This implies that during year 2, cumulative suspended sediment load increased more rapidly than cumulative water volume did, i.e. a given unit of water had a higher concentration of suspended sediment during year 2 than it did during year 1; during year 3 the concentration of suspended sediment fell again, but not quite back to year 1 levels. As there was hardly any change in the gradient of the relationship between water volume and suspended sediment at Site 1, it is inferred that the restoration was responsible for the higher concentrations of suspended sediment during years 2 and 3. The fall in the gradient from year 2 to year 3 suggests that by the second flood season the system had nearly recovered, with suspended sediment concentrations only slightly higher than they were before the restoration. These effects were unlikely to be due to different climatic conditions between the flood seasons, as changes in suspended sediment concentration were not observed at the reference site that was unaffected by the restoration (Site 1).

The steep gradient in the relationship between water volume and suspended sediment during year 1 at Site 3 (gradient = 0.055), implies a high concentration of suspended sediment during this period – there was no evidence of this at the other sites during year 1. The most likely explanation is therefore that the results from Site 3 for year 1 were incorrect, and were an outcome of the unreliable calibration of suspended sediment concentration from discharge. This is assumed to be the case as year 1 was the only period when that calibration was used, and Walling (1977) notes that sediment rating curves tend to overestimate suspended sediment loads. If this explanation is accepted, and the Site 3 year 1 data are ignored, the decrease in suspended sediment concentrations at Site 3 from year 2 to year 3 implies that during year 2, suspended sediment concentrations were high due to the restoration work, but that they fell during year 3 as the system started to recover from the impacts of the restoration. This then would suggest that the channel planform restoration works impacted suspended sediment concentrations at Site 3 which was 1.5 km downstream from the downstream end of the works.

Both Sites 2 and 3 (prior to restoration) were incised into silty clays (Figure 6.8), which provided a supply of fine sediment, and no overbank flow occurred at these sites during year 1. Site 2 was actively eroding its bed, illustrated by the rapid headward migration of a knick point (approx. 10 metres during the first flood season) marking the upstream limit of incision (Figure 6.9). After the restoration, however, fine sediment concentrations increased due to fine sediment being available from: (i) old channels that were re-activated; (ii) new gravels that had fines in them that were used to infill over-deepened channels (e.g. Figure 6.10); and (iii) the disturbed and re-connected floodplain. During the second flood season after restoration (year 3) suspended sediment concentrations fell at Site 2, but were still higher than prior to the restoration due to the large amounts of new sediment used as infill. Suspended sediment concentrations were still high at Site 3, partly due to the downstream transport of fine sediment from the restoration, but also because much of the channel was still not restored, and it was therefore actively incising its channel banks.

Figure 6.8 Channel incised into silty clays (Site 2 before the restoration).

Figure 6.9 Knick point marking the upstream limit of channel incision into clay, located upstream of Site 2.

Figure 6.10 New gravels with fines that were used to infill over-deepened channels.

Elevated suspended sediment concentrations persisting for more than one flood season after restoration works have been recorded from other restoration projects. For example, Marsh *et al.* (2004) found that suspended sediment yield increased by approximately 100% during restoration work on Echidna Creek, southeast Queensland, and suspended sediment yield was still elevated at the completion of the three year study monitoring period. However, the authors anticipate a gradual decline in suspended sediment yield to the same, or lower levels, than pre-restoration.

In all three graphs (Figure 6.7) there are slight 'wiggles' in the relationships between cumulative suspended sediment and cumulative water volume. They appear to be accentuated downstream, as they are more pronounced in the Site 2 and 3 graphs than in Site 1. They *are* present in Site 1, however, therefore they are unlikely to be due to the restoration. It is proposed that they represent periods of sediment 'exhaustion'; the 'falling limb' of the wiggles represents periods when an increase in water volume was only associated with a very small increase in suspended sediment. The 'rising limb' of the wiggles then represents periods when the river had had time to accumulate fine sediment, perhaps after a period of low flows, and a small increase in flow led to a large increase in suspended sediment.

6.2.4 Suspended sediment load and catchment area

During year 2, peak suspended sediment concentrations reached 745 mg l^{-1} at the Restored site (Site 2) with an associated discharge of 1.43 m^3s^1, and 962 mg l^{-1} at Site 3, with a discharge of 2.0 m^3s^1. These values are low compared with suspended sediment concentrations observed in other British rivers, which range between 500 to 5000 mg l^{-1} (Walling and Webb, 1987). In order to compare the suspended sediment loads from Sites 2 and 3 (affected by the restoration) with a reference reach unaffected by the restoration (Site 1), and to place them in the context of other UK rivers, annual total suspended sediment loads (t yr^{-1}) were estimated for the three sites for years 2 and 3 (they were not estimated for year 1 due to the paucity of data coverage during the first flood season) (Table 6.4). Data were not logged for summer periods due to flows frequently falling below the base of the probes. These data were therefore estimated using low flow Q and turbidity values (calculated from an average of the lowest 25% of flows, e.g. Old *et al.* (2006)). In total, approximately 40% of year 2 data and 50% of the year 3 data were estimated in this way. Overall, this method was likely to underestimate sediment transport as, although sediment transport during low flows will have been overestimated, it is during high flows that most sediment was transported (Walling and Webb, 1987) (Table 6.5).

Table 6.4 Annual total flow and total suspended sediment load for Site 1, 2 and 3 for years 2 and 3.

Site	Year	Catchment area (km^2)	Annual total flow (x 10^6 m^3)	Annual Suspended sediment load (t yr^{-1})	Specific sediment load (Annual Suspended sediment load / catchment area) (t km^{-2} yr^{-1})
1	2	3.455	0.9	24.3	7.0
1	3	3.455	1.2	35.7	10.3
2	2	4.646	1.3	39.0	8.4
2	3	4.646	1.9	61.0	13.1
3	2	7.571	2.6	100.5	13.3
3	3	7.571	2.8	108.7	14.4

Table 6.5 Percentage of load transported during storms at Site 2.

Year	Percentage of load transported during storms (flow > 2 x baseflow)	Percentage of time of storm flow
1	92.3	11.2
2	87.5	5.7
3	86.5	19.0

Table 6.4 shows that, for all three Sites, annual suspended sediment load increased from year 2 to year 3, with an increase in total flow. Loads were higher for Sites 2 and 3 than for Site 1 during both years. This was likely to be due to the larger catchment areas of Sites 2 and 3 compared with Site 1, and also to the impacts of the restoration.

Annual suspended sediment transported by UK rivers is low by world standards (Walling and Webb, 1983), and ranges from <1 to nearly 500 t km^{-2} yr^{-1} (Walling and Webb, 1987). As can be seen from Figure 6.11, sediment load at the three monitored sites was broadly comparable with data from other UK catchments. Increasing loads between the sites corresponded with increased catchment areas. The loads were slightly lower (in relation to catchment area) than those recorded from other sites in the UK, which is likely to be due to the vegetated nature of the catchment (e.g. Walling and Webb, 1983; Wood and Armitage, 1997; Marsh *et al.*, 2004).

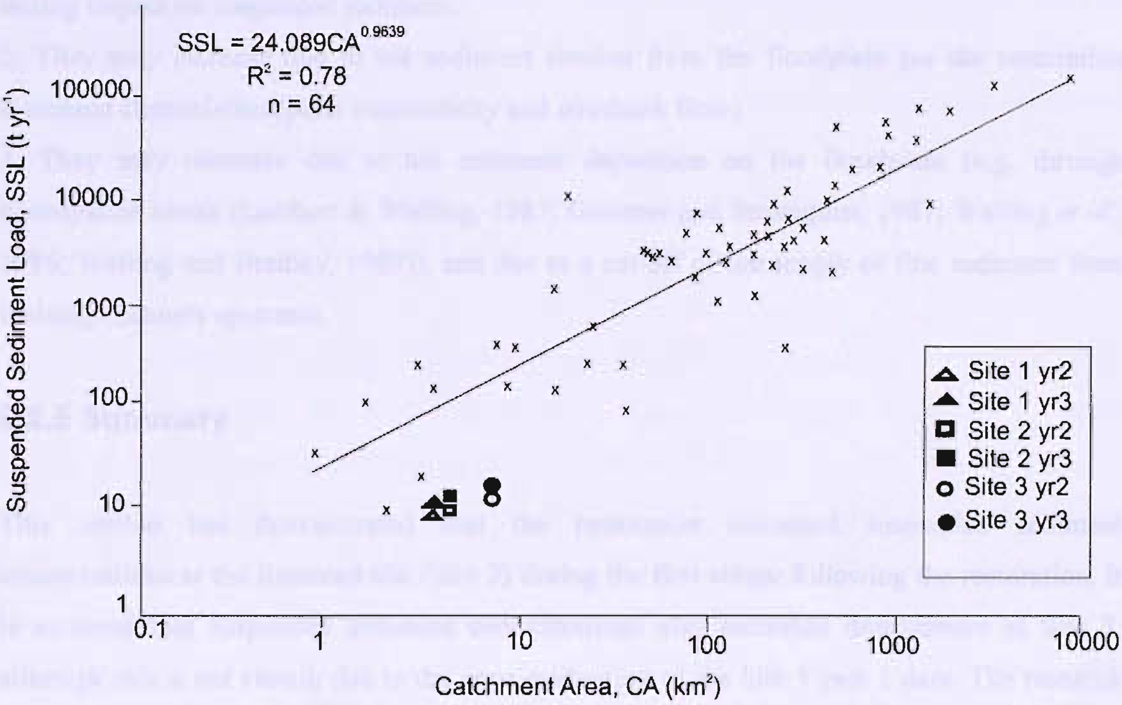


Figure 6.11 Relationship between annual suspended sediment load and catchment area for selected UK catchments, including the 3 sites monitored in this study (adapted from Old *et al.*, 2006).

As identified in Table 6.4, flows during year 2 were generally fairly low, and Site 2 had a total flow of 1.3 x 10^6 m^3 (compared with 1.9 x 10^6 m^3 in year 3). Therefore, even though suspended sediment concentrations were high, total suspended sediment transported downstream was still low. Consequently, detrimental downstream impacts of high fine sediment yields (e.g. accumulation in the interstices of coarse gravel which affects fish spawning (Wood and Armitage, 1997; Greig *et al.*, 2005)) and interactions between surface water and ground water (Sear *et al.*, 1999) would have been minimal. Furthermore, the results indicate that already by the second flood season after the restoration works, suspended sediment concentrations were reduced significantly (with the gradient of the trendline depicting the relationship between suspended sediment and water volume falling from 0.063

in year 2 to 0.043 in year 3, Figure 6.7), although not quite back to pre-restoration levels (when the trendline gradient was 0.025).

Longer term monitoring is needed to identify any lasting impacts of the restoration on suspended sediment concentrations. Some suggestions of possible future trends in suspended sediment concentrations are given below:

1. They may return to pre-restoration levels, indicating that the restoration has not had a lasting impact on suspended sediment.
2. They may increase due to net sediment erosion from the floodplain (as the restoration increased channel-floodplain connectivity and overbank flow).
3. They may decrease due to net sediment deposition on the floodplain (e.g. through conveyance losses (Lambert & Walling, 1987; Gretener and Stromquist, 1987; Walling *et al.*, 1986; Walling and Bradley, 1989)), and due to a cut-off of the supply of fine sediment from incising channels upstream.

6.2.5 Summary

This section has demonstrated that the restoration increased suspended sediment concentrations at the Restored site (Site 2) during the first winter following the restoration. It is assumed that suspended sediment concentrations also increased downstream at Site 3, although this is not certain due to the poor calibration of the Site 3 year 1 data. The research has demonstrated that during the second winter after restoration (year 3), suspended sediment concentrations fell, but not quite back to pre-restoration levels, indicating that the system was rapidly recovering from the disturbance caused by the restoration but had not yet fully recovered. Whether or not suspended sediment concentrations will continue to fall until they reach pre-restoration levels, or if they will remain slightly higher or lower due to the changed nature of the reach (i.e. increased overbank flow and floodplain activity caused by the restoration may result in long term higher or lower fine sediment loads) is uncertain. It is recommended that monitoring continues in order to establish the longer term impacts of the restoration on suspended sediment transport.

Fine sediment transport monitoring also provided records of sediment yield / supply to the floodplain on an annual and event basis that were used in relation to sedimentation on the floodplain (Section 6.3).

6.3 Overbank deposition

6.3.1 Introduction

Chapter 5 identified that semi-natural reaches had geomorphologically diverse floodplains created by the processes of deposition and erosion of sediment during overbank flows. In contrast, overbank flows rarely reach the floodplain in channelised reaches, removing the potential for sediment to be deposited on, and eroded from, these floodplains. This section sets out to determine if the restoration was able to establish these processes that can potentially lead to diverse floodplain geomorphology. The section starts by looking at patterns of sediment deposition across the floodplain upstream and downstream of wood jams, and before and after restoration, in relation to a semi-natural reference site. It goes on to examine how sediment deposition is influenced by the type of floodplain vegetation. (Floodplain erosion is covered in Chapter 7).

Traditional models of floodplain sedimentation on non-forested floodplains (e.g. James, 1985, Pizzuto, 1987) suggest that the amount and grainsize of sediment deposited overbank decreases with increasing distance from the channel (discussed in Section 3.5.2) due to sediment being transported by diffusion. Increasingly it is recognised that floodplain topography and vegetation complicate this pattern through altering floodplain flow hydraulics (e.g. Nicholas and Walling, 1997a; Steiger *et al.*, 2001b; Jeffries *et al.*, 2003). Research by Jeffries (2002) and Jeffries *et al.* (2003) has demonstrated that, in this system, in-channel wood jams play a dominant role in controlling the spatial distribution of overbank sediment deposition at the meso-scale (10^1 m) through creating local flow ponding. Most deposition occurred at the junction between ponded and flowing water, and immediately around a wood jam. At the micro-scale (10^{-1} m), sediment deposition patterns were controlled by the complex hydraulic environment created by irregular topography, large wood and trees.

In light of the above research, it was decided to monitor contemporary overbank sediment deposition (annual and over individual flood events) across floodplains upstream and downstream of in-channel wood jams, and in response to restoration. The influence of different types of floodplain vegetation on overbank deposition was also investigated.

6.3.2 Method

Astroturf sediment traps

Various methods have been used to quantify contemporary rates of overbank sedimentation, for example: conveyance losses (e.g. Walling *et al.,* 1986; Lambert and Walling, 1987; Gretener and Stromquist, 1987; Walling and Bradley, 1989); reconnaissance topographic surveys (e.g. Kesel *et al.,* 1974; Brown, 1987); artificial marker horizons; erosion pins; and sediment traps (for details of the different methods see Steiger *et al.* (2003)). Different types and sizes of sediment trap have been used. Lambert and Walling (1987) were the first to publish sedimentation rates from the floodplain of reaches of the River Culm, Devon using Astroturf mats held in place by steel pins. Subsequently many others have used this technique (e.g. Walling and Bradley, 1989; Asselman and Middelkoop, 1995; Simm, 1995; Nicholas and Walling, 1996; Middelkoop and Asselman, 1998; Steiger *et al.,* 2001b; Steiger & Gurnell, 2002; Goodson *et al.,* 2003; Jeffries *et al.,* 2003; Keesstra, 2007). Walker (1995, cited in Steiger *et al.,* 2003) used 0.2 m x 0.2 m tightly woven, nylon felt carpet squares stitched onto 5 mm wide aluminium frames, fixed to the floodplain by driving stakes into ground through nylon loops attached to each corner, to study sedimentation in forests flanking the Rio Taruma Mirimi (Central Amazon); Dezzeo *et al.* (2000) used smooth sheets of plastic (0.25 m x 0.35 m); Steiger & Gurnell (2002) used fire-clay roof-tiles; because of their weight they did not have to be secured to the floodplain surface; Pinay *et al.* (1995) used flat, smooth plates (area 0.06 m^2) on the Garonne River, France; and Gretener and Stromquist (1987) used 0.5 m x 0.5 m plain hardboard plates to study overbank sedimentation rates in the Lower River Fryisan, Sweden.

Astroturf sediment traps (see Figure 6.12) were used in this study to examine (i) the effect of restoration on floodplain sedimentation, and (ii) the influence of wood jams on the pattern of sediment deposition across the floodplain. Astroturf mats were used due to their following advantages (from Steiger *et al.* (2003) and Middelkoop and Asselman (1998)):

1. Their surface roughness reduces the potential for sediment to be removed by floodwaters or rainfall;
2. Their pliable base allows installation on irregular surfaces and slopes;
3. They can be securely attached to the ground with metal pins;
4. They are robust and can withstand repeated floods and laboratory processing;
5. They are light-weight and so are easy to manipulate in the field;

6. It is possible to fully recover deposited sediment from them in order to determine the amount of sediment and a range of other analyses;
7. They can be used in areas of low overbank deposition.


Figure 6.12 Partially submerged Astroturf sediment trap.

Authors have used sediment traps of different sizes to investigate overbank sedimentation, for example 0.50 m x 0.50 m (Gretener and Stromquist, 1987), 0.275 m x 0.165 m (Steiger & Gurnell, 2002), 0.40 m x 0.35 m (Steiger *et al.*, 2001b), 0.275 m x 0.165 m (Steiger *et al.*, 2001a), 0.20 m x 0.35 m (Simm, 1995), and 0.20 m x 0.20 m (Jeffries, 2002; Jeffries *et al.*, 2003). Mats 0.20 m x 0.20 m were used in this study because deposition on the floodplain in this environment was found by Jeffries (2002) to be so variable that boundaries between zones of deposition and erosion were often approx. 0.20 m.

Procedure for deploying and changing sediment traps

The procedure used for changing the mats during the flood seasons of 2003/2004 (before the restoration) and 2004/2005 (the first flood season after restoration) was the same as has been used in many other studies (e.g. Steiger *et al.*, 2001b; Steiger & Gurnell, 2002; Goodson *et al.*, 2003; Jeffries *et al.*, 2003). Mats were secured onto the floodplain surface using metal or wooden pins, and were changed after the flood waters of overbank events had subsided. After removal the mats were placed into sealed plastic bags and transported to the laboratory. Due to time constraints, during the flood season of 2005/2006 (the second flood season after the restoration), mats were not changed between events, but instead they were left on the floodplain for the entire flood season, and then returned to the laboratory for processing.

Laboratory analyses

Once in the laboratory, all the sediment was washed off the mats, through a 2 mm sieve, into a plastic container where the sediment and water were retained and allowed to settle for a few days before the clear water was siphoned off. Organic material retained within the 2 mm sieve was discarded (much of this was fallen leaf litter and the focus of the study was material deposited by overbank flows). Very little inorganic material was retained in the 2 mm sieve, but if any was present it was picked out using tweezers and added to the rest of the material in the plastic container. Sediment in the plastic container was air-dried and then weighed to give a total dry mass of sediment collected on each mat.

Samples from the flood seasons of 2003/2004 and 2004/2005 were then mixed with sodium hexametaphosphate to disperse clay particles (see Goudie, 1990). To determine the percent of organic material < 2 mm, sub-samples were taken, oven dried (to remove any moisture) at 105°C until a constant weight was reached (usually overnight), and then loss of ignition (LOI) was performed on them (samples were weighed, then left in a furnace at 450°C for 4 hours, and then re-weighed (see Heiri *et al.* (2001) for a full description of the method).

The rest of the sample was passed through a 1 mm sieve. The material that was retained in the sieve was sorted by hand into organic and inorganic material and each expressed as a percentage of the total sample. A sub-sample of the material that passed through the sieve was taken to do finer particle size analysis (PSA). The sub-samples were analysed using a Malvern Mastersizer 2000. Several runs were made for each sample and average particle size distributions were obtained. From the distributions, the D_{50} and values of sand (between 63μm and 1000μm), silt (between 4μm and 63μm), and clay (<4μm), expressed as a percentage of volume, were extracted. To obtain estimates of the amount of sand, silt and clay in grammes in each deposit, it was assumed that the sub-samples used for PSA were representative of the total deposits.

Some samples were very small, and sub-samples could not be taken for LOI or PSA. If there was enough sample material for one analysis but not for the other, samples were used for PSA rather than LOI. Some samples continuously gave unrealistic readings during the PSA, possibly due to pieces of large organic matter being caught up in the lens; in these instances it was not possible to undertake PSA on the samples.

Analysis of organic material and PSA was not done on samples from 2005/2006 as these data were obtained at the very end of the monitoring period when there was insufficient time remaining to undertake the analysis. Furthermore, the data already obtained was deemed adequate to illustrate the spatial patterns in these variables.

Location of sediment traps

Overbank sedimentation was monitored at Sites 1, 2 and 3 before restoration (see Figure 6.1 for location of sites). At Site 1, 12 Astroturf mats were placed on the floodplain upstream and downstream of a wood jam that spanned the width of the floodplain. At sites 2 and 3, mats were set up in a similar arrangement, although in both cases there were no wood jams so the mats were placed in two transects about 5 metres apart from each other. Figures 6.13 to 6.18 show the locations of Astroturf mats in planform and cross-section as they were set up in Sites 1, 2 and 3 before the restoration (year 1).

For the two flood seasons after the restoration (2004/2005) and (2005/2006), the mats at Sites 1 and 3 were kept in the same positions; mats were replaced on the restored floodplain (Site 2), upstream and downstream of a wood jam that was created during the restoration; and due to low levels of deposition recorded during the first flood season, they were also emplaced upstream and downstream of Millyford wood jam (Site 4) (a site that had been shown to experience frequent overbank flow by Jeffries *et al.* (2003)) to ensure that some deposition values were obtained against which the Restored site (Site 2) could be compared. Figures 6.19 to 6.22 show the locations of Astroturf mats in planform and cross-section as they were set up in Sites 2 and 4 after the restoration (years 2 and 3).

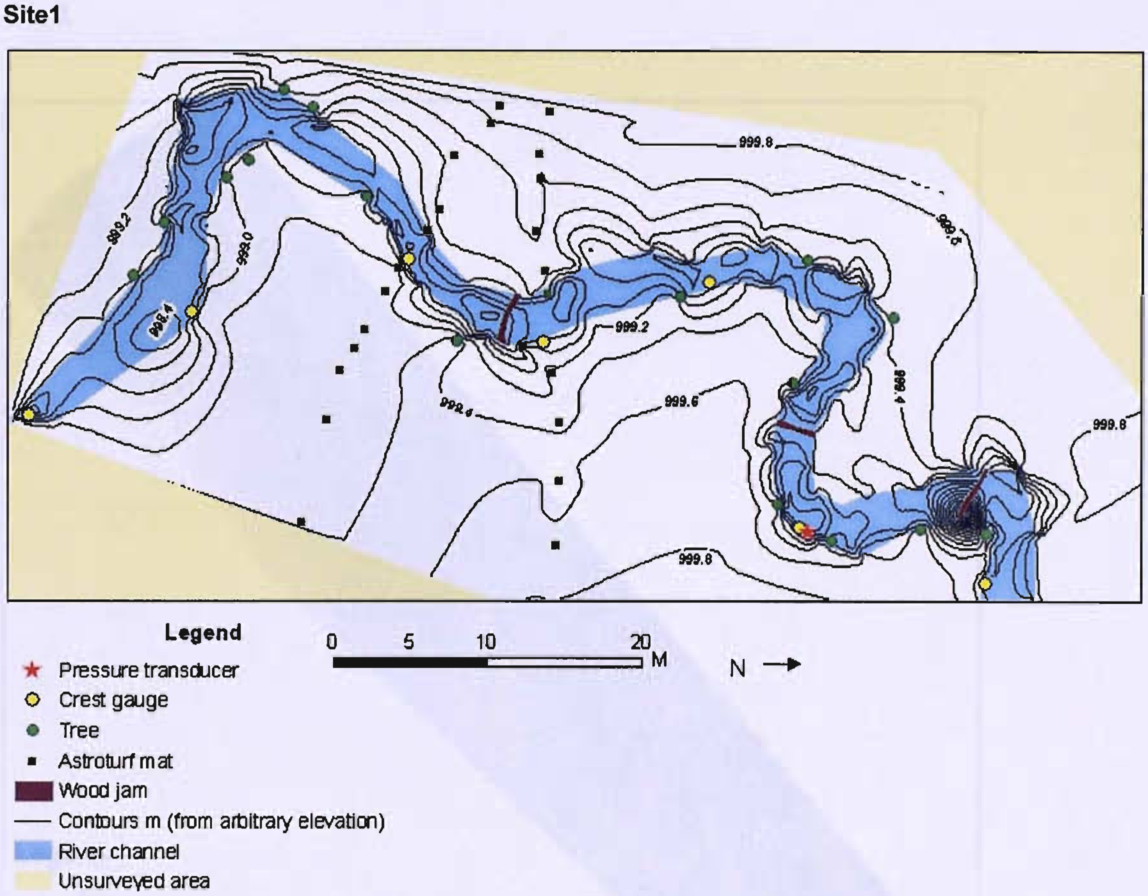


Figure 6.13 Distribution of Astroturf mats at Site 1 for all three years monitored, shown in planform. Flow is from right to left of page.

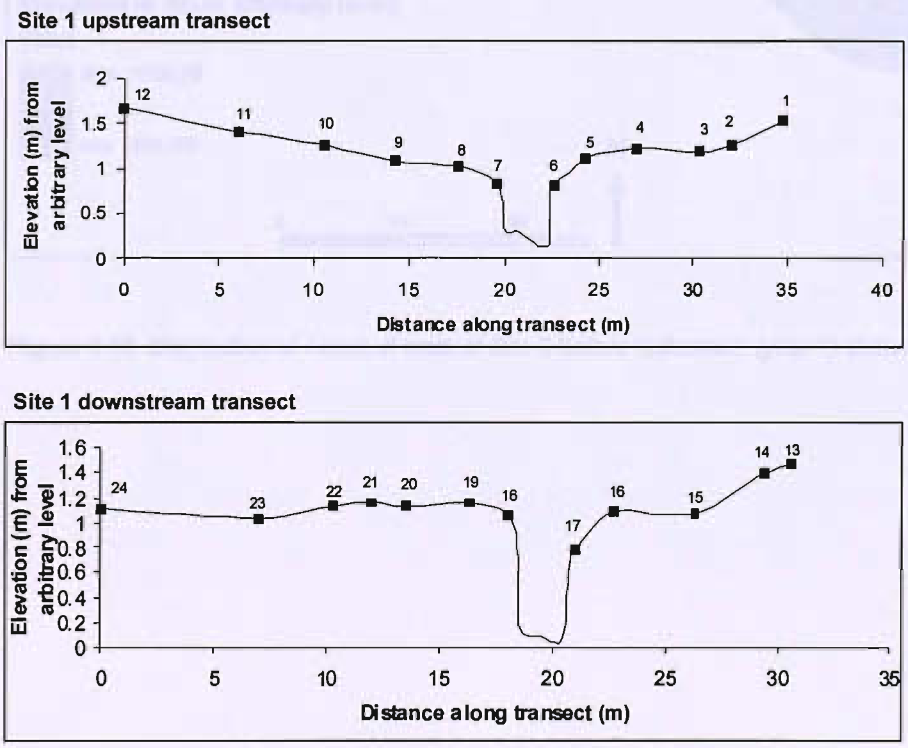


Figure 6.14 Distribution of Astroturf mats at Site 1 upstream and downstream of a wood jam shown in cross-section looking downstream.

Site 2

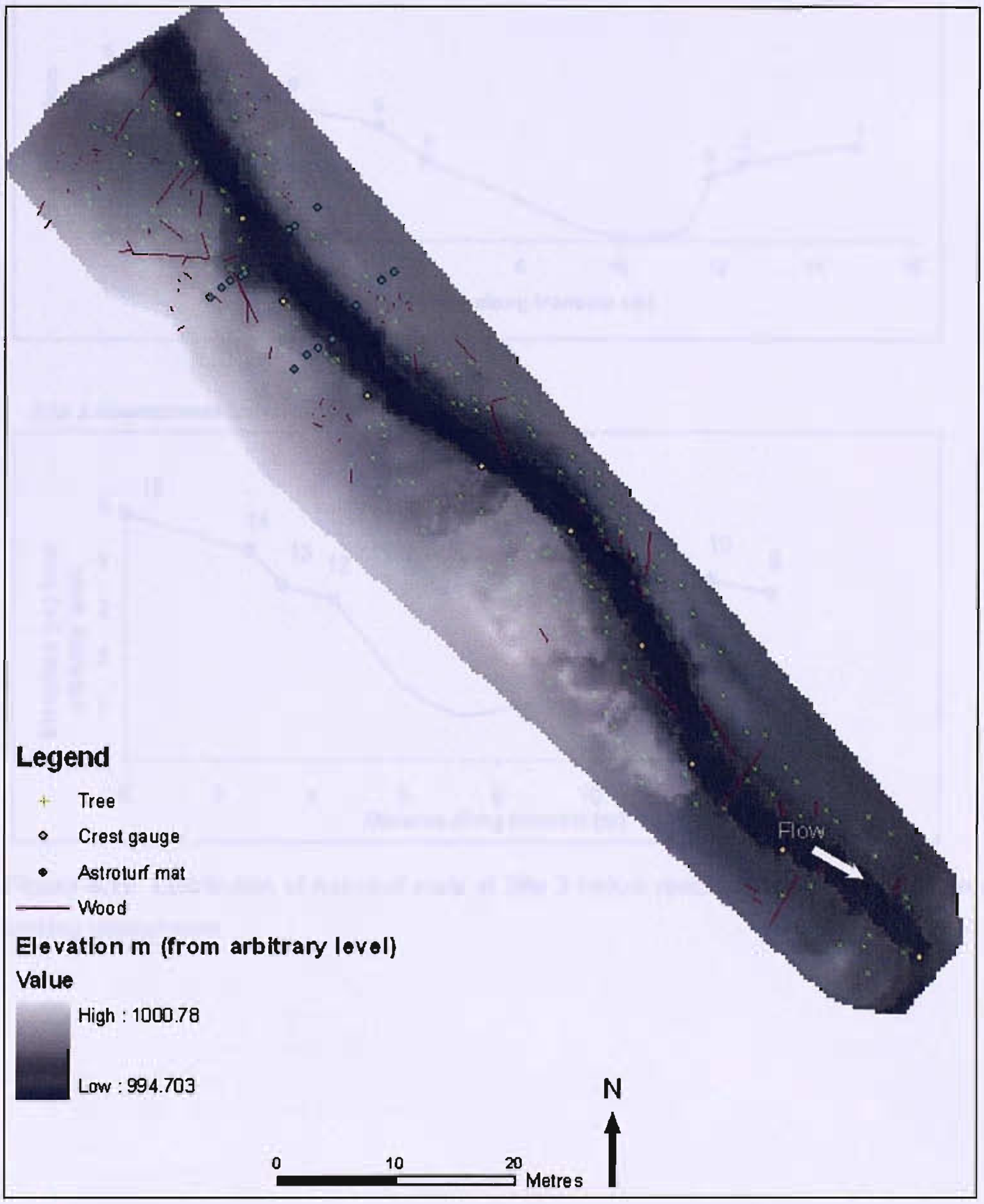
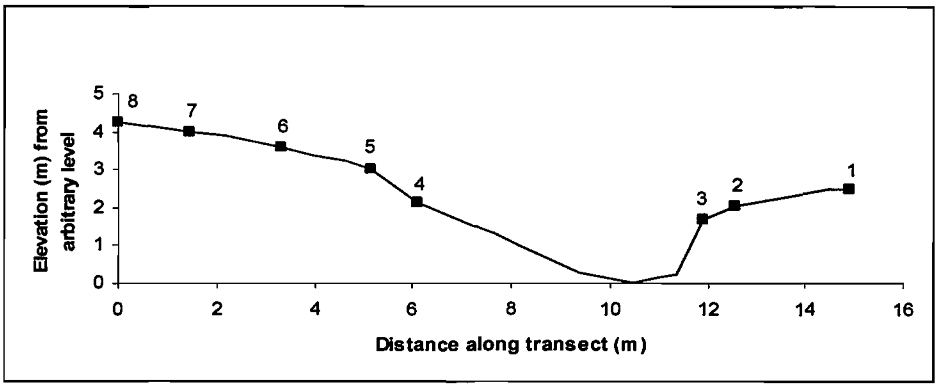


Figure 6.15 Distribution of Astroturf mats at Site 2 before restoration (year 1) shown in planform.

Site 2 upstream transect



Site 2 downstream transect

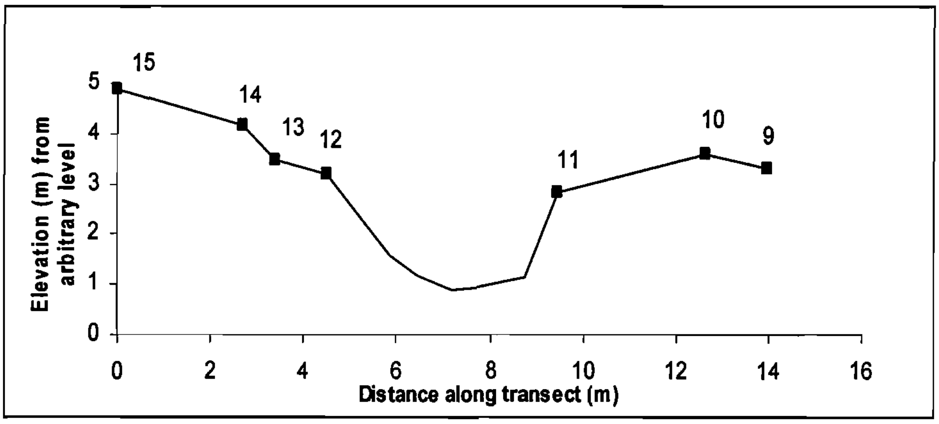


Figure 6.16 Distribution of Astroturf mats at Site 2 before restoration (year 1) shown in cross-section looking downstream.

Site 3

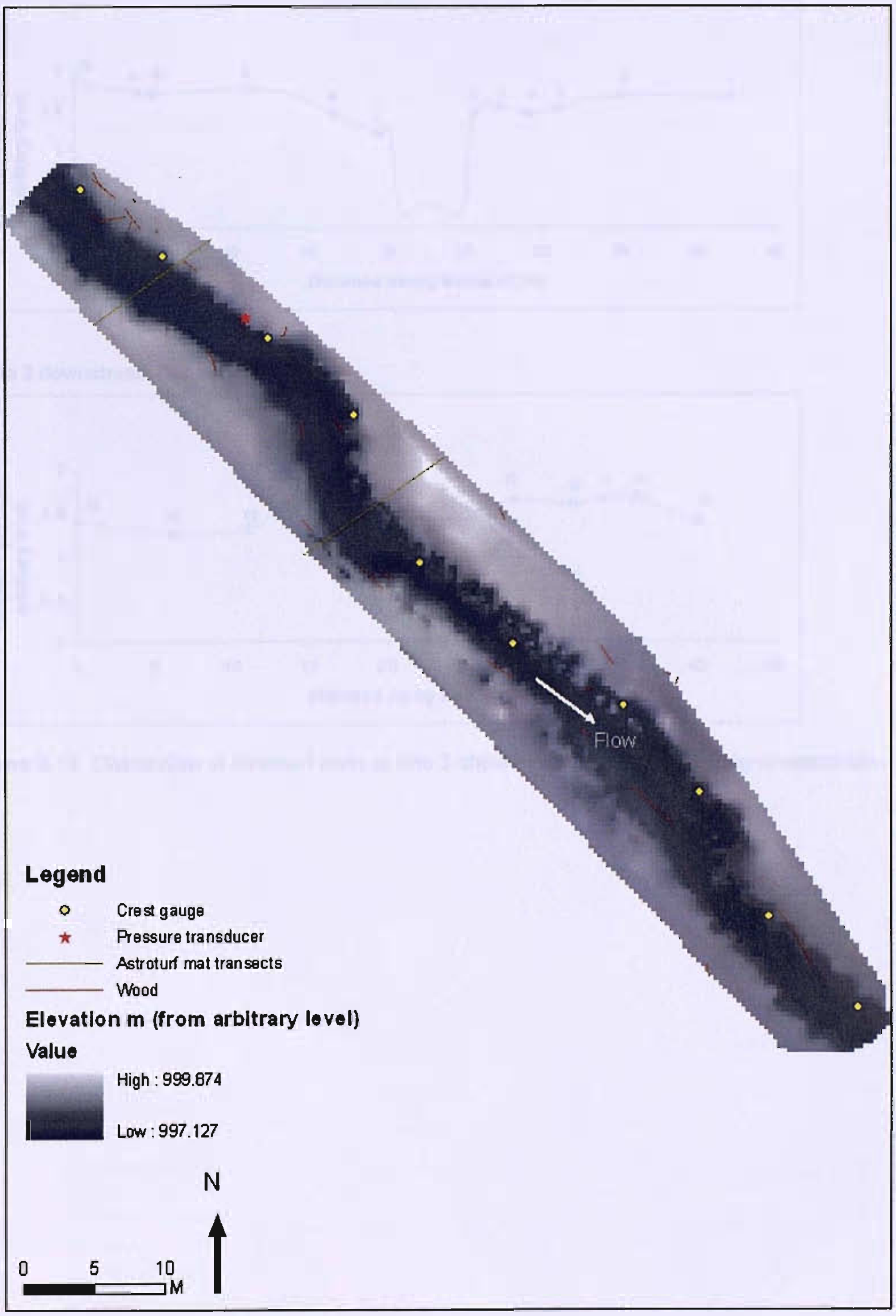
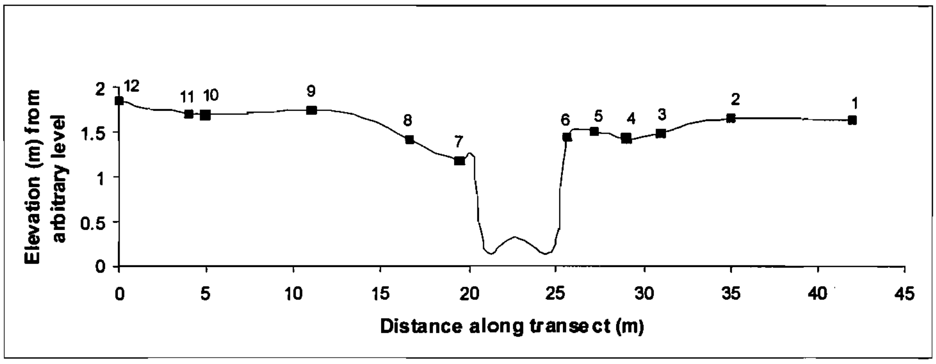


Figure 6.17 Location of Astroturf mat transects at Site 3 for all three years monitored shown in planform.

Site 3 upstream transect



Site 3 downstream transect

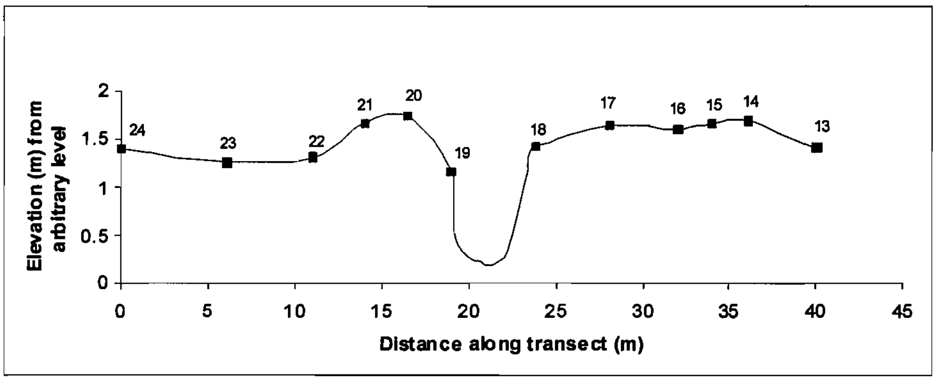


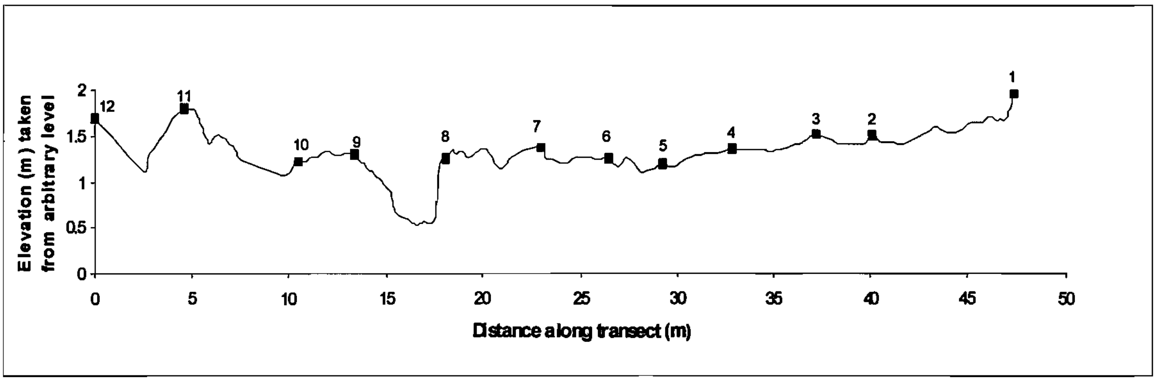
Figure 6.18 Distribution of Astroturf mats at Site 3 shown in cross-section looking downstream.

Location of sediment traps after the restoration

Site 2

Figure 6.19 Distribution of Astroturf mats at Site 2 post-restoration (years 2 & 3) shown in planform.

Site 2 upstream transect



Site 2 downstream transect

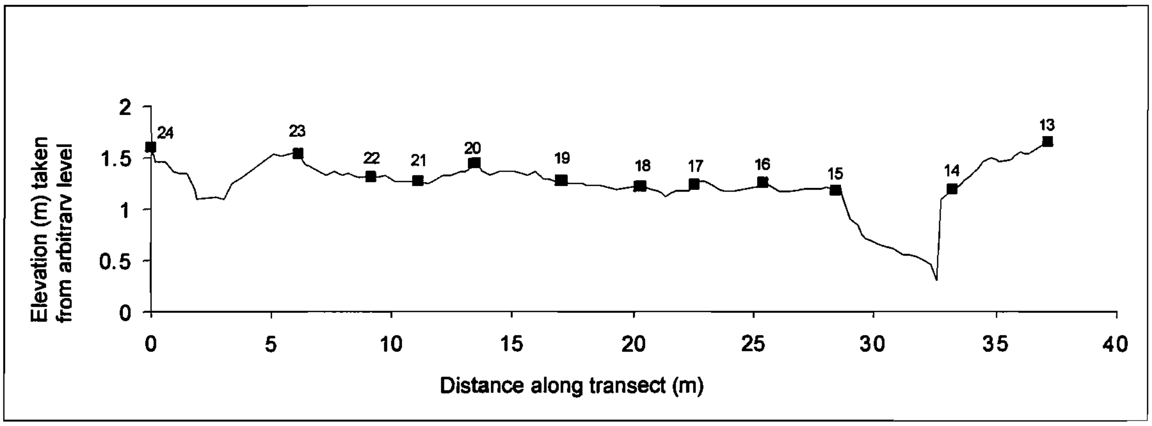


Figure 6.20 Distribution of Astroturf mats at Site 2 upstream and downstream of a wood jam post-restoration (years 2 & 3) shown in cross-section looking downstream.

Site 4

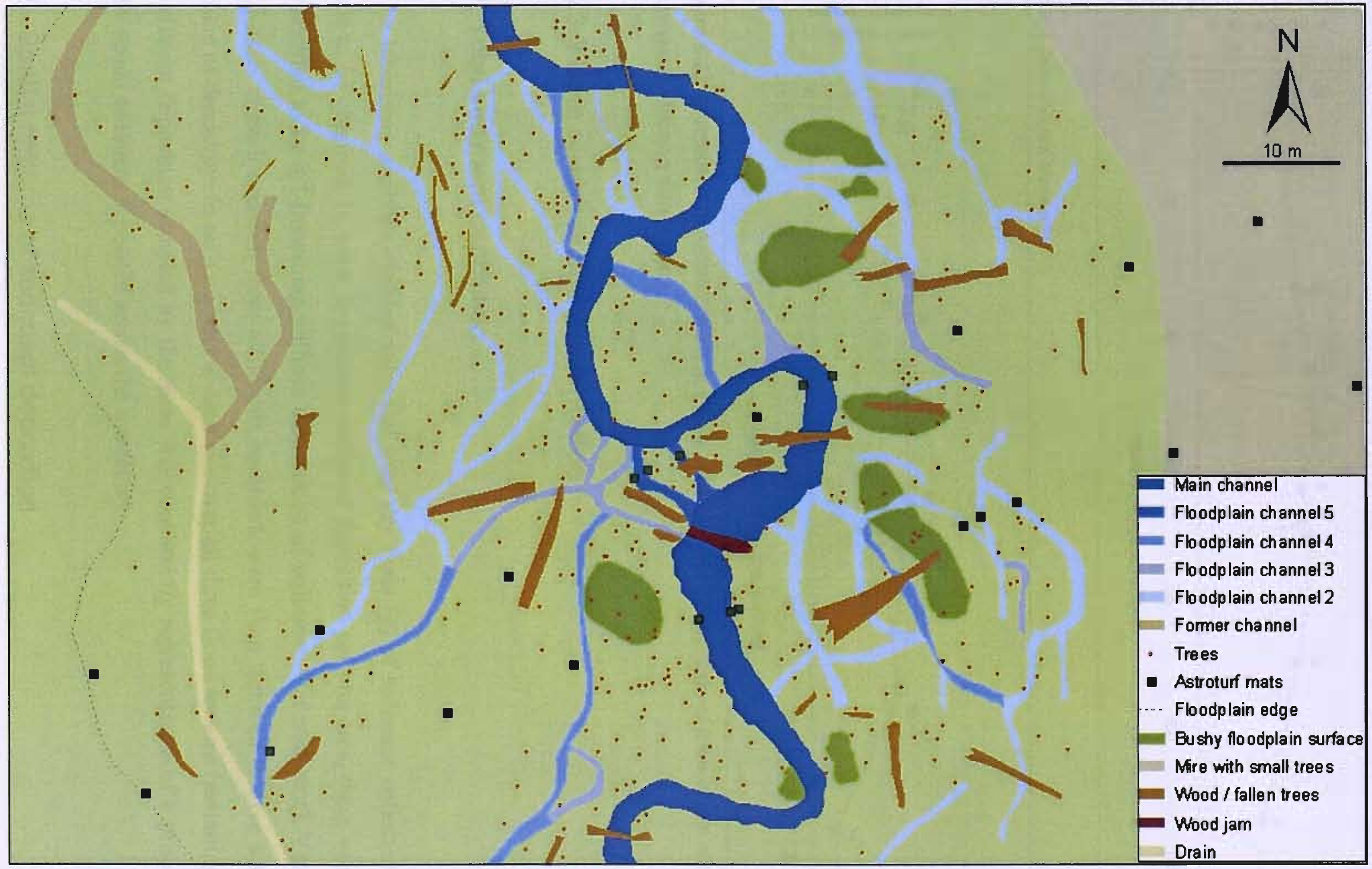
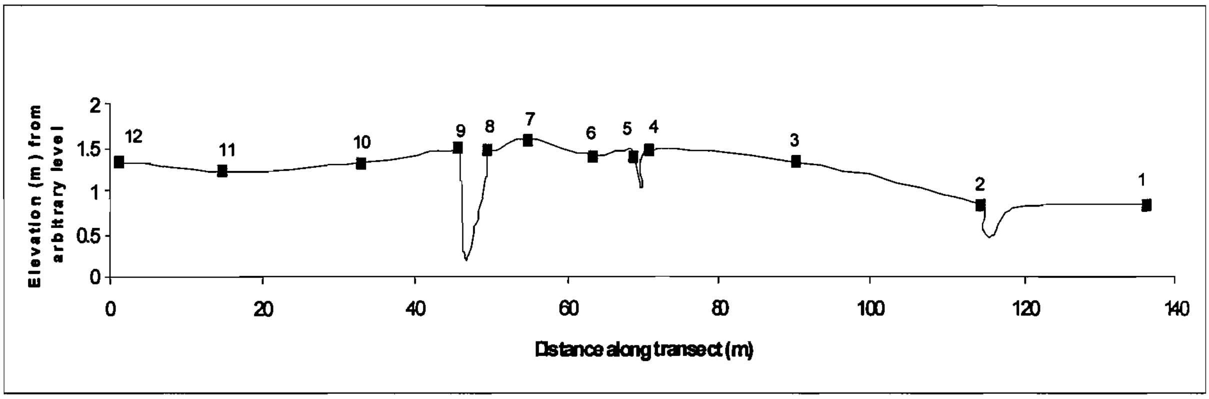


Figure 6.21 Distribution of Astroturf mats at Site 4 shown in planform (flow is down the page).

Site 4 upstream transect



Site 4 downstream transect

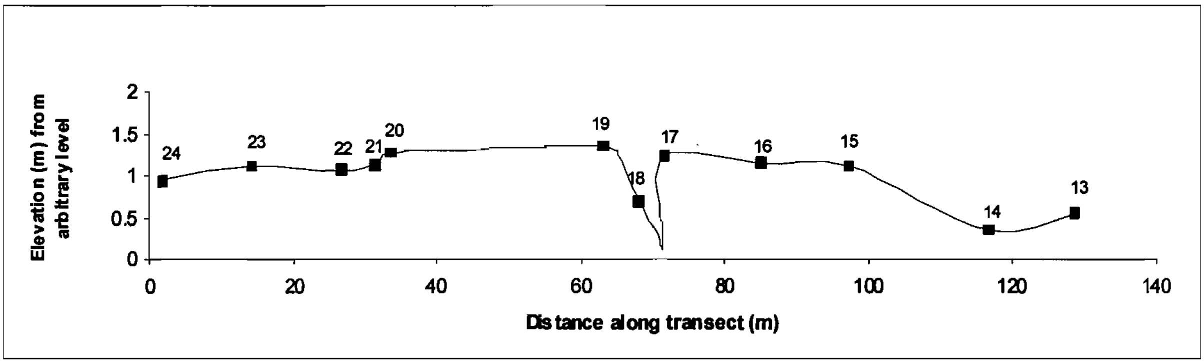


Figure 6.22 Distribution of Astroturf mats at Site 4 upstream and downstream of a wood jam shown in cross-section looking downstream.

6.3.3 Data analyses and presentation

1. Total sediment deposition

The laboratory analyses enabled values of total dry mass (g) of sediment collected on each mat to be obtained. In order to estimate sediment deposition per unit area, these values were converted to kg m^{-2} (assuming uniform distribution of sediment over each mat). Values from all mats in each transect, from all events recorded, were then summed to give a summary value of deposition in each transect at each site over all three flood seasons (assuming that the sediment deposition sampled by the mats was consistently representative of a proportion of the actual sediment deposited across the transects).

2. Spatial patterns of sediment deposition

(a) To analyse the spatial patterns in deposition across the floodplains, mass (g) of sediment retained on each mat from each event recorded was plotted on cross-sections of the floodplains depicting the locations of mats. The spatial distribution of inorganic sediment (represented as a total for each mat for a flood season) was then plotted for the two flood seasons monitored post-restoration (2004/2005 and 2005/2006). Graphs from 2004/2005 also display the percentage of organic material (< 2 mm) and the particle size distributions of the deposits from 2004/2005.

(b) To interpret the spatial patterns of overbank sedimentation, floodplain deposition was compared from different areas of the floodplain: adjacent to the main channel; on the floodplain surface; and in floodplain channels.

3. Floodplain hydrology and sediment deposition

In order to identify the level of control that floodplain hydrology had on sediment deposition, the supply of water and sediment to the floodplain during overbank flows was calculated. Relationships between water volume and suspended sediment and deposition (inorganic material, organic material, and the particle size distributions of deposits) were then identified.

6.3.4 Results

1. Total sediment deposition

(i) Before restoration

No mats at either Site 2 or Site 3 received deposition during the first flood season (2003/2004) as no flow came out of channel at these sites. At Site 1, only mats 6 and 7 (mats either side of the channel in the upstream transect) did, with a total dry mass of 0.14 kg m^{-2} (see Table 6.6). This was partly due to it being a dry winter (see Met Office records: http://www.metoffice.gov.uk/climate/uk/2006/april/averages1.html), but also due to site characteristics - large discharges were needed for flow to go overbank and inundate the mats (see Table 6.7 for discharges required for overbank flow at each of the sites and the associated frequency of these discharges).

Table 6.6 Sediment deposited on mats at Site 1 during winter 2003/2004.

Date mat collected	Mat number	Amount of sediment (kg m^{-2})
13/01/2004	7	0.016
13/01/2004	6	0.084
20/04/2004	7	0.006
20/04/2004	6	0.012
11/05/2004	6	0.022
Total		0.140

Table 6.7 Average discharges required for overbank flow upstream and downstream of wood jams and the associated frequency of these discharges at the different sites.

Site	Before / after restoration	Upstream or downstream of wood jam	Avg. discharge required for overbank flow ($m^3 s^{-1}$)	Flow frequency (% time flow exceeded)
1	Yr 1	u/s	1.00	0.15
		d/s	1.80	0.00
	Yr 2	u/s	1.00	0.30
		d/s	1.80	0.00
	Yr 3	u/s	1.00	0.40
		d/s	1.80	0.00
2	Yr 1	no jam	7.35	0.00
	Yr 2	u/s	0.33	1.40
		d/s	0.60	0.50
	Yr 3	u/s	0.33	4.00
		d/s	0.60	1.40
3	Yr 1	no jam	2.17	0.00
	Yr 2	no jam	2.17	0.00
	Yr 3	no jam	2.17	0.00
4	Yr 1	u/s	0.55	7.60
		d/s	2.20	0.00
	Yr 2	u/s	0.55	3.00
		d/s	2.20	0.00
	Yr 3	u/s	0.55	8.00
		d/s	2.20	0.00

(ii) After restoration

Table 6.7 shows that the restoration reduced channel capacity at Site 2 so that the discharge required for overbank flow was reduced from 7.35 $m^3 s^{-1}$ before the restoration to 0.33 $m^3 s^{-1}$ upstream of the wood jam, and 0.6 $m^3 s^{-1}$ downstream of the wood jam, after the restoration. Consequently the frequency of overbank flow increased from zero before the restoration in year 1, to 1.4% of the time upstream of the wood jam, and 0.5% of the time downstream of the wood jam, in year 2; and to 4% of the time upstream of the wood jam, and 1.4% of the time downstream of the wood jam, in year 3.

During the first two flood seasons after the restoration, mats at Site 1, 2 and 4 received deposition (mats at Site 3 did not). The total amount of deposition at each site varied. During the flood season of 2004/2005, Site 4 received the most sediment deposition with a total mass of 72.5 kg m^{-2}, followed by Site 2 with 62.5 kg m^{-2} and Site 1 with 4 kg m^{-2} (Table 6.8). These values are considerably lower than those recorded at Site 4 during 2000/2001 by Jeffries *et al.*

(2003) (see discussion in Section 6.3.5.). Transects upstream of wood jams at all sites received more than twice the amount of sediment than downstream transects did (Table 6.8 and Figure 6.23). Similar to the previous year, the downstream transect at Site 1 did not receive any deposition, and it was only the two mats on either side of the channel in the upstream transect (mats 6 and 7 Figure 6.14) that received sediment (see Figure 6.23).

During the flood season of 2005/2006, Site 4 again received the most sediment deposition, with a total of 98.87 kg m^{-2}, however there was less of a difference between the upstream transect (53.99 kg m^{-2}) and the downstream transect (44.88 kg m^{-2}) than in the previous year. Site 2 received less sediment deposition than the previous year, with a total of 33.01 kg m^{-2}, although there was a greater difference between the upstream transect (26.26 kg m^{-2}) and the downstream transect (6.75 kg m^{-2}). The upstream transect at Site 1 experienced more deposition than the previous year (8.19 kg m^{-2}) and again the downstream transect did not receive any sediment deposition.

Both Site 1 and Site 4 received more deposition in total during 2005/2006 (8.19 and 98.87 kg m^{-2} respectively) than during 2004/2005 (4.0 and 72.5 kg m^{-2}), although the amount at Site 2 decreased from 2004/2005 (62.5 kg m¯2) to 2005/2006 (33.01 kg m^{-2}). This could be due to increased sediment supply brought about by the restoration; during 2004/2005 (immediately following the restoration) there was lots of unconsolidated sediment both in the channel and on the floodplain, that could potentially be deposited on the floodplain at Site 2 (see Section 6.2). By 2005/2006 much of the unconsolidated fine material had probably washed out of the gravels in the channel, and the floodplain had started to become re-vegetated, therefore sediment supply was reduced.

Table 6.8 Total sediment deposited in transects upstream and downstream of wood jams for the three flood seasons monitored (n/a indicates mats were not monitored at that site during that flood season).

	Total sediment deposition (kg m^{-2})								
	2003/2004			2004/2005			2005/2006		
Site	u/s	d/s	Total	u/s	d/s	Total	u/s	d/s	Total
Site 1	0.14	0.00	0.14	4.00	0.00	4.00	8.19	0.00	8.19
Site 2	0.00	0.00	0.00	42.50	20.00	62.50	26.26	6.75	33.01
Site 3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Site 4	n/a	n/a	n/a	50.00	22.50	72.50	53.99	44.88	98.87

2. Spatial patterns of sediment deposition - description

The mass of inorganic sediment deposited on each mat from overbank events during the flood season of 2004/2005 is shown in Figure 6.23. 'Elevation' is calculated from a bench mark with an arbitrary elevation; 'distance' represents distance across the floodplain; flow is into the plots (a downstream view); the size of the bubbles represents the mass of inorganic sediment deposited on each mat in grammes; and filled squares represent mats with no deposition. It was not possible to change the mats between events 1, 2 and 3 at Site 4, so the three events are combined on one graph. Site 1 only received deposition during events 1-4; Site 2 received deposition during events 1, 2, 3, 4, 6 and 7; Site 3 did not receive any deposition; and Site 4 received deposition during events 1-9.

(a) Site 1

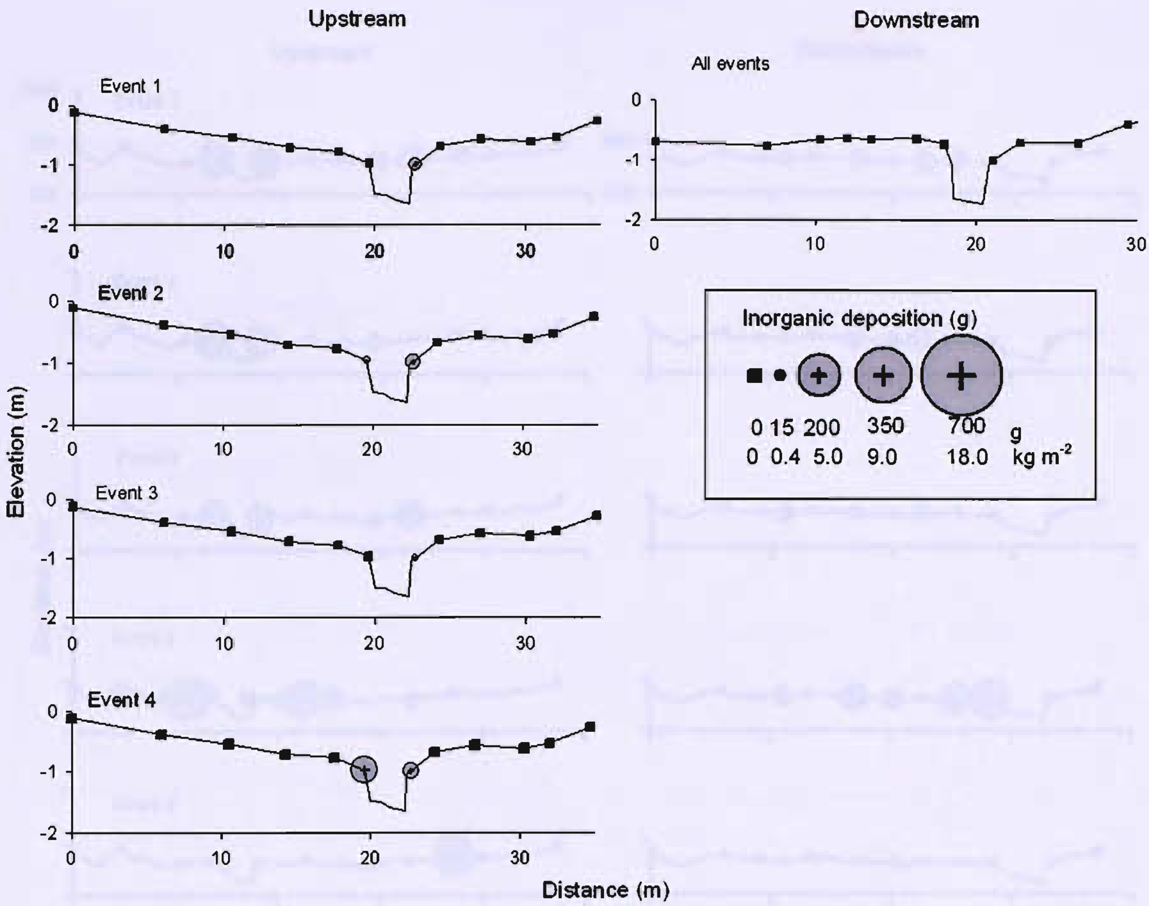


Figure 6.23 Mass of inorganic sediment deposited on each mat from individual overbank events during the flood season of 2004/2005 for (a) Site 1, (b) Site 2 and (c) Site 4.

(b) Site 2

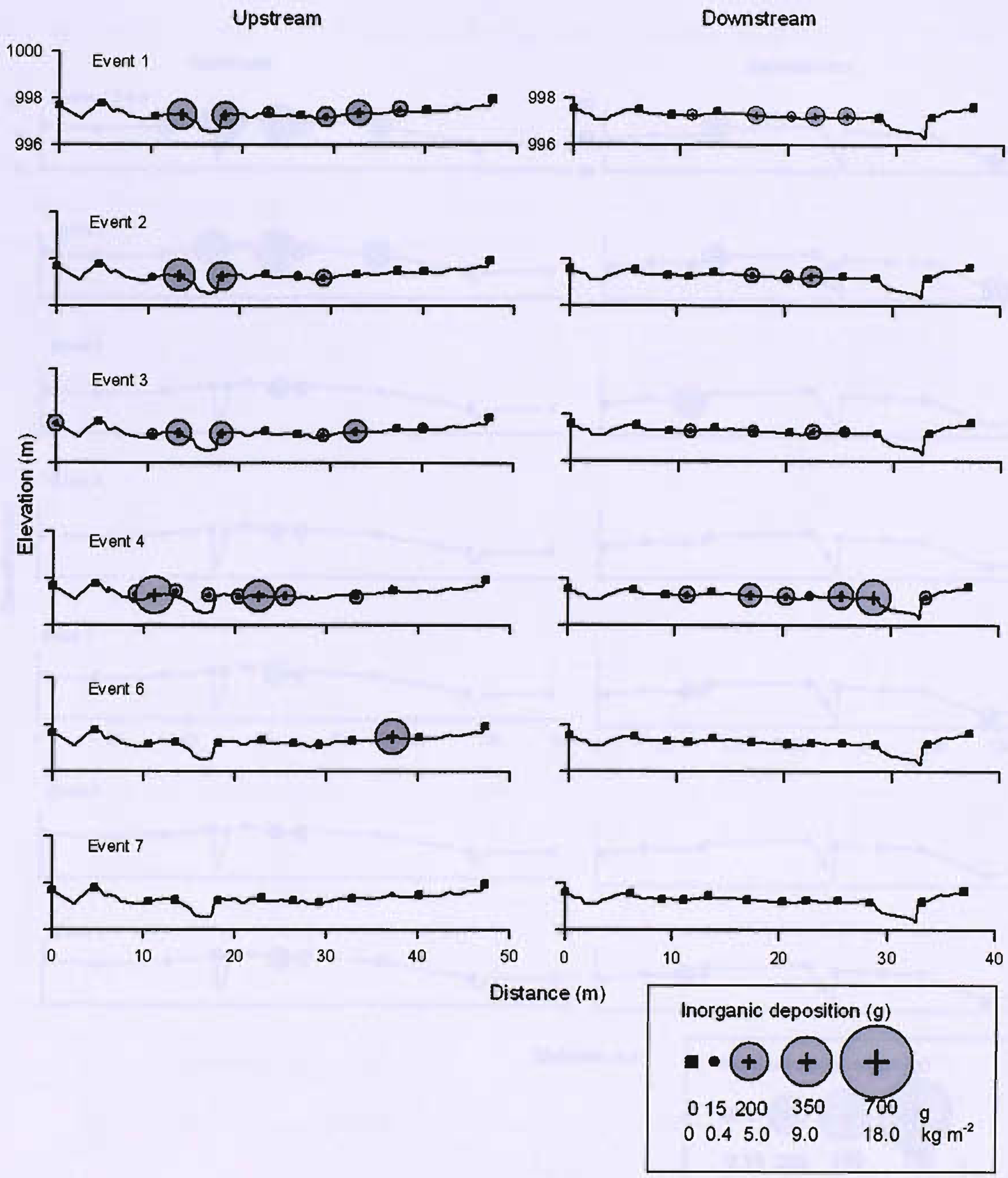


Figure 6.23 Continued

(c) Site 4

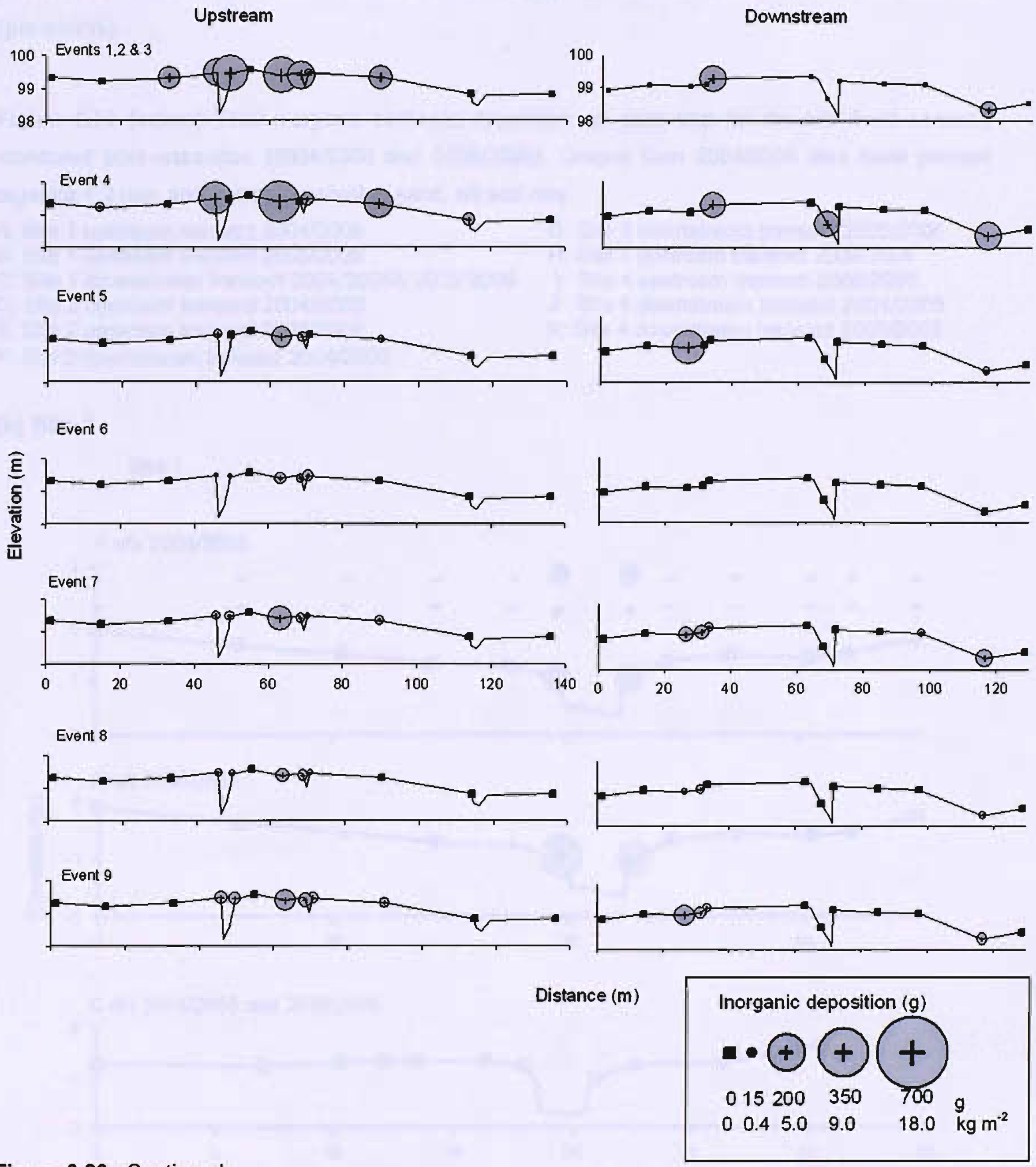


Figure 6.23 Continued.

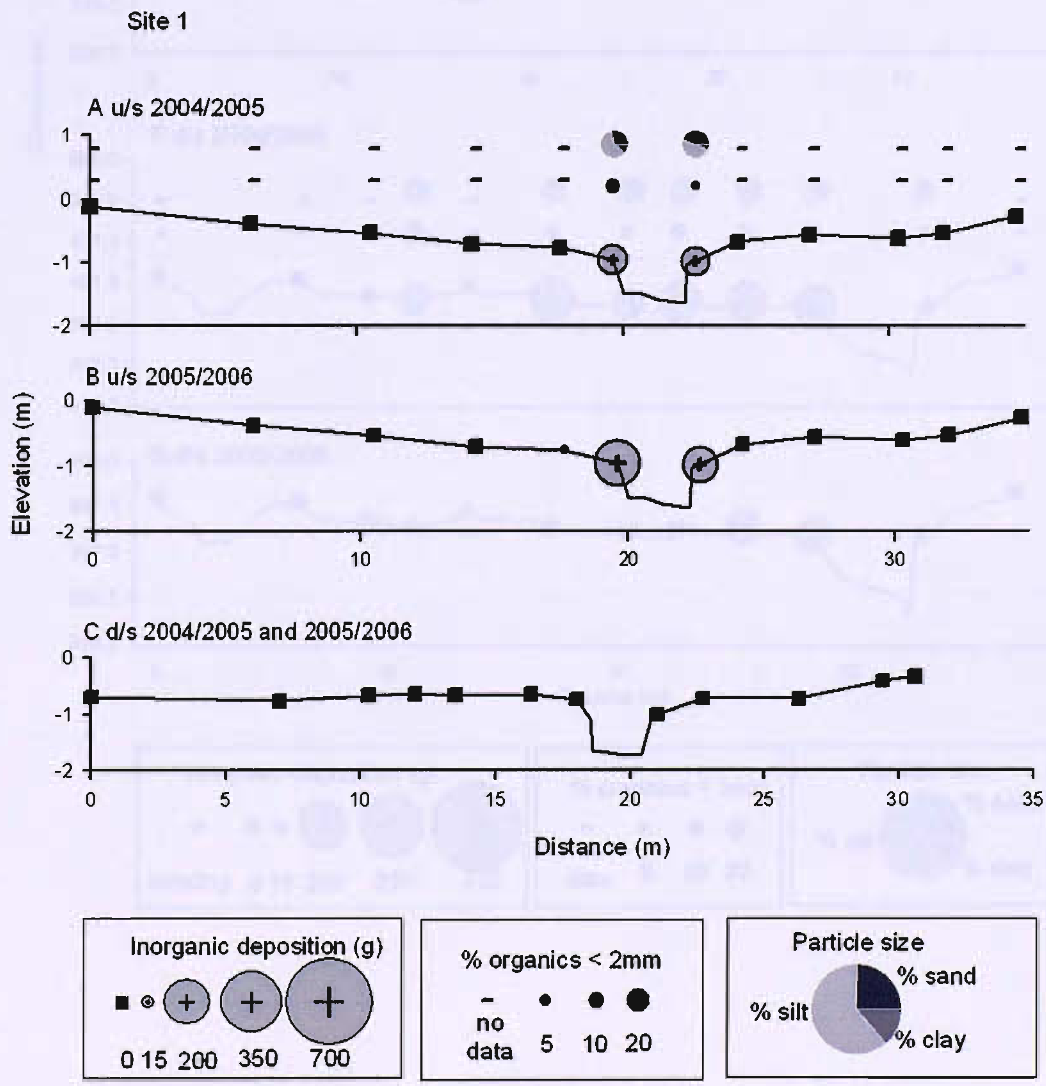
Figure 6.23 shows that, from all events at the three sites, there was more deposition in the transects upstream of the wood jams than downstream. Patterns of deposition across the floodplains were highly variable, with more deposition close to the main channel in the upstream transects than in the downstream transects. Furthermore, the amounts and patterns of deposition varied between events.

Figure 6.24 shows *total* inorganic sediment deposited on the mats during the flood seasons of 2004/2005 and 2005/2006 (grey circles with crosses). The graphs from 2004/2005 also show percent organics < 2 mm (solid circles) and average percent of sand, silt and clay on each mat (pie charts).

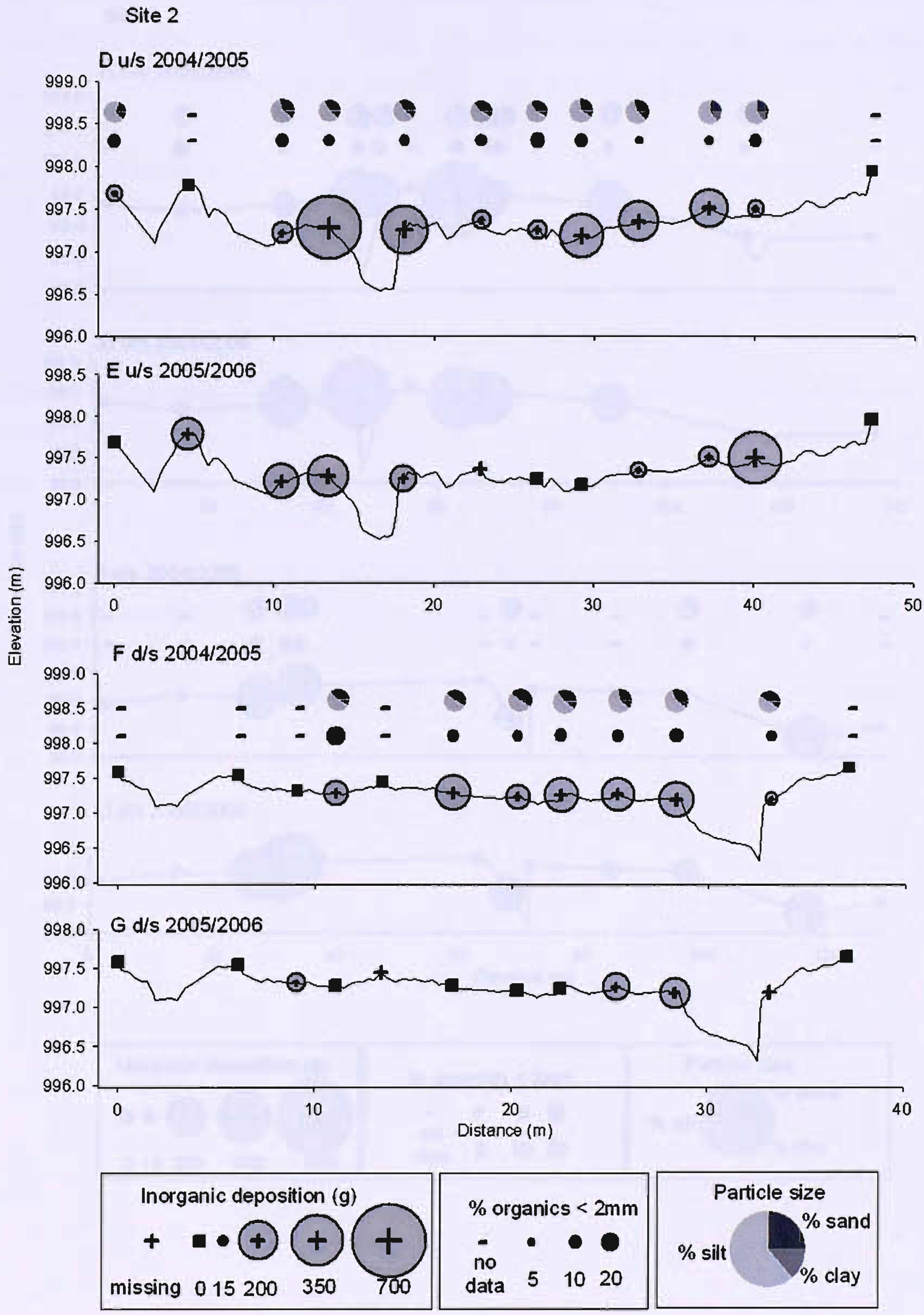
Figure 6.24 (below) Total inorganic sediment deposition on each trap for the two flood seasons monitored post-restoration (2004/2005 and 2005/2006). Graphs from 2004/2005 also have percent organics < 2 mm, and average percent of sand, silt and clay.

A: Site 1 upstream transect 2004/2005
B: Site 1 upstream transect 2005/2006
C: Site 1 downstream transect 2004/2005& 2005/2006
D: Site 2 upstream transect 2004/2005
E: Site 2 upstream transect 2005/2006
F: Site 2 downstream transect 2004/2005
G: Site 2 downstream transect 2005/2006
H: Site 4 upstream transect 2004/2005
I: Site 4 upstream transect 2005/2006
J: Site 4 downstream transect 2004/2005
K: Site 4 downstream transect 2005/2006

(a) Site 1

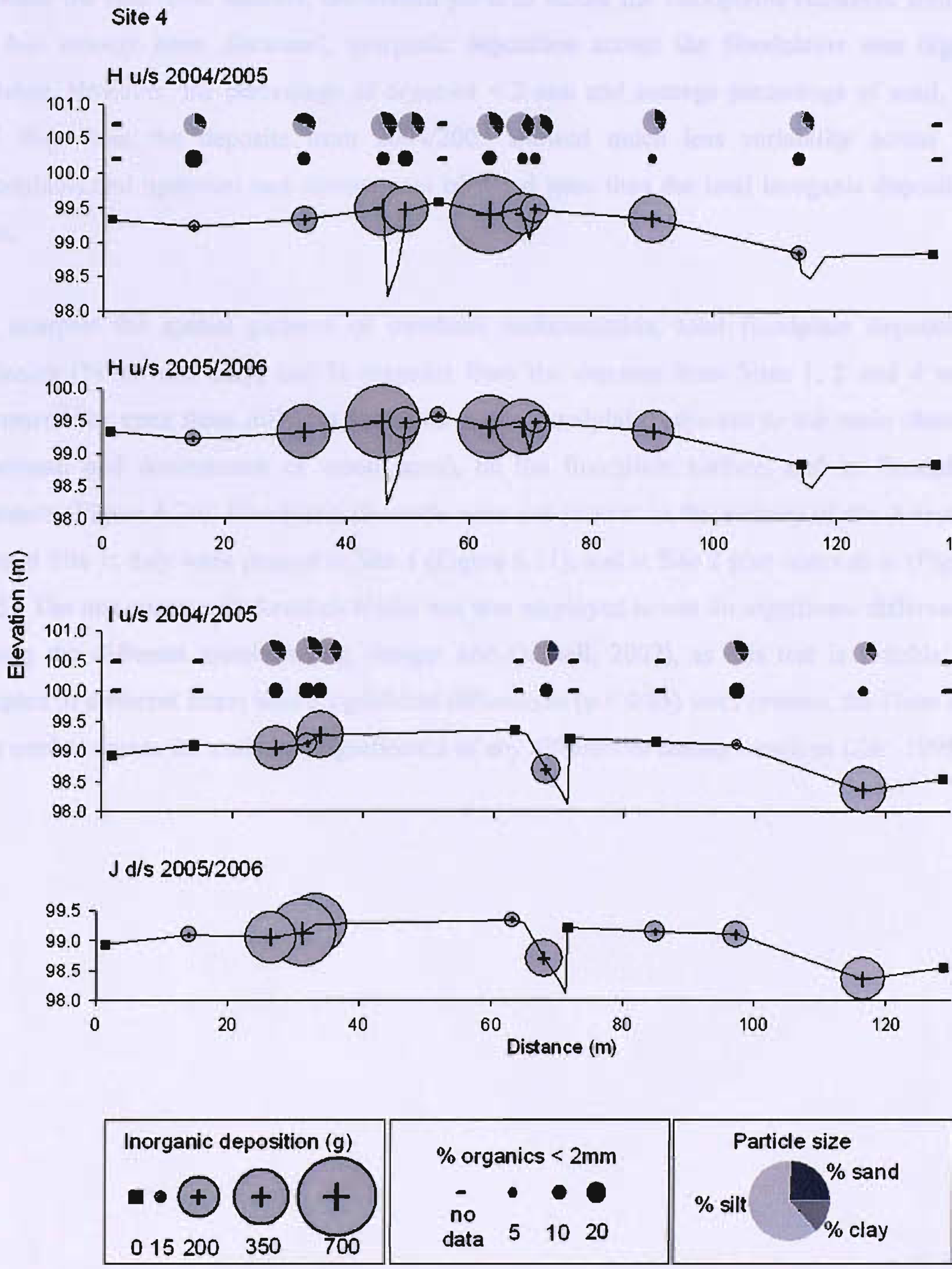


(b) Site 2



Site 2
D u/s 2004/2005
E u/s 2005/2006
F d/s 2004/2005
G d/s 2005/2006
Elevation (m)
Distance (m)
Inorganic deposition (g)
missing 0 15 200 350 700
% organics < 2mm
no data 5 10 20
Particle size
% sand
% silt
% clay

(c) Site 4



Site 4
H u/s 2004/2005
H u/s 2005/2006
I u/s 2004/2005
J d/s 2005/2006
Elevation (m)
Distance (m)
Inorganic deposition (g)
0 15 200 350 700
% organics < 2mm
no data
5 10 20
Particle size
% sand
% silt
% clay

Figure 6.24 demonstrates that, although the total amounts of inorganic deposition varied between the two flood seasons, the overall patterns across the floodplains remained similar. As has already been discussed, inorganic deposition across the floodplains was highly variable. However, the percentage of organics < 2 mm and average percentage of sand, silt and clay from the deposits from 2004/2005 showed much less variability across the floodplains and upstream and downstream of wood jams than the total inorganic deposition does.

To interpret the spatial patterns of overbank sedimentation, total floodplain deposition, grainsize (% silt and clay) and % organics from the deposits from Sites 1, 2 and 4 were compared for mats from different locations of the floodplain: adjacent to the main channel (upstream and downstream of wood jams), on the floodplain surface, and in floodplain channels (Figure 6.26). Floodplain channels were not present in the vicinity of the Astroturf mats at Site 1; they were present at Site 4 (Figure 6.21), and at Site 2 post-restoration (Figure 6.25). The non-parametric Kruskal-Wallis test was employed to test for significant differences among the different locations (e.g. Steiger and Gurnell, 2002), as this test is suitable for samples of different sizes; where significant differences ($p < 0.05$) were present, the Dunn test was used to assess the statistical significance of any differences among locations (Zar, 1999).

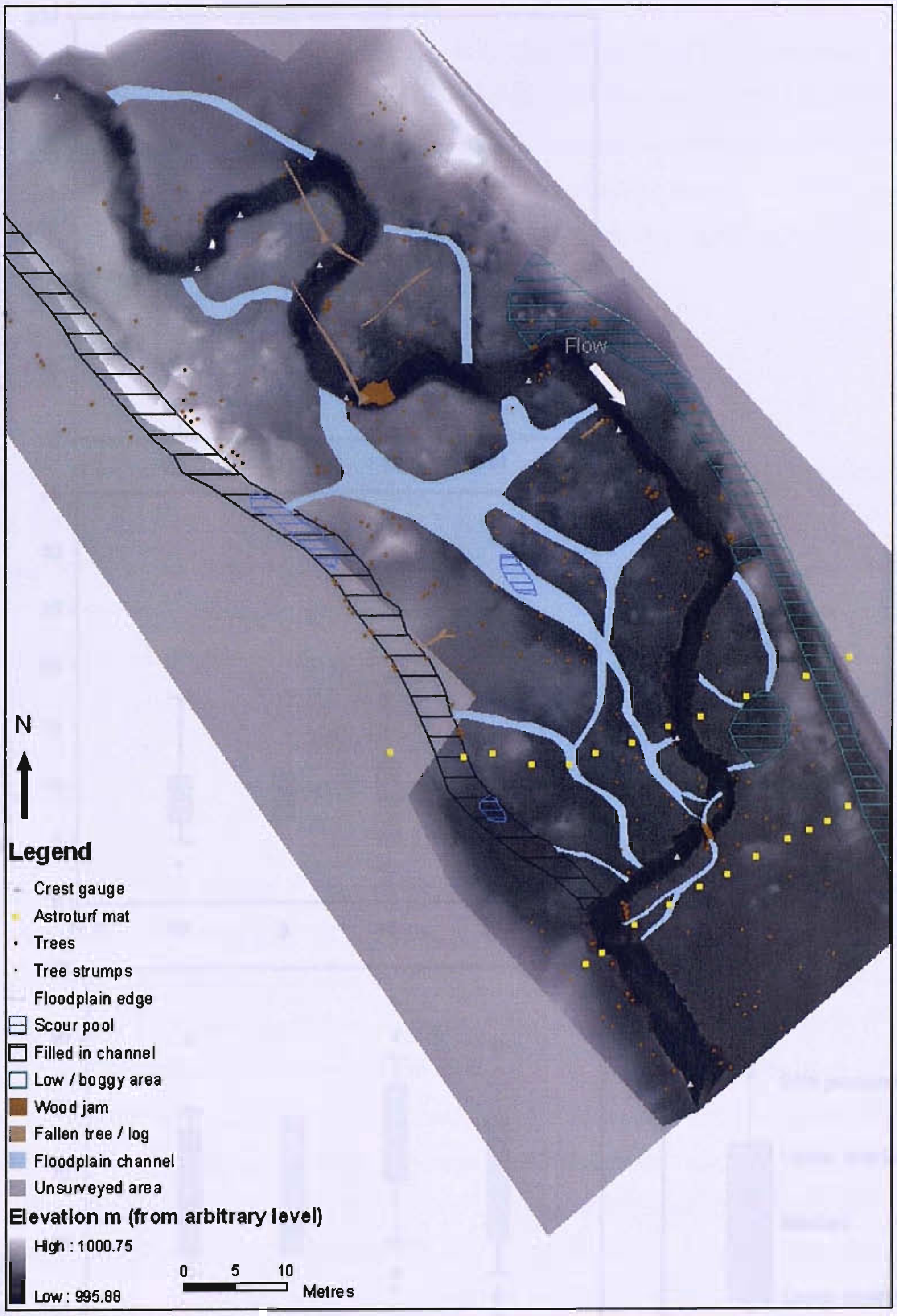


Figure 6.25 Site 2 post-restoration showing the location of floodplain channels.

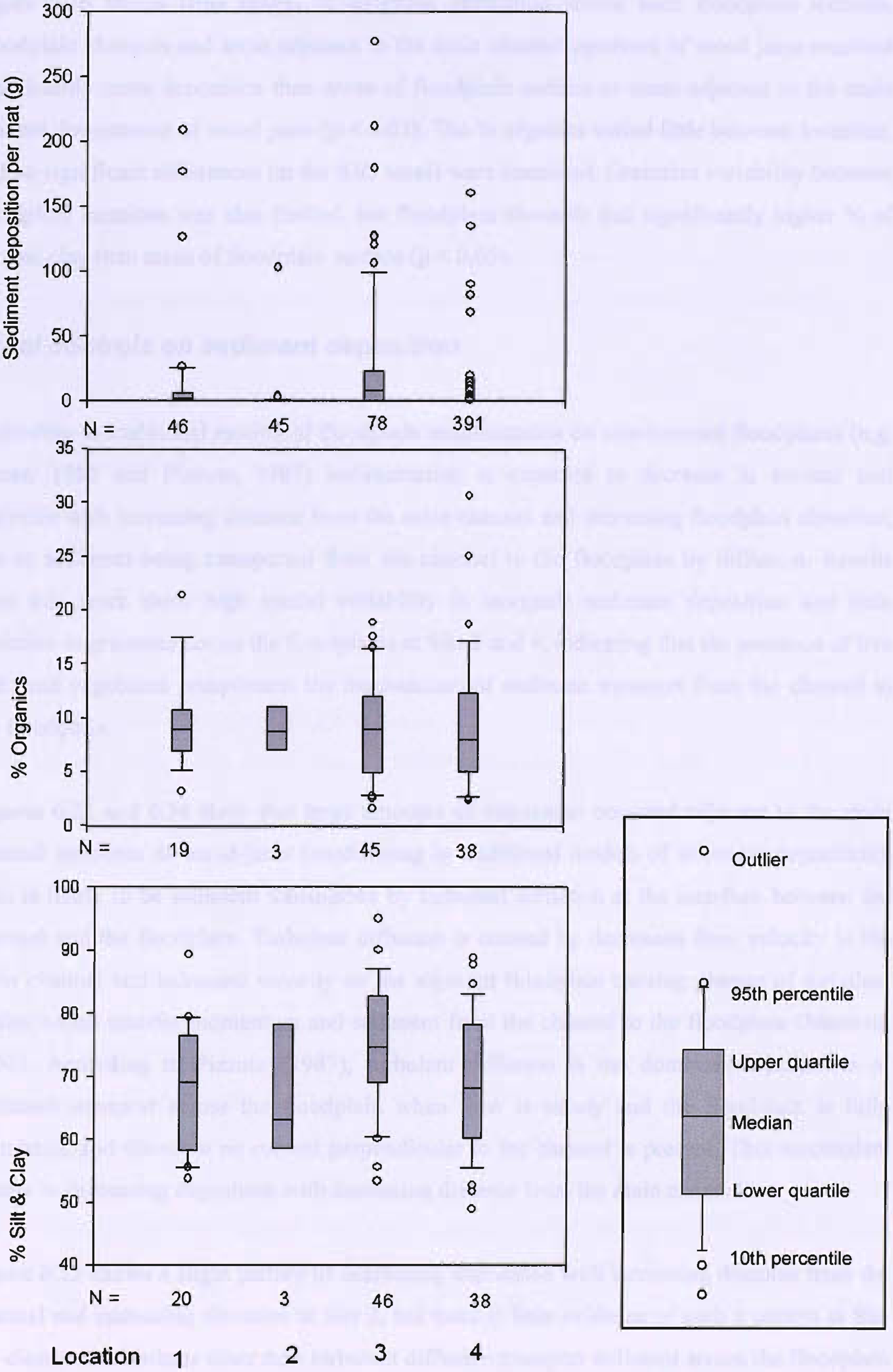


Figure 6.26 Box and whisker plots of % silt & clay, % organics, and sediment deposition for mats from different locations. Location 1: Adjacent to the main channel, upstream of wood jam; 2: Adjacent to the main channel, downstream of wood jam; 3: Floodplain channel; 4: Floodplain surface.

Figure 6.26 shows large ranges in sediment deposition within each floodplain location. Floodplain channels and areas adjacent to the main channel upstream of wood jams received significantly more deposition than areas of floodplain surface or areas adjacent to the main channel downstream of wood jams ($p < 0.01$). The % organics varied little between locations, and no significant differences (at the 0.05 level) were identified. Grainsize variability between floodplain locations was also limited, but floodplain channels had significantly higher % of silt and clay than areas of floodplain surface ($p < 0.05$).

Local controls on sediment deposition

According to traditional models of floodplain sedimentation on non-forested floodplains (e.g. James, 1985 and Pizzuto, 1987) sedimentation is expected to decrease in amount and grainsize with increasing distance from the main channel and increasing floodplain elevation, due to sediment being transported from the channel to the floodplain by diffusion. Results from this work show high spatial variability in inorganic sediment deposition and little variation in grainsize across the floodplains at Site 2 and 4, indicating that the presence of live and dead vegetation complicates the mechanisms of sediment transport from the channel to the floodplain.

Figures 6.23 and 6.34 show that large amounts of deposition occurred adjacent to the main channel upstream of wood jams (conforming to traditional models of sediment deposition). This is likely to be sediment transported by turbulent diffusion at the interface between the channel and the floodplain. Turbulent diffusion is created by decreased flow velocity in the main channel and increased velocity on the adjacent floodplain causing plumes of turbulent eddies which transfer momentum and sediment from the channel to the floodplain (Marriott, 1998). According to Pizzuto (1987), turbulent diffusion is the dominant mechanism of sediment transport across the floodplain when flow is steady and the floodplain is fully inundated, and therefore no current perpendicular to the channel is present. This mechanism results in decreasing deposition with increasing distance from the main channel.

Figure 6.23 shows a slight pattern of decreasing deposition with increasing distance from the channel and increasing elevation at Site 2, but there is little evidence of such a pattern at Site 4 – clearly mechanisms other than turbulent diffusion transport sediment across the floodplain contributing to the observed patterns of deposition, and these mechanisms appear to be of greater importance at Site 4 than at Site 2.

Mechanisms of sediment transport and deposition experienced in these forested floodplains are related to in-channel wood jams (Jeffries *et al.,* 2003). The patterns of deposition upstream and downstream of wood jams were very different; at all sites there was more deposition upstream of wood jams than downstream (Table 6.8), and there was significantly more deposition adjacent to the main channel upstream of wood jams than downstream ($p < 0.01$) (Figure 6.26). These patterns were likely to be due to flow ponding upstream of the jams (as suggested by Jeffries *et al.,* 2003), and increased water surface elevations, resulting in overbank flows occurring at lower discharges upstream than downstream (Brummer *et al.,* 2006).

In transects upstream and downstream of wood jams there were certain mats that were far from the main channel that received large amounts of deposition. This is likely to be due to the fact that, in this environment, flow was not steady and the floodplain was rarely completely inundated: floodplain channels transferred sediment by convection across the floodplain creating different sediment environments - 'hotspots' of deposition interspersed by areas of no, or very little, deposition (demonstrated by significantly more deposition recorded in floodplain channels than on the floodplain surface ($p < 0.01$) (Figure 6.26)). As discussed in Chapter 5, these floodplain channels generally formed upstream of wood jams where the water elevation was higher and overbank flood frequency was increased. Results from this section have demonstrated that this led to increased deposition of sediment upstream of wood jams. Water from this zone was advected via floodplain channels across other areas of the floodplain.

Additional sediment (and organics) may have been sourced by erosion of material from the floodplain itself (see Chapter 7). Erosion is particularly important on wooded floodplains where threads of high velocity flow (floodplain channels) are formed by topographic variations and the distribution of trees (Brown and Brookes, 1997). As floodplain channels are predominantly erosional features, they would be expected to transport a high sediment load - the traps in the floodplain channels may have actively 'scavenged' sediment from the water column. Furthermore, erosion may have occurred in the floodplain channels during the early phases of floods when overbank flows were rapid, but as the floods subsided and flows started to become ponded, sediment deposition may have dominated (Jeffries, 2002). From work on Coastal Plain rivers in the south-eastern USA, Hupp (2000) also reports high rates of deposition near sloughs (floodplain channels) and their anabranches, which have a direct flow path to the river.

Sediment may have been deposited on areas of floodplain surface adjacent to floodplain channels during large floods when floodplain channels overspilled. Higher % silt and clay were recorded from floodplain channels than from areas of floodplain surface ($p < 0.05$), indicating that on average the grainsize of deposited material in floodplain channels was finer than that on the floodplain surface. This could be due the fact that the data represent deposition from a sequence of floods of varying magnitude, and that it was only the largest floods (and therefore those able to transport the coarser particles) that reached the floodplain surface, explaining why coarser sediment was found on the floodplain surface compared with in floodplain channels. Another explanation for this difference could be that deposition of fine material occurred in the floodplain channels as flows waned.

Less deposition was recorded immediately downstream of wood jams due to flow sheltering in these regions. Flow ponding upstream of wood jams caused the floodplain immediately downstream to be sheltered, and to experience overbank flow rarely. Although large amounts of sediment deposition were recorded on the edge of the channel downstream of the wood jam at Site 2 during Event 4, this is possibly from flow re-entering the main channel from the floodplain, rather than from flow being pushed onto the floodplain from the adjacent main channel (see Figures 6.27 (a) and (b)).

Similarly, Figures 6.25 and 6.28 demonstrate that the source of water that inundated the mats did not necessarily come from the adjacent main channel. In many instances flow overtopped the channel banks further upstream and flowed downvalley on the floodplain in floodplain channels (Figure 6.25). Mat 3 at Site 2 received a surprisingly large amount of inorganic deposition during Event 5 (Figure 6.23); during other events in 2004/2005 this mat hardly received any deposition. However, during 2005/2006 mat 2, which was close to mat 3, also received large amounts of deposition. A likely explanation is that water and sediment were supplied to the mat from flow in a nearby depression created by the filled-in channel, rather than from overbank flow directly from the adjacent main channel (see Figures 6.25 and Figure 6.28).

(a)

(b)

Figure 6.27 (a) Overbank flow re-entering the main channel through a floodplain channel (between red pegs; blue arrow indicates flow direction); **(b)** A trashline pushed up against vegetation, deposited by overbank flow routed back to the main channel from the floodplain (blue arrow indicate flow direction).

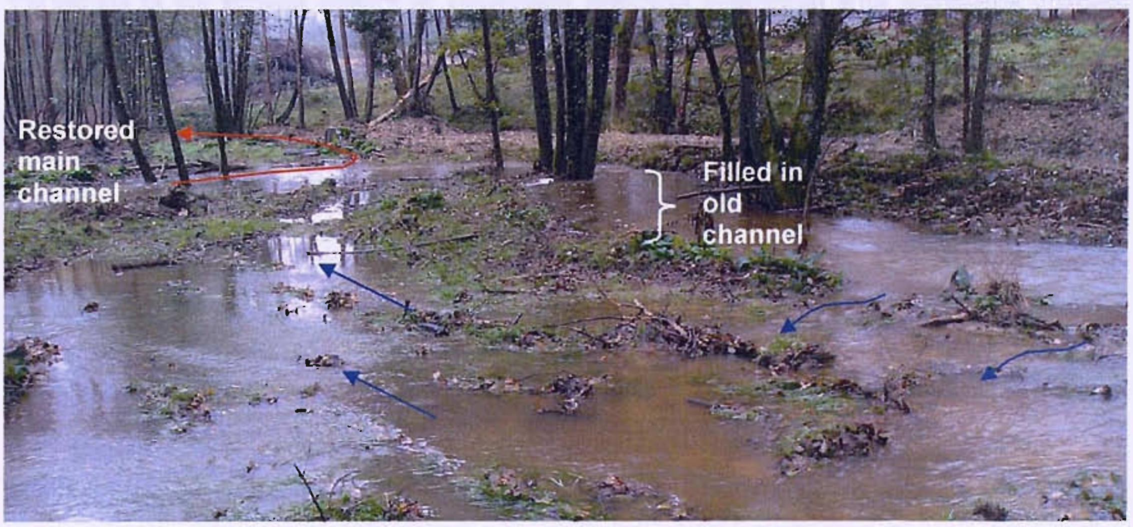


Figure 6.28 Flow from the filled-in channel depression spilling into floodplain channels and back into the main channel (Site 2) (blue arrows = floodplain flow; red arrow = main channel flow).

Figure 6.24 shows that there was a higher percentage of sand and a lower percentage of silt in the deposits at Site 2 than at Site 4 (approximately 30% sand, 55% silt and 15% clay at Site 2, compared with 25% sand, 60% silt and 15% clay at Site 4). At Site 4 and Site 1 the D_{50} was between 20 and 30 μm, whereas at Site 2 it was slightly higher, between 20 and 40μm. The differences are likely to be due to the particle size distribution of the material used for the restoration being slightly different to the natural material found in the catchment.

The lack of significant differences in % organics between locations (Figure 6.26) could be due to the organic fraction being transported on the surface of the water along dominant flow vectors as it is less dense than water (Jeffries, 2002). Therefore it may not be influenced by internal flow structures of inundating flow, but rather transported ubiquitously over the floodplain wherever overbank flow reaches.

6.3.5 Discussion

The amounts of overbank deposition per flood recorded in this study are comparable with deposition from other lowland rivers (Table 6.9). However, the maximum range of deposition recorded (0.0-6.92kg m^{-2} per mat during 2004/2005 at Millyford, Site 4) was considerably less than that recorded at Millyford during 2000/2001 (0.0-26.04 kg m^{-2}) by Jeffries *et al.* (2003) using a similar method (Astroturf mats). Compared with other studies shown in Table 6.9, the results from Jeffries *et al.* (2003) are extremely high. This is most likely due to 2000/2001 being an unusually wet winter. It therefore seems reasonable that the results from the current study are more representative of contemporary deposition rates at the site.

Variations in the general pattern of decreasing sediment deposition with increasing distance from the main channel caused by variable overbank flow hydraulics resulting from irregular floodplain topography have been identified within the literature, e.g. on the River Culm, UK (Nicholas and Walling, 1997 a and b; Nicholas and Walling, 1998), on the River Severn, UK (Marriott, 1992), and in the Rhine-Meuse Delta in the Netherlands (Middelkoop and Asselman, 1998). However, these variations have been attributed to irregular topography, rather than to the effects of vegetation (e.g. Jeffries *et al.*, 2003), as observed in this study.

As total deposition typically decreases with increasing distance from the main channel, so too does grainsize, with deposition of sand-sized particles being limited to the channel margins (e.g. Middelkoop and Asselman, 1998; Nicholas and Walling 1997a; 1998). However, similar to this study, Marriott (1992) observed sand deposition across the floodplain of the River Severn, UK. The author reports a sharp drop in the % sand beginning after 20 m (see Figure 3.12), which is attributed to a shortage of coarse sediment supply beyond 20 m. The presence of sand-sized particles in deposits across the floodplain observed in the current study was likely to be due to a combination of the high competence of floodplain channel flows, distributing sand-sized sediment across the floodplain, and remobilisation of sediment sourced from the floodplain.

Table 6.9 Amounts of overbank deposition recorded for selected lowland rivers. Adapted from Jeffries *et al.* (2003).

Amount of overbank deposition per flood ($kg\ m^{-2}$)	River and location	Source
0.0-0.084[b]	Site 1 '03/'04 Highland Water, England	This study
0.0	Site 2 '03/'04 (before restoration) Highland Water, England	This study
0.0-1.96[b]	Site 1 '04/'05 Highland Water, England	This study
0.0-4.64[ab]	Site 2 '04/'05 (after restoration) Highland Water, England	This study
0.0-6.92[b]	Site 4 '04/'05Highland Water, England	This study
0.0-26.04[b]	Millyford (Site 4) '00/'01 Highland Water, England	Jeffries et al. (2003)
0.097-6.78[a]	Cole, England	Briggs (1999)
0.004-4.414[a]	Brede, Denmark	Kronvang et al. (1998)
0.52-1.93	Meuse, Netherlands	Asselman & Middelkoop (1995)
0.36-1.57	Waal, Netherlands	Asselman & Middelkoop (1995)
0.008-0.721	Culm, England	Nicholas & Walling (1995)
0.008-0.227	Culm, England	Lambert & Walling (1987)
0.185	Mississippi, Mississippi	Gomez et al. (1998)
0.11-0.25	Meuse, Netherlands	Middelkoop & Asselman (1998)
0.11-0.3	Waipaoa, New Zealand	Gomez et al. (1998)
0.008-0.24	Fyrisån, Sweden	Gretener and Strömquist (1987)

[a] Restored rivers, readings taken between 1 to 3 years after restoration.

[b] Process influenced by a wood jam.

The percentage of organics in deposits recorded in this study (generally ranging from 5-12 %) are similar to values recorded in other studies, e.g. Jeffries (2002) reports values ranging from 2.1- 12.0 % from the same study site (Site 4) during 2000/2001; Steiger *et al.* (2001b) recorded percentage ranging from 3-10 % on the floodplain of the River Severn, UK; and Goodson *et al.* (2003) report percentages of organics of 5-10 % on the River Dove, UK.

6.3.6 Conclusion

Results from this section have demonstrated considerable spatial variability in floodplain deposition, largely due to the presence of in-channel wood jams and resulting floodplain channels that distribute flow and sediment to the floodplain. Floodplain channels and areas adjacent to the main channel upstream of wood jams received significantly more deposition than areas of floodplain surface or areas adjacent to the main channel downstream of wood jams ($p < 0.01$). Deposition also varied temporally between flood events; as deposition potential is related to suspended sediment availability (Hupp, 2000), floodplain hydrology is likely to be the driving force behind these temporal variations in sediment deposition.

6.4 Floodplain hydrology and overbank sediment deposition

6.4.1 Inorganic sediment deposition

To understand the observed patterns of inorganic deposition between events (Figure 6.23), floodplain deposition was compared with the supply of water and suspended sediment to the floodplain, as the amount of suspended sediment available is likely to affect the deposition potential (e.g. Hupp, 2000). This analysis was undertaken at Site 2 (the Restored site) as the necessary monitoring equipment was in place (a pressure transducer and a turbidity probe), and a very detailed topographic survey (one point every 0.25 m^2) had been undertaken at this site, which helped with interpreting the results.

Total water and total suspended sediment supplied to the floodplain during overbank flows were calculated for periods of overbank flow during the flood seasons of 2004/2005 and 2005/2006 (Figure 6.29). Field observations and crest gauge data indicated that overbank flow over most of the local area was initiated at a Q of approximately 0.33 $m^3 s^{-1}$, so this value was used to represent the Q at which the mats were inundated. It is recognised that this assumption brings in a degree of uncertainty to the data analysis as the mats would not all have been inundated at exactly the same Q. The relationship between overbank suspended sediment and overbank Q was generally consistent for both flood seasons, with r^2 values of 0.99. However, this relationship was inconsistent during the first event in the flood season of 2004/2005 (immediately after the restoration), when the concentration of suspended sediment was exceptionally high, representing the first sediment pulse post restoration (shown by the open square in Figure 6.29); therefore this outlier was excluded from the correlation.

The gradient of the trendline on Figure 6.29 for the 2004/2005 data is steeper than that for the 2005/2006 (0.1366 compared with 0.0497), indicating a higher concentration of suspended sediment per unit volume of water during 2004/2005 compared with 2005/2006. This was likely to be due to the restoration work during the summer of 2004 rendering large amounts of fine sediment available for transport during the flood season of 2004/2005, which was reduced by the following flood season (see Section 6.2).

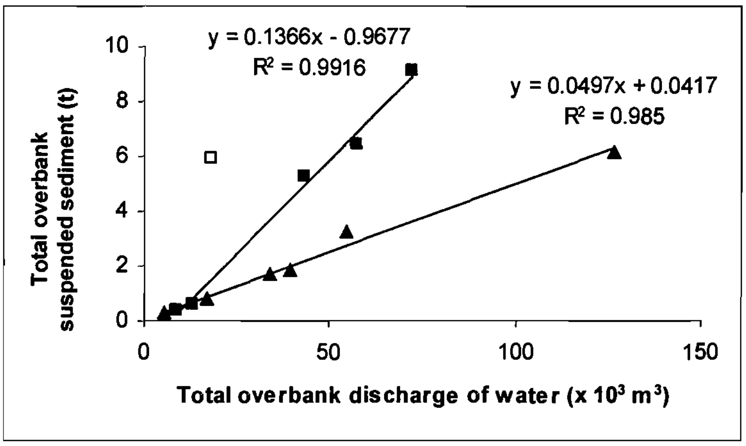
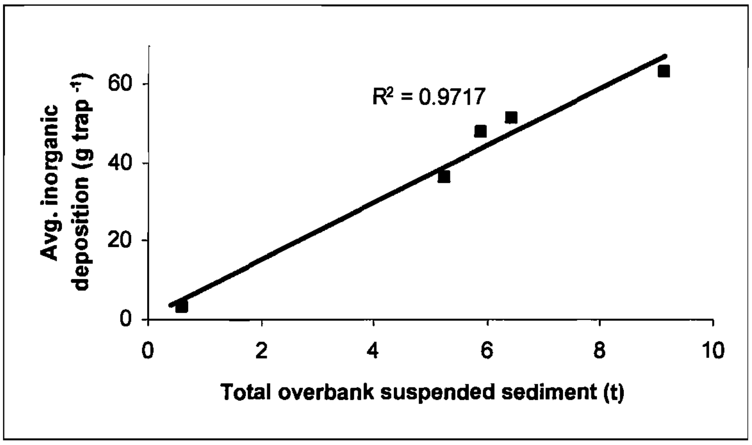


Figure 6.29 Relationships between total overbank discharge of water and total overbank suspended sediment (tonnes) for the flood seasons of 2004/2005 (squares) and 2005/2006 (triangles). The open square represents data from the first event after the restoration, when the concentration of suspended sediment was exceptionally high – it is considered to be an outlier and is therefore not included in the regression relationship.

Average inorganic deposition on the mats for each event during the flood season of 2004/2005 was related to total overbank suspended sediment and total water volume (Figure 6.30 (a) and (b)). The close relationships shown on the graphs clearly demonstrate that inorganic deposition was a function of both suspended sediment and water supplied to the floodplain. The three variables are shown together in bubble plots (Figure 6.31 (a) and (b)). The dotted bubble in Figure 6.31 (b) represents an average of the total inorganic sediment deposited on each mat during 2004/2005, and the hatched bubble represents the same data for 2005/2006. This graph further demonstrates the reduced concentration of suspended sediment during 2005/2006, when more water flowed overbank, but similar values of total suspended sediment and average total inorganic deposition were recorded compared with 2004/2005.

(a)



(b)

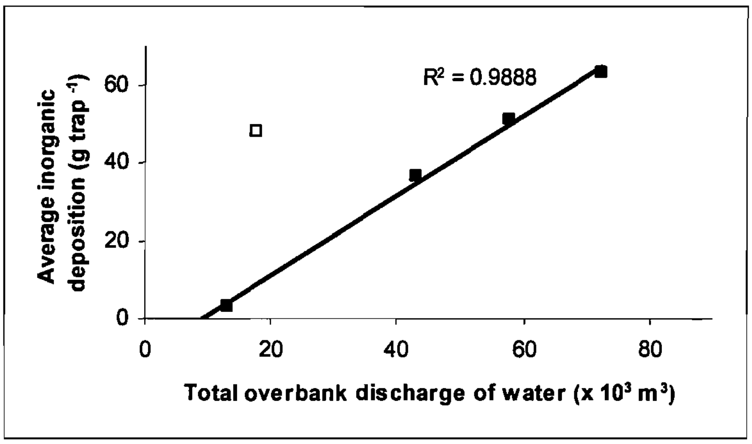
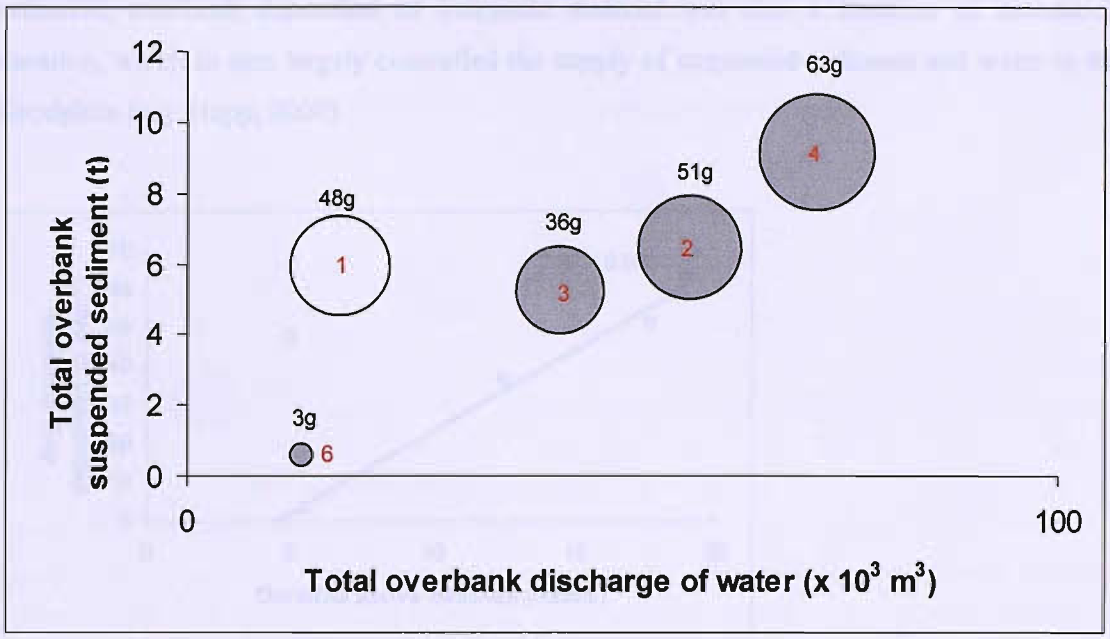


Figure 6.30 Average inorganic deposition per trap during 2004/2005 (only including those traps that had > 0g of material deposited on them) as a function of (a) total overbank suspended sediment and (b) total overbank water discharge (the trendline in (b) excludes the outlier (open square)).

(a)



(b)

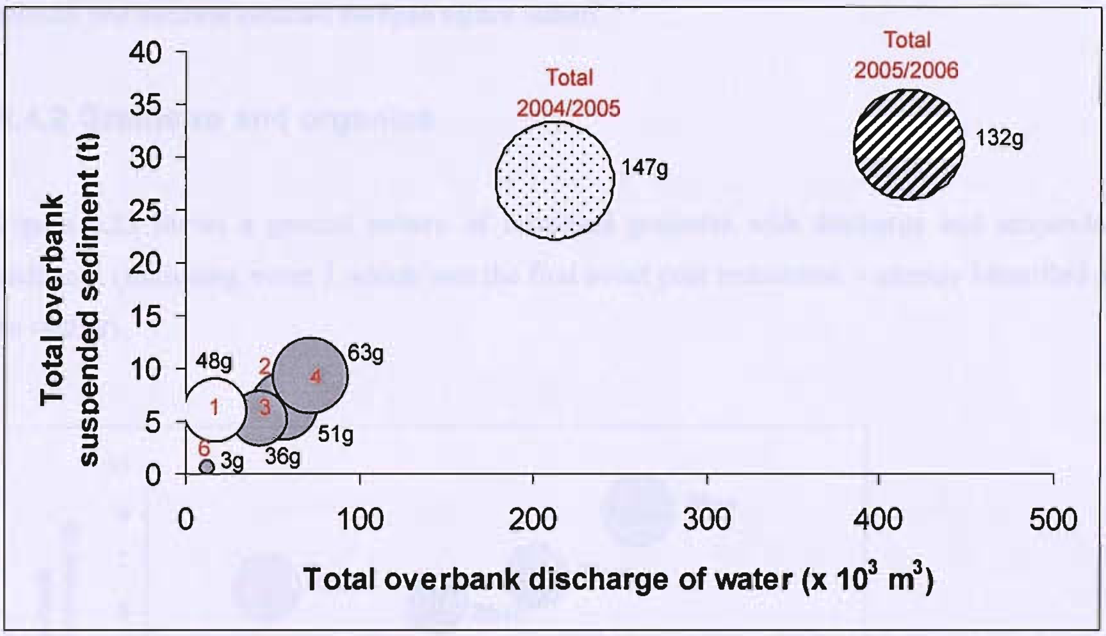


Figure 6.31 (a) Average amounts of inorganic sediment deposited on the mats in relation to total overbank discharge of water and total overbank suspended sediment during 2004/2005 (grey bubbles). The open bubble is an outlier, representing data from the first event in 2004/2005. The red numbers indicate event number. (b) As for (a) but with average total inorganic sediment deposited on each mat during 2004/2005 (dotted bubble) and 2005/2006 (hatched bubble) included.

Figure 6.32 demonstrates that, as well as being related to the supply of water and suspended sediment, overbank deposition of inorganic material was also a function of inundation duration, which in turn largely controlled the supply of suspended sediment and water to the floodplain (e.g. Hupp, 2000).

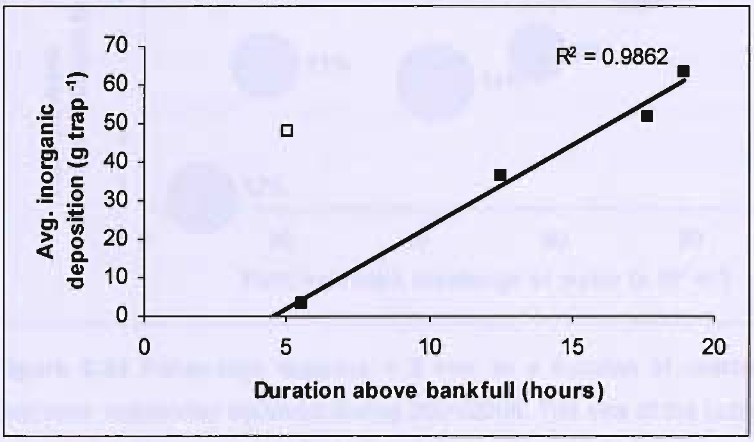


Figure 6.32 Average inorganic sediment deposition per trap compared with duration of flow above bankfull (the trendline excludes the open square outlier).

6.4.2 Grainsize and organics

Figure 6.33 shows a general pattern of increased grainsize with discharge and suspended sediment (excluding event 1 which was the first event post restoration – already identified as an outlier).

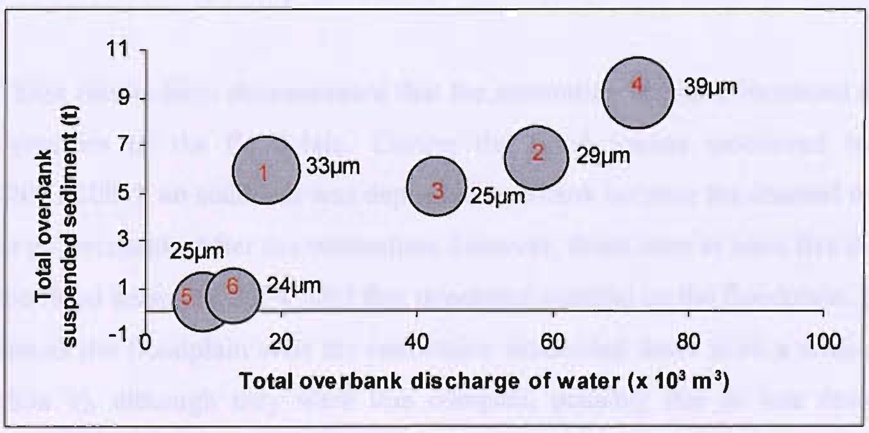


Figure 6.33 Average D_{50} as a function of overbank discharge of water and total overbank suspended sediment during 2004/2005. The size of the bubbles and the numbers beside them indicate the average D_{50}, and the red numbers indicate event number.

Figure 6.34 shows a decrease in the percentage of organics < 2 mm found on the traps in relation to water volume and suspended sediment supplied to the floodplain.

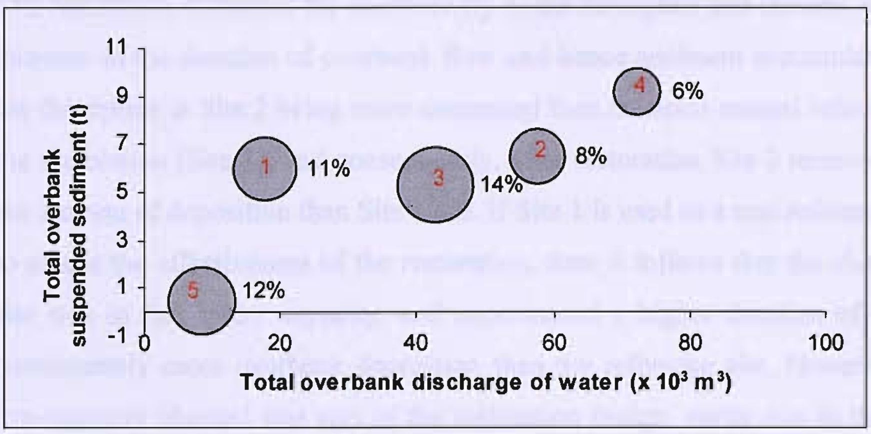


Figure 6.34 Percentage organics < 2 mm as a function of overbank discharge of water and total overbank suspended sediment during 2004/2005. The size of the bubbles and the numbers beside them indicate the % organics < 2 mm, and the red numbers indicate event number. There was too little material from Event 6 to do both PSA and LOI, so only PSA was done, hence Event 6 is missing from the graph.

As event magnitude increased, grainsize increased and the percentage of organics decreased. This was likely to be due to larger floods having a higher competence and therefore being able to transport larger particle sizes; the decrease in percentage of organics may also have been due to a dilution effect during larger floods.

6.5 Summary: impacts of restoration

These results have demonstrated that the restoration at Site 2 increased the geomorphological dynamics of the floodplain. During the flood season monitored before the restoration (2003/2004), no sediment was deposited overbank because the channel was too deep for flows to go overbank. After the restoration, however, there were at least five overbank flows during the flood season of 2004/2005 that deposited material on the floodplain. Patterns of deposition across the floodplain after the restoration resembled those from a semi-natural reference site (Site 4), although they were less complex, possibly due to less dense vegetation on the floodplain (which was the result of a combination of inadvertent disruption caused by machinery during the restoration, and felling of conifers as part of the restoration). Patterns of deposition at this site are likely to become increasingly complex as vegetation re-colonises the floodplain and wood jams build up in the channel and on the floodplain. Vegetation re-colonisation is likely to be promoted by dynamic floodplain deposition supplying seeds to the floodplain and creating fertile sites for seed germination (Hughes, 1997). A longer study period is required to monitor the response of the floodplain vegetation to the restoration.

The restoration increased the connectivity of the floodplain and channel at Site 2 leading to an increase in the duration of overbank flow and hence sediment accumulation. This resulted in the floodplain at Site 2 being *more* connected than the semi-natural reference site upstream of the restoration (Site 1), and consequently, after restoration Site 2 received more than 7 times the amount of deposition than Site 1 did. If Site 1 is used as a true reference site against which to assess the effectiveness of the restoration, then it follows that the channel at the Restored site was in fact *under* capacity, and experienced a higher duration of overbank flows and consequently more overbank deposition than the reference site. However, the creation of a low-capacity channel was part of the restoration design, partly due to the importance placed on re-connecting the floodplain, but also because a smaller capacity was thought to focus much of the available energy within a smaller channel cross-section, which effectively would provide excess stream power that the channel could then use for self-adjustment to a stable regime.

The lack of overbank flow and sediment deposition at Site 3 (a site restored only through the addition of wood jams) provides evidence that wood jams on their own were insufficient to connect the floodplain. However, the addition of wood jams, channel in-fill and re-meandering that was undertaken at Site 2 did re-connect the floodplain.

6.6 Overbank sediment deposition and floodplain vegetation

6.6.1 Introduction

The previous section identified that in-channel vegetation (in the form of wood jams) significantly affected the spatial distribution of overbank deposition. However, vegetation on the floodplain is also thought to influence deposition by increasing the hydraulic roughness of the floodplain surface leading to decreased flow velocity and competency to transport sediment, and hence increased settling of particulate matter (e.g. Wolman & Leopold, 1957). The type, spacing, density, extent, height and rigidity of vegetation influences flow characteristics (Fathi-Maghadam and Kouwen, 1997) and consequently also sediment deposition. It is therefore hypothesised that different types of vegetation found on the New Forest floodplains trap different amounts and grainsizes of sediment.

Astroturf mats were used in the previous section to represent short grass, the dominant form of low-level vegetation found on the grazed floodplains in the New Forest. However, other forms of understory vegetation were also present on the floodplain, particularly rushes (*Juncus spp.*) and bracken (*Pteridium aquilinium*) (e.g. Figure 6.35 (d)). It therefore seemed prudent to investigate whether or not different types of understory vegetation on the floodplain trapped different amounts and grainsizes of sediment, particularly as the nature of the understory vegetation on the floodplain at the Restored site was likely to change post-restoration due to the floodplain being re-connected with the channel and therefore experiencing overbank flows, and also due to the area being opened up to grazing by ponies. Prior to the restoration, the dominant understory vegetation on the floodplain was fairly long grass, with patches of bracken and *Juncus spp.* (Figure 6.35 (a)); immediately post restoration, areas of bare earth were exposed due to the restoration works (Figure 6.35 (b)); and subsequently vegetation re-established and was grazed by ponies (Figure 6.35 (c)), resulting in mainly short grass with patches of *Juncus sp.* and bracken (Figure 6.35 (d)).

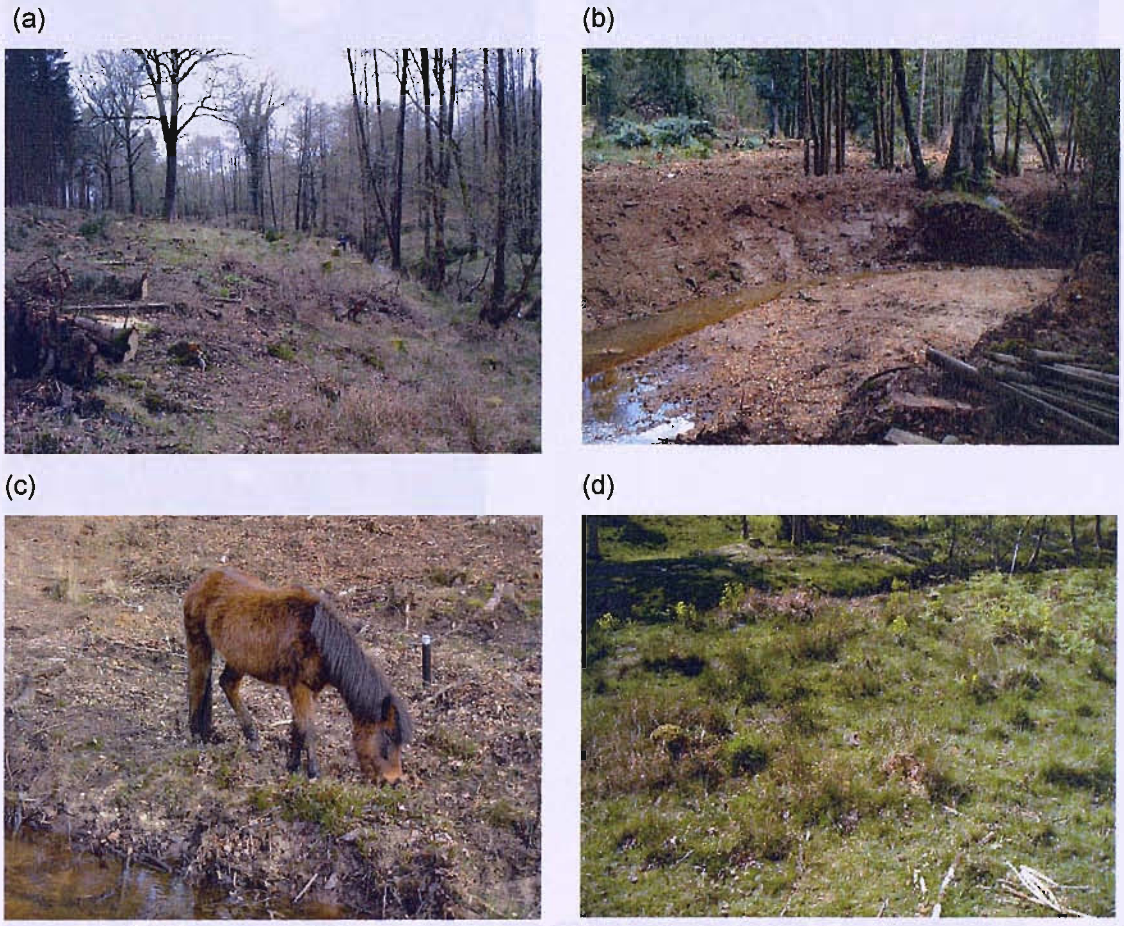


Figure 6.35 Low-level floodplain vegetation at Site 2: (a) Long grass with patches of bracken and *Juncus spp.* before restoration; (b) Bare earth exposed during the restoration; (c) Floodplain vegetation grazed by ponies post-restoration; (d) Low-level floodplain vegetation post-restoration consisting mainly of short grass with patches of *Juncus spp.* and bracken.

6.6.2 Method

To test the hypothesis, four different types of sediment trap were used (each 0.2 m x 0.2 m) representing different vegetation or surface types (Figure 6.36): Astroturf mats (representing short grass); bare vinyl tiles that were slightly textured (representing bare soil); the same vinyl tiles but with five sprigs of bracken attached (representing bracken); the same tiles but with five portions of long plastic grass attached to the surface (representing *Juncus* spp. or long grass (Figure 6.36 (b))).

(a)

(b)

(c)

Figure 6.36 (a) Vegetation traps; (b). *Juncus* spp. on the floodplain of Site 2; (c) Distribution of vegetation mats.

Vegetation traps were only used during the flood season of 2004/2005 (the first flood season after the restoration). They were deployed on the floodplain at Site 2 and at Site 4 (Figures 6.38 and 6.39). At both sites, three replicates of each mat were used (Figure 6.37). The mats were arranged in three groups (locations), with each group containing one mat of each type of surface being represented (Figure 6.36 (c) and 6.37). The arrangement of the different mats was kept the same in each location and each time the mats were changed, so that they could be treated as replicates for statistical analysis (Prescott, 2005, pers comm.). Other authors, for example Briggs (1999), changed the order of mats between events in order to eliminate the potential effects of local conditions on sediment deposition; however this also eliminated the potential for robust statistical analysis to be carried out on the data. The three locations were in close proximity to each other and at similar elevations so that all groups would be inundated at the same time, therefore local variations in conditions were considered minimal.

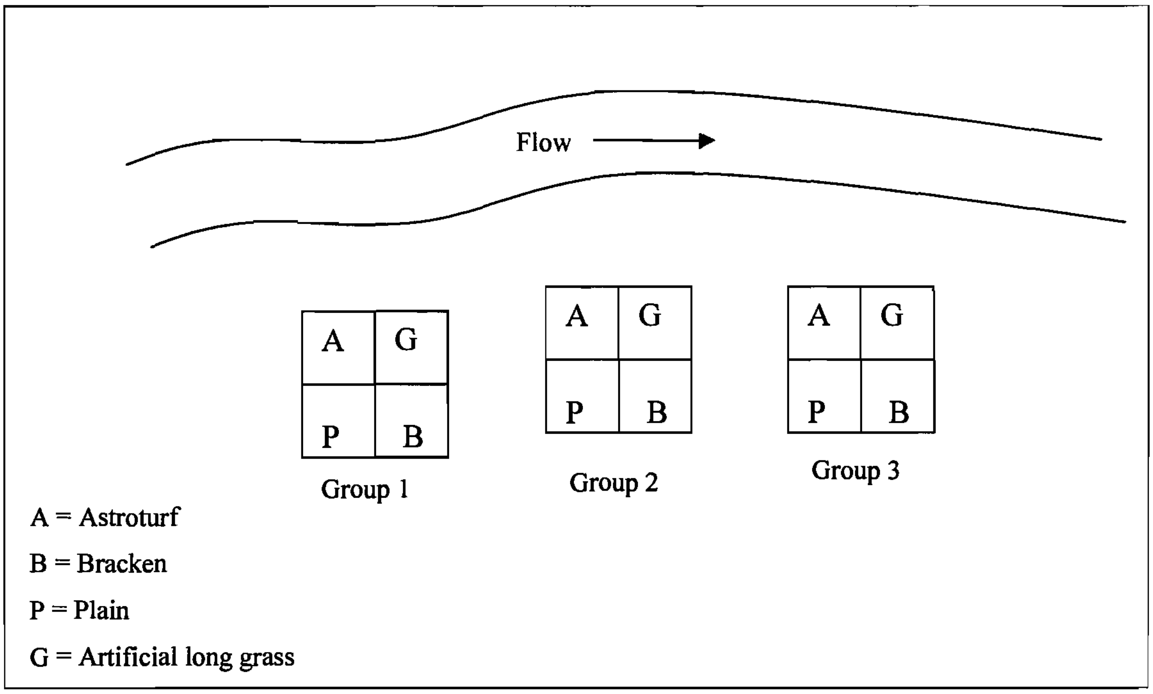


Figure 6.37 Schematic distribution of vegetation mats.

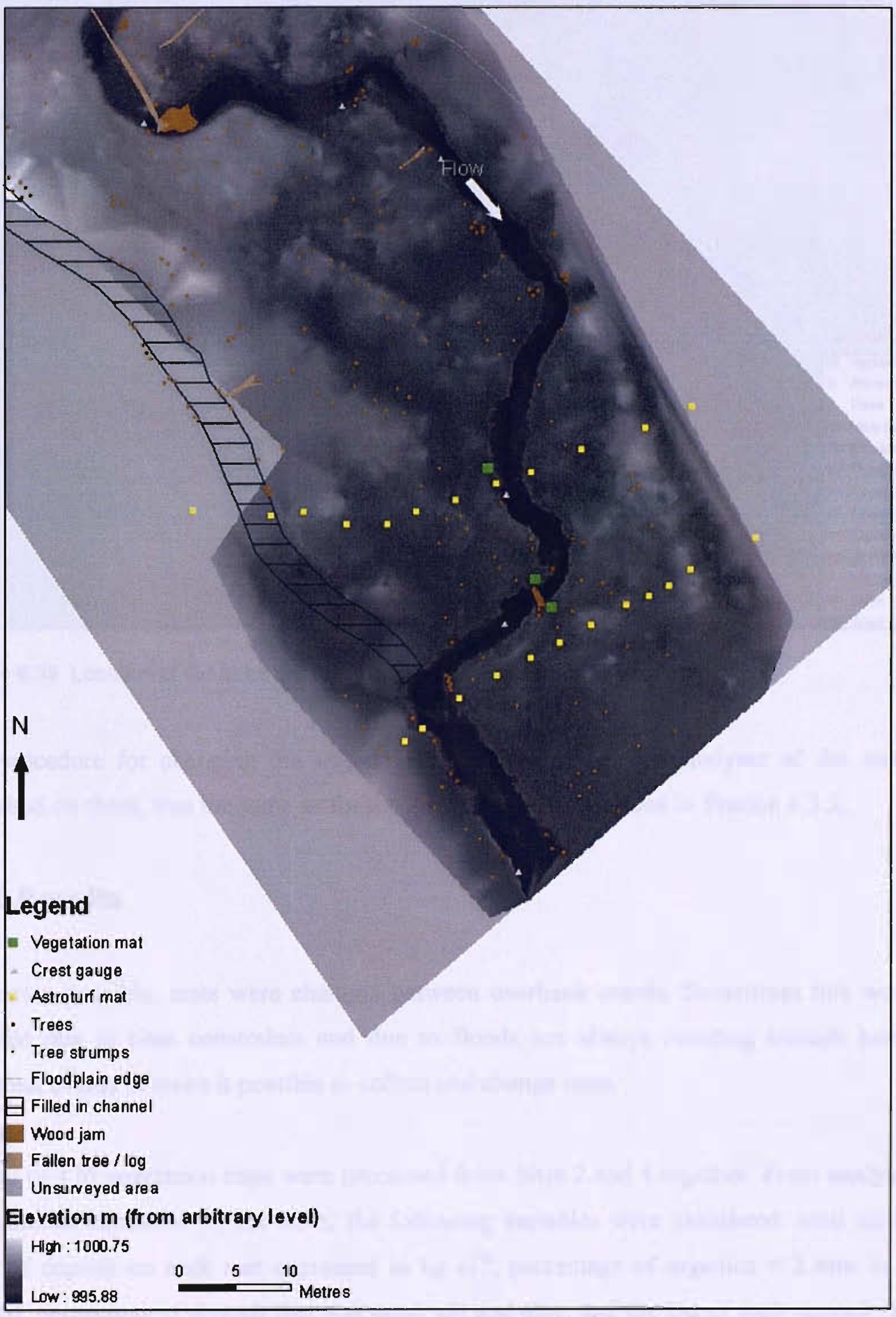


Figure 6.38 Location of the three groups of vegetation mats at Site 2 (green squares).

Figure 6.39 Location of the three groups of vegetation mats at Site 4 (green squares).

The procedure for changing the vegetation mats, and laboratory analyses of the material deposited on them, was the same as for the Astroturf mats described in Section 6.3.2.

6.6.3 Results

Whenever possible, mats were changed between overbank events. Sometimes this was not possible due to time constraints and due to floods not always receding enough between overbank events to make it possible to collect and change mats.

A total of 176 vegetation traps were processed from Sites 2 and 4 together. From analyses of the material deposited on the mats, the following variables were calculated: total air-dried mass of deposit on each mat expressed in kg m^{-2}; percentage of organics < 2 mm in each deposit; percentage of deposit that was sand, silt and clay; and the D_{50} of each deposit. Table 6.10 shows the total, mean and standard deviation of dry mass of deposited sediment from the different types of mat. As can be seen from the table, Astroturf mats trapped the most sediment with a mean of 1.4 kg m^{-2}, followed by Bracken (1.0 kg m^{-2}), and Grass and Plain both had a mean of 0.6 kg m^{-2}. The standard deviations were similar for all mat types and ranged from 1.0 kg m^{-2}and 1.5 kg m^{-2}.

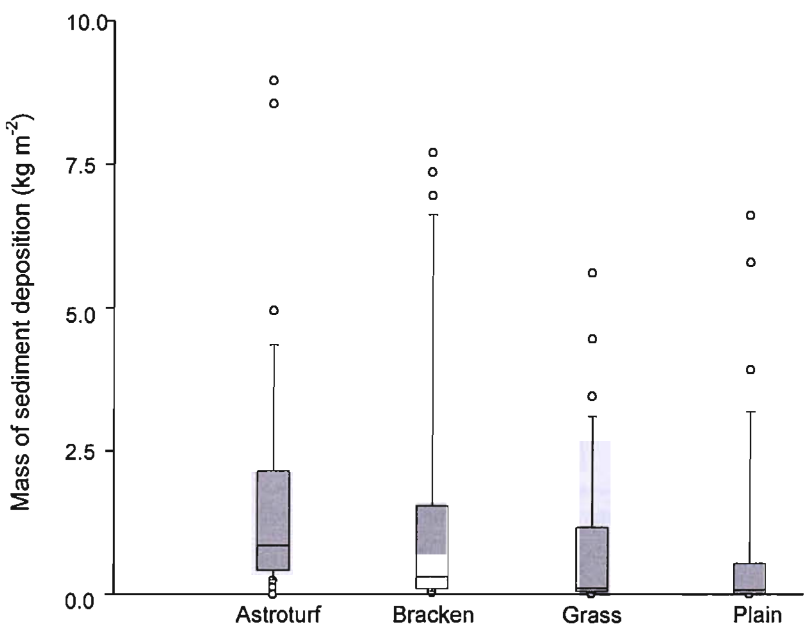
Table 6.10 Sediment deposition on each mat type.

Mat type	Total (kg m^{-2})	Mean (kg m^{-2})	Standard dev. (kg m^{-2})	Number of mats
Astroturf	61.5	1.4	1.2	44
Bracken	45.2	1.0	1.5	44
Grass	27.3	0.6	1.0	44
Plain	27.0	0.6	1.2	44

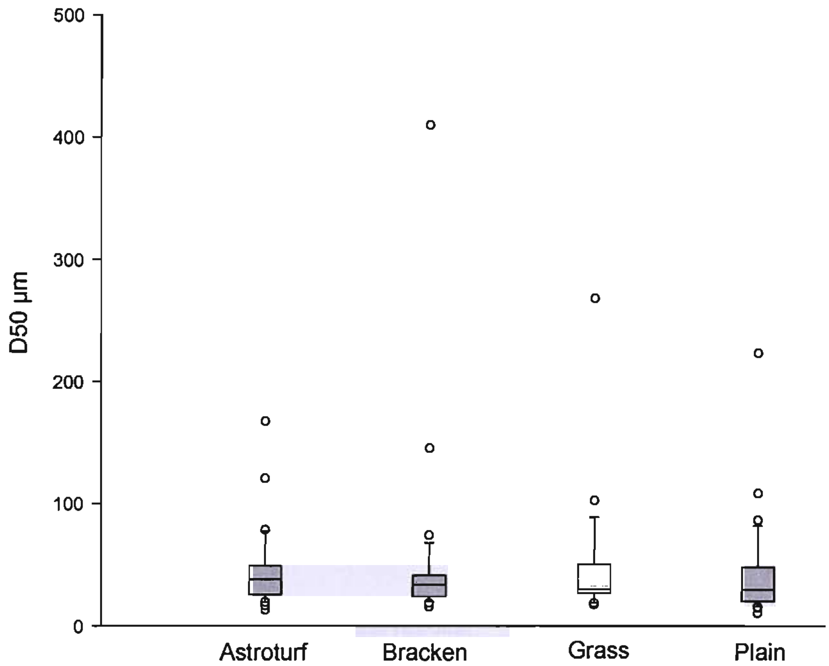
The boxplots in Figure 6.40 show the median and inter-quartile ranges of the dry mass, percentage organics and D_{50} for each mat type. The boxplots show that on average the mats trapped a mass of approximately 0.5 kg m^{-2} of sediment. Average percentage of organics < 2 mm was approximately 10 %, and the D_{50} of the deposits was approximately 45 μm (silt). The median amount of sediment deposition was highest for Astroturf, followed by Bracken, Grass, and then Plain mats. However, the values from individual mats were variable, with many outliers and extreme cases. The D_{50} was similar for all the mat types, with low interquartile ranges. Deposits from all mat types had a similar percentage of organics < 2 mm (approx. 10%) with little variability.

Figure 6.40 (below) Boxplots showing: (a) Mass of sediment deposition and mat type; (b) D_{50} μm and mat type; and (c) Percentage organics <2 mm and mat type. N = 44 for each mat type.

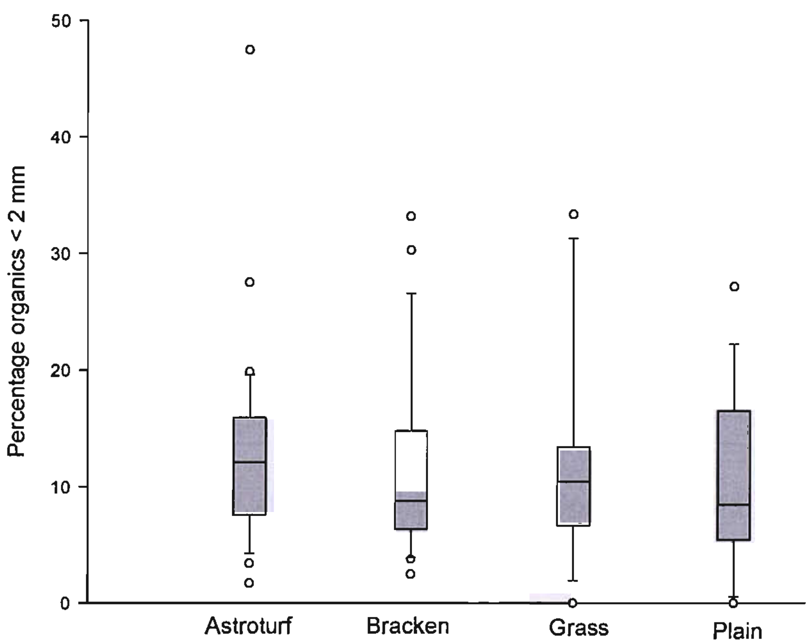
a)



b)



c)



In order to determine if any of the variables differed significantly between the different mat types, a factorial ANOVA test was carried out for each of the variables. The raw data for the variables were not normally distributed, so they were transformed for the test either by taking the square root or the log, whichever was most appropriate.

Table 6.11 ANOVA test results from the different mat types at the 0.05 level.

Variable	p-value	Significant difference or no significant difference
Square root of mass of sediment	0.007	Significant
Square root of % of organics	0.610	Not significant
log D_{50}	0.688	Not significant

Table 6.11 shows that, at the 0.05 level, there was a significant difference between the amounts of sediment deposited on the different types of mat; it shows no significant difference between the percentage of organics or grainsize (D_{50}) in the deposits from the different mat types.

In order to identify which mats trapped significantly different amounts of material, a Tukey HSD post Hoc test was carried out.

Table 6.12 Tukey HSD post Hoc test results.

Vegetation type	p-value
Astroturf & Bracken	*0.010
Astroturf & Plain	*0.000
Astroturf & Grass	*0.000
Bracken & Plain	*0.036
Bracken & Grass	0.104
Plain & Grass	0.971

*significant difference at the 0.05 level

Table 6.12 shows significant differences at the 0.05 level in the amount of sediment deposited on the following pairs of mats: Astroturf and Bracken, Astroturf and Plain, Astroturf and Grass, and Bracken and Plain.

The Tukey HSD test also divided the 'vegetation types' into homogenous sub-sets (Table 6.13). As can be seen from Table 6.13 Plain and Grass mats fell together trapping the least sediment; Grass was also paired with Bracken, trapping a medium amount of sediment, and Astroturf mats were in their own sub-set, trapping the most sediment.

Table 6.13 Homogenous sub-sets of mat type based on the Tukey test.

Subset		
1	**2**	**3**
Plain		
Grass	Grass	
	Bracken	
		Astroturf

Grainsize

The dominant grainsize of the material trapped on the mats was approximately 45 µm (silt) (Figure 6.40 (b)). Table 6.14 shows average percentages of the different grainsize classes for the different mat types. Similar proportions of sand (approx. 35%), silt (approx. 55%) and clay (approx. 11%) were trapped on the different types of mat.

Table 6.14 Average percentages of different grainsize classes and mat type.

Mat type	Avg. D50 (µm)	Sand 2000-63µm (Avg. expressed as %)	Silt 63-4µm (Avg. expressed as %)	Clay <4µm (Avg. expressed as %)
Astroturf	46	36	53	11
Bracken	53	32	57	11
Grass	46	36	53	11
Plain	36	31	57	12

6.6.4 Discussion and implications for restoration

The different types of vegetation mats trapped significantly different amounts of sediment, supporting the first part of the hypothesis that vegetation type influenced deposition *amount*. However, significant differences were not observed in the grainsize or in the percentage of organics < 2 mm in the deposits from the different mat types. Therefore, based on the four types of vegetation mats tested within this environment, the second part of the hypothesis that vegetation type influenced deposition *grainsize*, was disproved.

Very few studies were found within the literature that focused specifically on the influence of different types of floodplain vegetation on sediment deposition. However, in order to determine if the surface roughness of sediment traps influenced the amount of sediment retained, Mansikkaniemi (1985) experimented with plywood boards with and without tufts of bristles 5-7 cm, and with rubber mats with a rough uneven surface to simulate ploughed fields. Unlike the data presented here, total sedimentation showed no significant variation between mats. In contrast, Brown and Brookes (1997) found that the amount of deposition on the floodplain of the River Soar, Leicestershire, did vary between plant types, and ranged from 0.005 kg m^{-2} to 0.14 kg m^{-2} for a single flood event (significantly lower than the results presented in this research, which ranged from 0.0 to < 8.96 kg m^{-2}).

In a similar experiment to the one reported here, Briggs (1999) compared sediment deposition on Astroturf traps, short-cropped grass, long cropped grass and bare soil (grid) on the floodplain of the River Cole, UK. The study only covered one period of time during which the number of overbank events was uncertain. The results showed that Astroturf traps, long turf and bare soil (grid) trapped similar amounts of sediment, whereas short-cropped grass trapped less than half the amount that the above materials did. The mean values for different materials were very similar to this study (Table 6.15). Briggs (1999) also found no significant difference in the particle sizes trapped by the different material (although the mean grain sizes were much larger than for this study (Table 6.16), probably due to variations in soils between the catchments).

Table 6.15 Deposition on different surfaces from the Highland Water (this study) and from the river Cole (Briggs, 1999).

Briggs (1999) River Cole				This study-Highland Water			
Material	Mean deposition (kg m^{-2})	Range of deposition (kg m^{-2})	No. mats	Material	Mean deposition (kg m^{-2})	Range of deposition (kg m^{-2})	No. mats
Astroturf	1.51	0.29-6.78	6	Astroturf	1.67	0.00-8.96	44
Long turf	1.33	0.36-2.67	3	Bracken	1.30	0.00-7.70	44
D/s of long turf	2.93	1.19-4.81	3	Long grass	0.80	0.00-5.61	44
Short turf	0.60	0.10-1.40	6	Plain	0.79	0.00-6.61	44
Grid	1.59	0.19-3.81	3				

Table 6.16 Grainsizes of deposits on different surfaces from the Highland Water and from the River Cole.

Briggs (1999) River Cole				This study-Highland Water				
Material	**Mean grain size (µm)**	**Range of grain size (µm)**	**No. mats**	**Material**	**Mean grain size (µm)**	D_{10}	D_{90}	**No. mats***
Astroturf	156.3	85.4-271.8	6	Astroturf	45.2	4.3	246.3	44
Long turf	97.0	48.4-128.6	3	Bracken	47.7	4.0	189.9	42
D/s of long turf	246.0	214.7-265.3	3	Long grass	46.9	4.2	223.9	41
Short turf	161.2	38.8-281.5	6	Plain	41.3	4.0	206.3	42
Grid	154.5	91.1-288.9	3					

* Some of the samples collected from the mats were too small for PSA, hence the variable number of mats for the different vegetation types.

The results from the vegetation experiment in this research showed that traps with different surface roughness trapped significantly different amounts of sediment: bare mats and mats with long plastic grass trapped less sediment than mats with bracken or Astroturf. These results have implications for the Astroturf transect experiment discussed in Section 6.3; the Astroturf mats may have been over-sampling floodplain deposition. Therefore, lower deposition values may have been obtained if bare mats had been used instead of Astroturf mats. However, as uniform Astroturf mats were used in all the locations, if they did over-sample, then they did so consistently between locations and between events, which means that inter-location and inter-event comparisons were still valid.

These materials did not represent 'real' floodplain surfaces exactly, but they had different surface roughnesses, which therefore implies that floodplain surface roughness influenced the amount of sediment deposited. Thus it follows that 'real' vegetation types with different roughnesses are also likely to have different sediment trapping abilities.

Therefore, if it is accepted that bare surfaces trap less sediment than surfaces with low level, dense vegetation (like the Astroturf mats), this has implications for restoration: floodplain sedimentation post-restoration is usually desirable as it provides sites and seed propagules for vegetation regeneration (Hughes, 1997). Thus it may be beneficial to avoid (as far as possible) creating bare surfaces during the restoration. Furthermore, if vegetation is planted as part of the restoration, dense, low level vegetation (e.g. short grass) is likely to trap more sediment than tall grasses, and grazing may help to achieve this.

Chapter 7. Monitoring restoration (2): floodplain erosion

7.1 Introduction

Floodplain processes include both overbank deposition and overbank erosion. Thus far deposition has been focused upon (Chapter 6). Overbank erosion is particularly important in forested floodplains (Brown and Brookes, 1997; Steiger *et al.*, 2005). Although floodplain channels transport flow and sediment, and receive sediment deposition (Chapter 6), they are ultimately erosional features scoured into the floodplain surface, frequently exposing tree roots (Figure 7.1). This chapter attempts to quantify depths of floodplain erosion, and to compare erosion recorded at the Restored site post-restoration with erosion recorded at semi-natural reference sites.

Figure 7.1 Tree roots exposed in a floodplain channel (Millyford).

7.2 Method

In order to quantify depths of floodplain erosion, erosion pins vertical in the floodplain surface were used. Repeated measurements of pin exposure or burial provided estimates of depth of erosion or deposition (e.g. Steiger *et al.*, 2003). Erosion pins have been used extensively to measure rates of channel bank erosion, particularly over short time scales (from 0.1 to 10 years) (e.g. Hagerty *et al.*, 1983; Stott, 1997). Lawler (1993) gives a detailed chronological review of studies using erosion pins in river banks, and discusses the advantages and disadvantages of their use. However, erosion pins have also been used to effectively measure erosion (and deposition) on horizontal surfaces (e.g. Ranwell, 1964; Gill, 1972; Aust *et al.*, 1991).

The pins used were approximately 10 cm long, 0.5 cm in diameter, and were made of firm plastic. Red tape was attached to the top for easy identification (Figure 7.2). Pins were inserted vertically into the floodplain surface and pushed down so that they were flush with the surface. Pin measurements were taken throughout the flood season of 2004/2005, and after the flood season of 2005/2006 by measuring the depth of exposure or burial (very few pins were re-located after 2005/2006 so the data presented are for 2004/2005). If pins were exposed (indicating erosion), the depth of exposure was measured from the top of the pin to the floodplain surface. As the pins may have protruded into the water column, they could potentially have impacted local flow conditions and therefore sediment deposition and erosion (Steiger *et al.*, 2003). Therefore, if the area immediately surrounding a pin was scoured more than the surrounding area, forming a 'pin crater' (Lawler, 1993), measurements were made to the surrounding surface that was believed not to be influenced by the pin. Measurements were taken on two sides of each pin and an average value obtained. Buried pins were measured by carefully removing the material from above them and measuring the depth from the floodplain surface down to the top of the pin (the location of pins relative to marker stumps was recorded in order to help locate them if they were buried). It is acknowledged, however, that during the process of uncovering the pins, the sediment was disturbed, which may have influenced its erodibility during the next overbank flood.

Figure 7.2 Erosion pins exposed on the floodplain surface.

Measurement precision

Measurement precision was +/- 1 mm (any changes in burial or exposure were consequently measured to a precision of +/- 2 mm). Measurement precision was quantified by measuring 32 pins twice (the mean difference between the two measurements was 1 mm).

Location of erosion pins

Pins were located on the floodplain downstream of Site 1 (semi-natural reference), on the floodplain at Site 2 (Restored site), and on the floodplain at Site 4 (semi-natural reference) (Figure 7.3). They were placed in lines with some pins in each line in floodplain channels and some in areas of floodplain that were not floodplain channels (termed 'floodplain surface') (see Table 7.1 for the number of pins in floodplain channels and in the floodplain surface in each line).

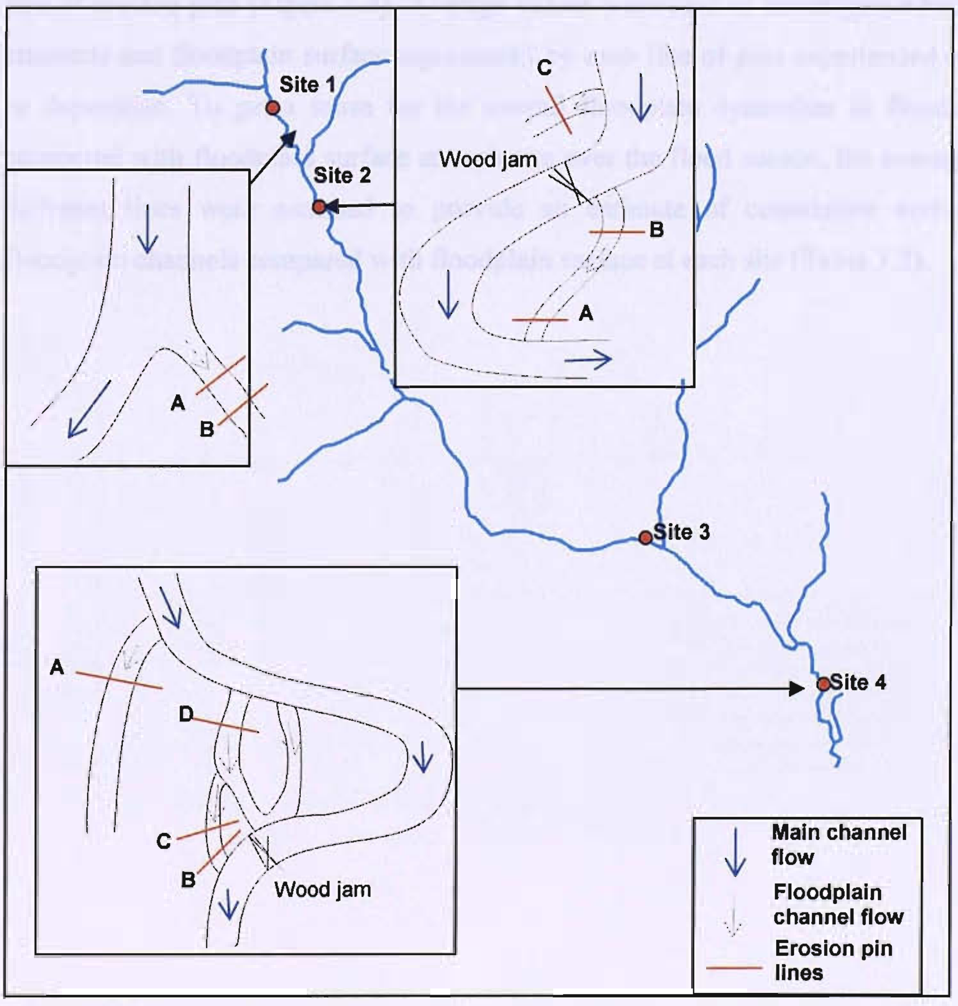


Figure 7.3 Schematic diagram of the location of erosion pins.

Table 7.1 Number of pins in each line

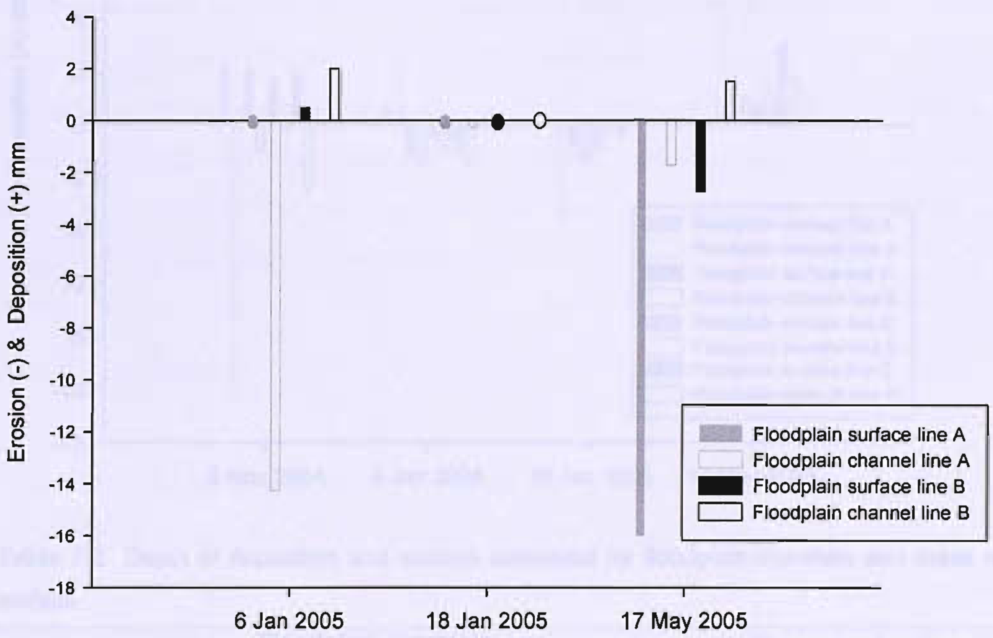
Site	Line	Floodplain channels	Floodplain surface (either side of floodplain channel)
1	A	4	4
	B	4	4
2	A	2	4
	B	2	4
	C	4	4
4	A	4	8
	B	4	8
	C	4	8
	D	4	8

7.3 Results

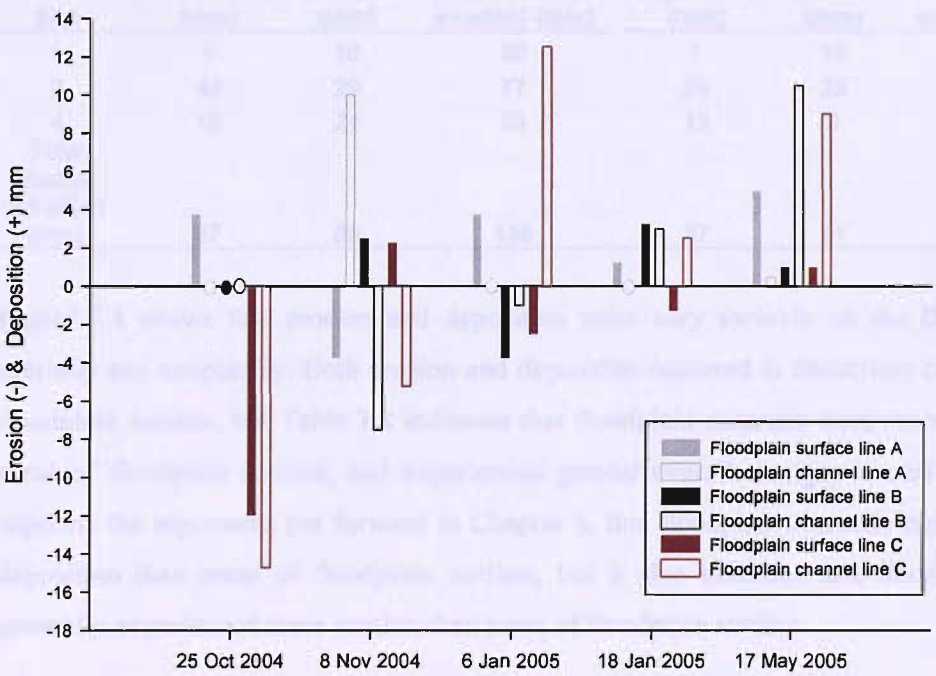
Average values of erosion and deposition between measurement dates were calculated for pins that were in the floodplain surface and for pins that were in floodplain channels, for each line of erosion pins (Figure 7.4). Average values were used to investigate whether floodplain channels and floodplain surface represented by each line of pins experienced overall erosion or deposition. To get a sense for the overall floodplain dynamism in floodplain channels compared with floodplain surface at each site over the flood season, the average values from different lines were summed to provide an estimate of cumulative vertical change in floodplain channels compared with floodplain surface at each site (Table 7.2).

Figure 7.4 (below) Graphs showing mean erosion (negative values) and deposition (positive values) in floodplain channels and in floodplain surface at each erosion pin line for different periods at (a) Site 1 (b) Site 2 and (c) Site 4. Circles indicate no change.

(a) Site 1



(b) Site 2



(c) Site 4

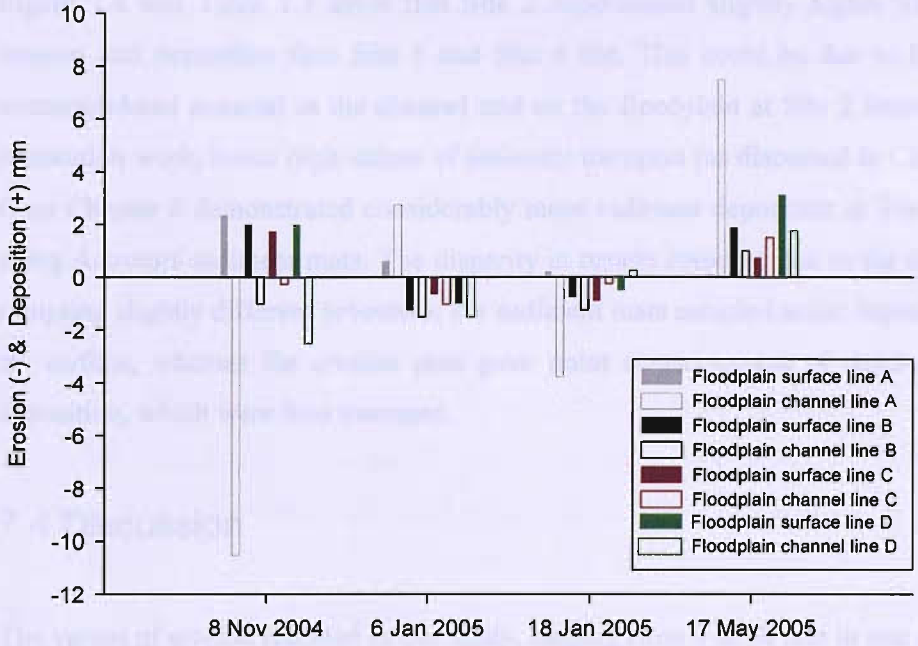


Table 7.2 Depth of deposition and erosion compared for floodplain channels and areas of floodplain surface.

	Floodplain channels			**Floodplain surface**		
Site	**Deposition (mm)**	**Erosion (mm)**	**Total change (deposition or erosion) (mm)**	**Deposition (mm)**	**Erosion (mm)**	**Total change (deposition or erosion) (mm)**
1	4	16	20	1	19	20
2	48	29	77	24	23	47
4	15	24	39	12	9	21
Total change (all sites) (mm)	67	69	**136**	37	51	**88**

Figure 7.4 shows that erosion and deposition were very variable on the floodplain, both spatially and temporally. Both erosion and deposition occurred in floodplain channels and on floodplain surface, but Table 7.2 indicates that floodplain channels were more *dynamic* than areas of floodplain surface, and experienced greater overall changes in surface level. This supports the arguments put forward in Chapter 6, that floodplain channels experienced more deposition than areas of floodplain surface, but it also indicates that floodplain channels generally experienced more erosion than areas of floodplain surface.

Table 7.3 Average erosion and deposition at each site over the flood season.

Pins	**Average erosion (mm)**	**Average Deposition (mm)**
Site 1	3.2	0.4
Site 2	3.1	3.8
Site 4	1.0	1.3

Figure 7.4 and Table 7.3 show that Site 2 experienced slightly higher values of average erosion and deposition than Site 1 and Site 4 did. This could be due to large amounts of unconsolidated material in the channel and on the floodplain at Site 2 immediately post the restoration work, hence high values of sediment transport (as discussed in Chapter 6). Results from Chapter 6 demonstrated considerably more sediment deposition at Site 4 than at Site 2 using Astroturf sediment mats. The disparity in results could be due to the different methods sampling slightly different processes; the sediment mats sampled aerial deposition over a 0.04 m^2 surface, whereas the erosion pins gave point measurements of depths of erosion and deposition, which were then averaged.

7.4 Discussion

The values of erosion reported in this study, ranging from 0 to 20 mm in one flood season, are considerably higher than those recorded in other studies. For example, Nicholas and Walling (1997b) report values of < 1 mm $year^{-1}$ on the River Culm, UK. The high rates in this study have been shown to be related to the presence of floodplain channels actively scouring material from the floodplain surface (as well as depositing material onto the floodplain), demonstrating the highly dynamic nature of these forested floodplains.

The depths of erosion recorded in this study demonstrate that floodplain channels can form rapidly – over just one flood season (although it needs to be kept in mind that the floodplain material at the Restored site was likely to be particularly erodible over the study period due to the floodplain disturbance caused by the restoration works). Rates of floodplain erosion recorded in this chapter of up to 20 mm $year^{-1}$ help to explain the deep floodplain channels observed in the New Forest in association with wood jams that, in some instances, have been in place for more than 23 years (Section 5.3.6) – this period of time would be sufficient for deep floodplain channels to form given these high erosion rates.

Floodplain development

As has been discussed in Chapter 3, there was a general view in the past that floodplains are developed by lateral accretion of coarse point-bar deposits, overtopped by a veneer of overbank, vertical deposits (e.g. Wolman and Leopold, 1957). Studies since then have demonstrated that vertical accretion (and erosion) are also important for floodplain development. For example, Nanson (1986) describes floodplains along high-energy, partially confined rivers in New South Wales, Australia, as periodically building up over a period of hundreds or thousands of years by overbank deposition, and then being stripped to a basal lag deposit by catastrophic erosion during a single large flood, or a series of moderate floods.

Lateral accretion has been shown to be relatively unimportant for semi-natural floodplain development in the New Forest over periods of decades (Jeffries, 2002), although where streams have been modified (straightened and steepened) recovery often occurs in the form of incipient floodplain development (Chapter 5) through lateral accretion of coarse material, with a thin overlying layer of fines, and this can create several metres of lateral accretion in as little as 30-40 years. Results from the current study indicate that contemporary semi-natural floodplain development in the New Forest is strongly influenced by in-channel wood jams (as proposed by Jeffries *et al.,* 2003) and associated floodplain channels that create 'hotspots' of floodplain erosion and overbank deposition. The precise locations of these 'hotspots' have been demonstrated to be both spatially (cm) and temporally (at the event-scale) variable, leading to a complex mosaic of floodplain habitats.

7.5 Conclusion

This chapter examined erosion and deposition on the floodplain surface and in floodplain channels using vertical erosion pins. Erosion and deposition both occurred on the floodplain surface and in floodplain channels, and ranged from 0 to 20 mm in one flood season. Floodplain channels were observed to be considerably more dynamic than areas of the floodplain surface, generally experiencing more deposition and erosion. Both erosion and deposition were characterised by high spatial and temporal variability, in accordance with the observed complexity of floodplain topography. The high rates of floodplain erosion help to explain the occurrence of deep floodplain channels observed in association with wood jams that have been in place for several years. Data from this chapter are used in conjunction with floodplain deposition data from Chapter 6 to suggest that contemporary floodplain development is strongly dependent upon in-channel wood jams and associated floodplain channels.

Chapter 8. Monitoring restoration (3): small-wood dynamics

8.1 Introduction

The effects of restoration on fine sediment transport and overbank sediment deposition and erosion have been discussed in Chapters 6 and 7; this is the third and final chapter on process monitoring, and it investigates the effects of channel type and restoration on small wood (< 1 m length and 0.1 m diameter) dynamics. The chapter provides a detailed account of the methodology used to compare in-channel wood movement before and after restoration using dowel tracers. The relative importance of different trapping sites is also investigated.

8.2 Monitoring aims

Although wood is important in terms of physical and ecological processes within rivers, little research has attempted to quantify the impacts of restoration (including the addition of wood jams) on wood retention (see Chapter 3 and Millington and Sear, 2007). The aim of this chapter is to investigate whether or not the restoration has been able to increase wood retention.

The following questions were addressed: (i) Does restoration reduce transport of small wood? (ii) Does restoration increase the frequency and type of small-wood trapping sites? (iii) Do wood jams trap more small wood than other trapping sites? (iv) Do shorter pieces of wood travel further than long pieces?

8.3 Methods

Wood retention has been estimated using a number of techniques, for example by tracing tagged wood (e.g. Bilby, 1984), and by estimating wood budgets (calculations of the difference between the amount of wood entering a river or reach compared with that leaving it) (see Chapter 3 and Millington and Sear (2007)). In this study, wood retention was investigated by tracing wood through three reaches (Reach 1, 2 and 3, Figure 8.1) that, as a result of their different geomorphological characteristics (see Table 8.1), displayed potentially different abilities to retain wood. In order to isolate reach retention from other factors influencing wood retention, notably the density and shape of the wood, standard wood pieces (wooden dowels cut to standard sizes) were used.

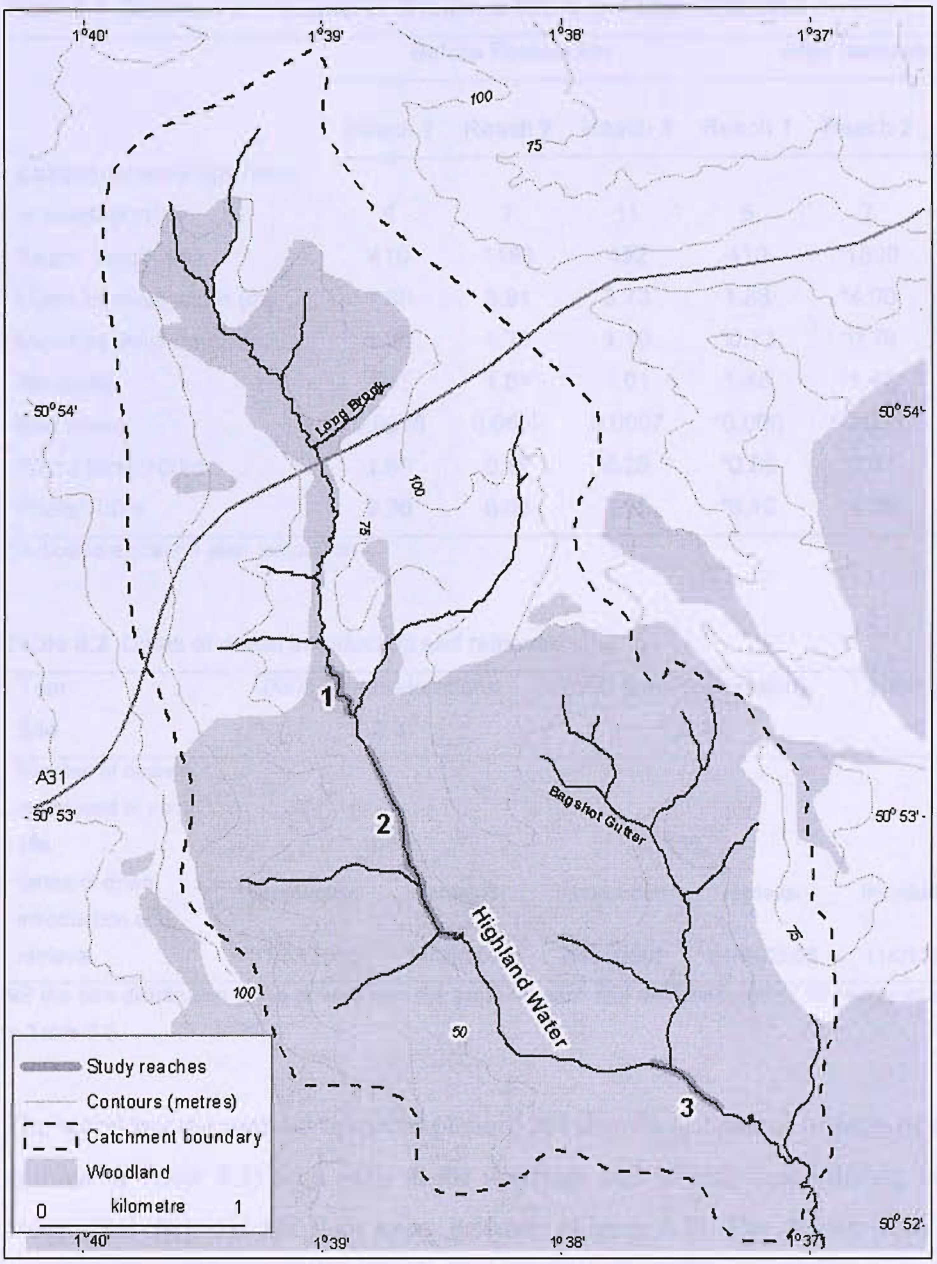


Figure 8.1 Highland Water catchment showing the reaches of river that were restored and the locations of study sites: 1. Channel bed level raised; 2. Old meander bends re-connected (some channel bed levels raised and some new channels cut where it was not possible to re-connect meanders); 3. Wood jams installed.

The tracing experiment was run during flood seasons in 2003/2004 (pre-restoration) and in 2004/2005 and 2005/2006 (post-restoration) (Table 8.2). Each year the experiment was run at the three study sites (Figure 8.1).

Table 8.1 Summary characteristics of reaches before and after restoration.

	Before Restoration			After restoration		
	Reach 1	Reach 2	Reach 3	Reach 1	Reach 2	Reach 3
Catchment area upstream of reach (km^2)	5	7	11	5	7	11
Reach length (m)	410	1183	452	410	*1598	452
Mean bankfull width (m)	1.88	5.91	3.73	1.88	*4.00	3.73
Mean bankfull depth (m)	1.20	1.70	1.10	*0.73	*0.78	1.10
Sinuosity	1.45	1.07	1.01	1.45	*1.45	1.01
Bed slope	0.0078	0.0080	0.0057	*0.006	*0.005	0.0057
Wood jams/100m	1.95	0.17	0.29	*0.98	*0.31	*0.66
Pools/100m	9.76	6.68	5.75	*6.10	*4.26	5.75

* Indicates a change after restoration

Table 8.2 Dates of dowel introduction and retrieval.

Year	2004 (pre-restoration)		2005 (post-restoration)		2006 (post-restoration)	
Site	1,2,3		1,2,3		1,2,3	
Number of dowels introduced at each site	108		108		108	
Dates of dowel introduction and retrieval	introduction	retrieval	introduction	retrieval	introduction	retrieval
	31/03/2004	14/05/2004	29/01/2005	01/04/2005	11/01/2006	04/03/2006

NB the size distribution of the dowels was the same for each trial and consisted of 12 pieces of each size class listed in Table 8.3.

The wood tracing method involved placing 108 dowels (12 pieces of each of the 9 size classes defined in Table 8.3) on a riffle at the upstream end of each reach during fairly low flow to ensure that they did not float away instantly (Figure 8.2). The dowels were labelled by site with a permanent marker to enable identification on retrieval. The starting locations were surveyed using a hand-held GPS (precision approximately 10 m). The same number (108) and size distribution (Table 8.3) of dowels were used at each site during each trial.

Figure 8.2 Dowels placed on a riffle at low flow at Site 3. For scale, the largest dowels are 1.06 m in length and 0.035 m in diameter.

Table 8.3 Numbers and size classes of wood dowels input into each reach.

Size			
Length (m)	Diameter (m)	Size class	Number of each class input at each site
0.184	0.006	1	12
0.184	0.012	2	12
0.184	0.035	3	12
0.340	0.006	4	12
0.340	0.012	5	12
0.340	0.035	6	12
1.060	0.006	7	12
1.060	0.012	8	12
1.060	0.035	9	12

To ensure that the dowels represented the size distribution of natural wood in the field as closely as possible, wood sizes were measured at a semi-natural reference site using a random walk sampling method, similar in principle to that used to sample bed surface grainsize (Bunte and Abt, 2001). The surveyor took a step and felt on the ground for a piece of wood; the diameter and length of the first piece touched was recorded. This continued across the floodplain and channel until 100 pieces had been measured.

As wood density influences its mobility (e.g. Gurnell *et al.*, 2002), the use of standard wood enabled control of density differences. All dowels were therefore of the same density

(0.75 g cm^{-3}). To estimate the density of natural wood, 18 pieces from the channel and 18 pieces from the floodplain were weighed and their volumes measured through water displacement. The average density of natural wood from the floodplain was 0.406 g cm^{-3} (standard deviation 0.16) and from the channel it was 1.2 g cm^{-3} (standard deviation 0.28). Consequently, the dowels were likely to be less mobile than natural wood from the floodplain and more mobile than natural wood that has been in the channel for a time. The dowels therefore represented a 'mean condition' of wood density that was similar to that observed under natural conditions. To make the dowels more representative of natural wood in the channel, they were soaked in a ponded area in the river for a month prior to seeding in 2004. However the density change after soaking was negligible, so soaking was abandoned in the following years.

To allow for channel-floodplain interactions, the dowels were left in the field for at least one overbank event. Recovery involved walking downstream from the seeding position at the most upstream reach (Reach 1), recording the grid reference of each dowel tracer found using a hand-held GPS and a description of the location in which each tracer was found. The search for the dowels continued for approximately 500 m beyond the most downstream dowel located. The locations of dowel retrieval were then entered into a GIS onto a base layer map of the channel. The distances from the seeding point to the point of retrieval along the course of the channel were calculated (to within +/- 20 m).

Discharge was estimated from stage-discharge relationships derived for each of the study reaches (see Chapter 6). Figure 8.3 shows hydrographs from Site 2 during the periods that the dowels were in the field.

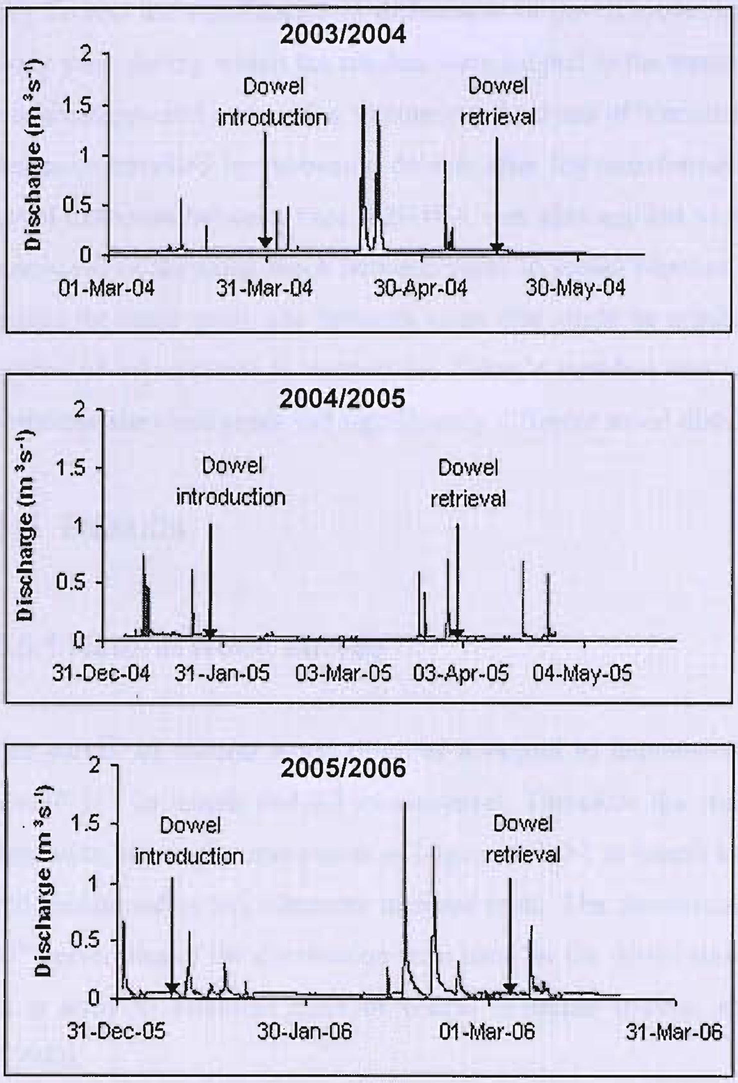


Figure 8.3 Hydrographs from Site 2 showing times of dowel introduction and retrieval.

8.4 Data analyses

Data were analysed as follows:

(i) Broad assessments and comparisons of results were achieved using descriptive statistics.

(ii) To allow for the skewed distribution of dowel distances, the average travel distance of dowels within each site and year was estimated using the following negative exponential model (see e.g., Larrañaga *et al.*, 2003; James and Henderson, 2005):

$$M_d = M_o e^{-kd}$$

Where 1/k is the mean travel distance (m),

M_d is the number of dowels that travelled to distance d and

M_o is the number of original dowels input.

(iii) To test the significance of differences in dowel movements between study sites in each study year, during which the reaches were subject to the same flow regime but different initial morphologies and restoration treatments, Analysis of Variance (ANOVA) was applied to the distances travelled by recovered dowels after log-transformation to equalise the variances in travel distances between sites. ANOVA was also applied to log-transformed travel distances monitored in the same reach between years to assess whether significant differences occurred within the same study site between years that might be attributable to either changes in flow regime or adjustments to restoration. Tukey's post-hoc test was then used to identify which particular sites and years had significantly different travel distances ($p < 0.05$).

8.5 Results

8.5.1 Natural wood survey

The survey of natural wood (Figures 8.4a and b) demonstrates that most of the wood was 'small' (<1 m length and 0.1 m diameter). Therefore the study was focused on small-wood dynamics, although some pieces of large wood (>1 m length and 0.1 m diameter) were present and functioned as key elements in wood jams. The dimensions of the 16th, 50th (median) and 84th percentiles of the distribution were used for the dowel sizes (Figure 8.4) (a similar method as is used to establish sizes of coarse sediment tracers, e.g. Haschenburger and Church (1998)).

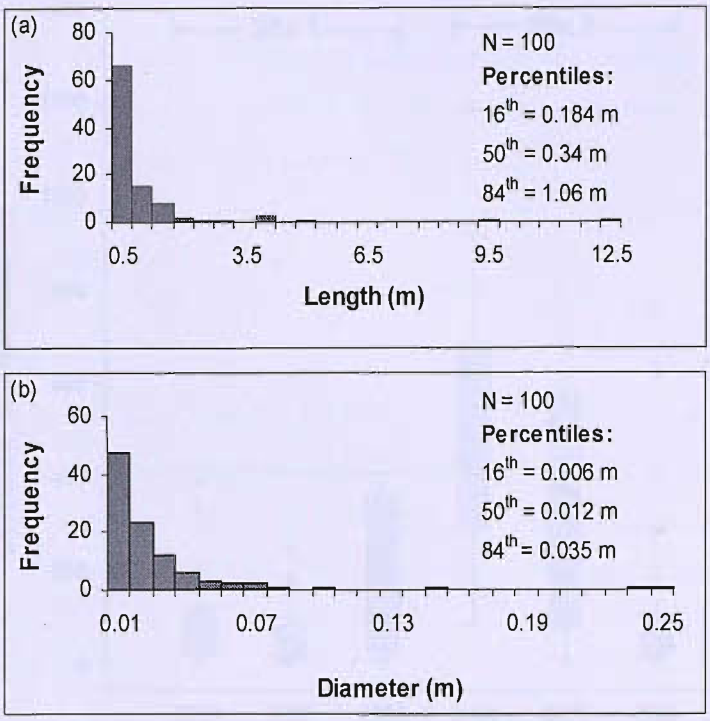


Figure 8.4 Histograms of (a) length and (b) diameter of natural wood survey sample, identifying 16 th, 50 th and 84th percentiles used for dowel sizes.

8.5.2 Dowel travel distance and restoration

Figure 8.5 presents boxplots of dowel travel distance and reports the percentage of dowels retrieved from each trial. Travel distances ranged from zero to over 1000 m (length of Reach 2), and were generally less in Sites 1 and 3 than in Site 2 (although note that reach length is much greater in Site 2 than in the other two sites). The percentage of dowels recovered ranged from 36% from Site 2 in 2004/2005 to 73% from Site 1 in 2003/2004. In general, higher percentages of dowels were retrieved from trials where the overall travel distance was relatively low, and fewer dowels were retrieved when travel distances were greater. Therefore, the results from trials with a low travel distance are generally more reliable than those from trials with larger travel distances, as the results are based on more data.

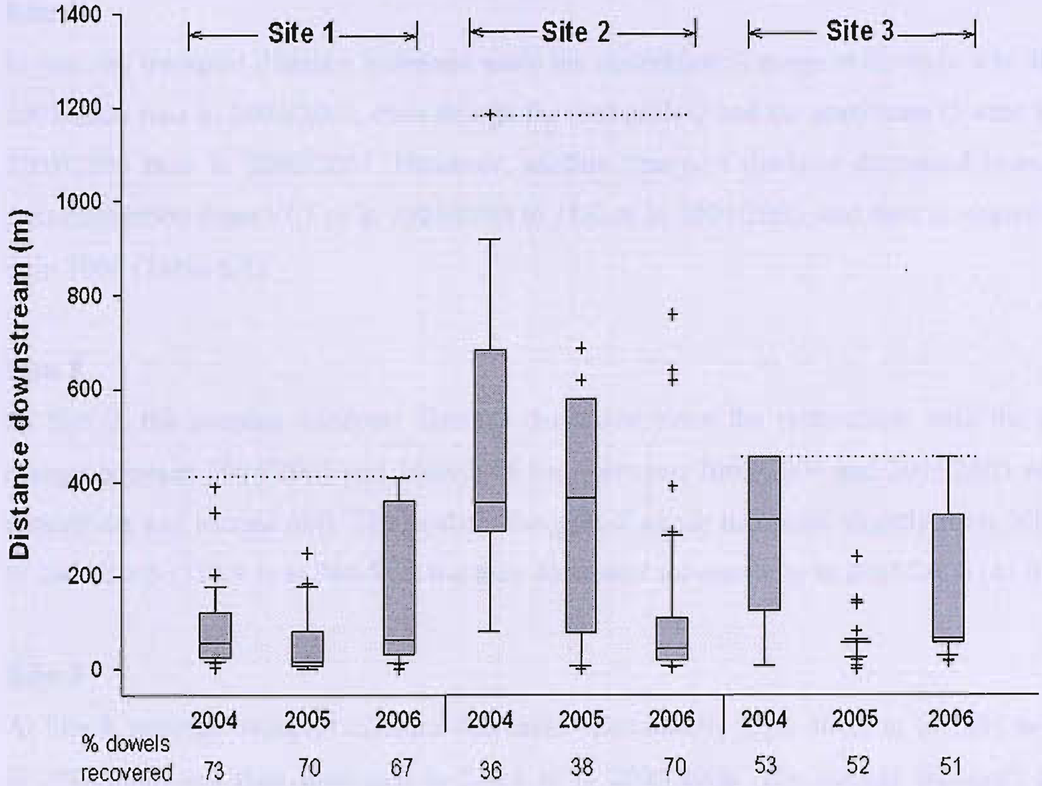


Figure 8.5 Boxplots of dowel travel distance by trial (dotted lines indicate reach length).

Table 8.4 summarises measures of average dowel transport distance and characteristics of flow. The peak discharge during the first flood after the dowels were input is included as most wood moves to a stable location during the first high rainfall event after it has been input / destabilised - subsequently it may not move even during events of higher magnitude (Bilby, 1984; Webster *et al.,* 1994).

Table 8.4 Measures of average dowel transport distance and characteristics of flow from the three sites before restoration (2003/2004) and during the two subsequent flood seasons after restoration (2004/2005 and 2005/2006).

	2003/2004			2004/2005			2005/2006		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Average transport distance (m)	113.6	333.3	400.0	181.8	270.3	48.5	370.4	208.3	256.4
Median transport distance (m)	57.1	357.9	318.4	18.0	366.5	57.0	63.5	45.0	66.0
Q (first peak) ($m^3 s^{-1}$)	0.90	1.50	1.90	0.27	0.60	0.95	0.47	0.89	1.50
Q (maximum) ($m^3 s^{-1}$)	0.90	1.50	1.90	0.30	0.70	1.36	0.98	1.73	2.59
Number of peaks*	6	6	6	3	3	3	6	6	6

* Peak is defined as flow exceeded 10% of the time

Site 1

In general, transport distance increased since the restoration. Transport distance was higher in 2005/2006 than in 2003/2004, even though the first peak Q and the maximum Q were lower in 2005/2006 than in 2003/2004. However, median transport distance decreased immediately post-restoration from 57.1 m in 2003/2004 to 18.0 m in 2004/2005, and then increased to 63.5 m in 2006 (Table 8.4).

Site 2

At Site 2, the average transport distance decreased since the restoration, with the greatest change between 2004/2005 and 2005/2006 (not between 2003/2004 and 2004/2005 when the restoration was carried out). The median transport distance increased slightly from 2003/2004 to 2004/2005 (357.9 m to 366.5 m) but then decreased substantially in 2005/2006 (45.0 m).

Site 3

At Site 3, average transport distance decreased substantially from 400.0 m in 2004 to 48.5 m in 2004/2005 and then increased to 256.4 m in 2005/2006. The median transport distance initially dropped sharply from 318.4 m in 2003/2004 to 57.0 m in 2004/2005 and then rose slightly to 66.0 m in 2005/2006.

Analyses of Variance

The ANOVA tests showed that significant differences ($p < 0.01$) in dowel travel distance occurred under the same flow regime at the three sites (Table 8.5). At each site, significant differences in dowel travel distance ($p < 0.01$) also occurred between years (Table 8.6). Tukey's post-hoc test identified which trials were significantly different to each other (Figure 8.6).

Table 8.5 Results from ANOVA tests of significant difference in dowel travel distance between sites during 2003/2004, 2004/2005 and 2005/2006.

Year	Degrees of freedom (between group)	Degrees of freedom (within group)	p
2003/2004	2	70	<0.01
2004/2005	2	171	<0.01
2005/2006	2	210	<0.01

Table 8.6 Results from ANOVA tests of significant difference in dowel travel distance between years at each of the three sites.

Site	Degrees of freedom (between group)	Degrees of freedom (within group)	p
1	2	178	<0.01
2	2	130	<0.01
3	2	143	<0.01

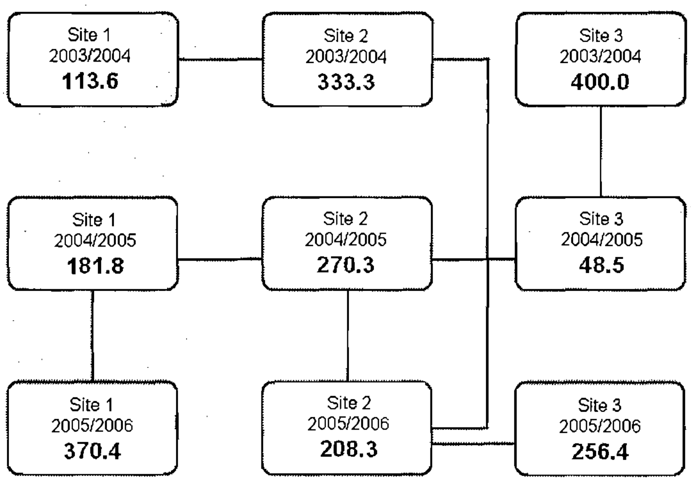


Figure 8.6 Average dowel transport distance (m) from the three sites during each trial (2003/2004, 2004/2005 and 2005/2006). Connector lines indicate significant difference between trials (Tukey's test).

The following significant differences in dowel travel distances ($p < 0.01$) were found between the sites during each year: in 2003/2004, distances were significantly higher in Site 2 than Site 1; in 2004/2005 distances were significantly higher in Site 2 than in Sites 1 and 3; and in 2005/2006 distances were significantly higher in Site 3 than Site 2. Significant differences ($p < 0.01$) were also found in dowel travel distances for each site across different years: in Site 1, distances were higher in 2005/2006 than in 2004/2005; in Site 2, distances were lower in 2005/2006 than in either 2003/2004 or 2004/2005; and in Site 3, distances were higher in 2003/2004 than in 2004/2005.

8.5.3 Trapping sites

Table 8.7 gives the number of dowels retrieved from different locations. Wood jams were the most important trapping location, trapping a total of 157 dowels (31.2% of the total retrieved within the study reaches). Other important trapping locations were pieces of natural wood in the channel (these were not in large accumulations and did not span the channel, hence not termed 'wood jams') (70 dowels, 14%); against bank vegetation (63 dowels, 12.5%); in pools (62 dowels, 12.3%); on the main floodplain (as apposed to more lower-lying, incipient floodplain) (54 dowels, 10.7%); and amongst exposed roots in the channel banks (53, 10.5%).

Table 8.7 Number of dowels retrieved from different locations during each trial.

	2003/2004			2004/2005			2005/2006			
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	
Number of dowels recovered from outside reaches	0	2	17	6	0	0	16	0	9	
Number of dowels not recovered	29	70	50	31	67	54	33	32	53	
Number of dowels recovered from different locations (within reach lengths)										Total
In wood jams	29	0	18	11	20	40	12	2	25	157
Amongst natural wood	10	12	0	12	2	2	13	12	7	70
Against bank vegetation	16	10	5	8	2	0	2	16	4	63
In pools	14	2	6	14	0	9	3	11	3	62
On main floodplain	0	0	0	0	13	0	15	25	1	54
Amongst exposed roots	5	10	2	15	0	1	11	5	4	53
On bars	5	2	8	1	0	0	0	0	0	16
Against equipment	0	0	0	0	0	0	2	5	0	7
On incipient floodplain	0	0	2	0	0	1	0	0	2	5
No movement	0	0	0	10	4	1	1	0	0	16

In order to determine whether or not wood jams trapped more dowels than other locations because they had a high trapping efficiency or because they occurred in higher abundance, the trapping efficiency of wood jams and pools was calculated. Trapping efficiency was calculated as the number of dowels retrieved from a location / the number of these features per 100 m of reach. Trapping efficiency was not calculated for other locations, as feature abundance could not easily be calculated for other trapping locations that did not have discrete boundaries, e.g. for 'bank vegetation', or 'floodplain'. The comparison of pools and jams as wood retention sites is also particularly appropriate along small woodland rivers such as the Highland Water where a functional, geomorphological link has been demonstrated between the two features (e.g. Gurnell and Sweet, 1998; Montgomery *et al.,* 1995). Table 8.8 shows that, in almost all instances, wood jams had a much higher trapping efficiency than pools did.

Table 8.8 Trapping efficiency of pools and wood jams, calculated as the number of dowels retrieved from a location / the number of these features per 100 m of reach.

Trapping feature	2003/2004			2004/2005			2005/2006		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Wood jams	14.87	0.00	62.07	11.22	64.52	60.61	12.24	6.45	37.88
Pools	1.43	0.30	1.04	2.30	0.00	2.71	0.49	2.58	0.90

Type and frequency of small-wood trapping sites

During 2003/2004, prior to the restoration, dowels were trapped in six different locations in Sites 1 and 3, and in five different locations in Site 2. After the restoration, during the 2004/2005 trials, dowels were trapped in the same number of locations in Sites 2 and 3, but in seven locations in Site 1. During the 2005/2006 trials, dowels were trapped in eight locations in Site 1, and seven locations in Sites 2 and 3. Therefore the number of different types of trapping site increased after the restoration.

Although the number of wood jams (the most important trapping location) decreased in Site 1 after the restoration, from 1.95 per 100 m to 0.98 per 100 m (largely due to burial from channel infill), they increased in Site 2 (from 0.17 per 100 m to 0.31 per 100 m) and in Site 3 (from 0 to 0.66 per 100 m).

8.5.4 Dowel length and travel distance

If short pieces of wood travel further than long pieces, then it can be hypothesised that a higher proportion of shorter pieces would travel out of the study reaches and not be recovered. Figure 8.7 shows that dowel retrieval decreased with decreasing dowel length (251 dowels of 1.06 m length were retrieved, compared with 194 dowels of 0.34 m and 108 dowels of 0.184 m).

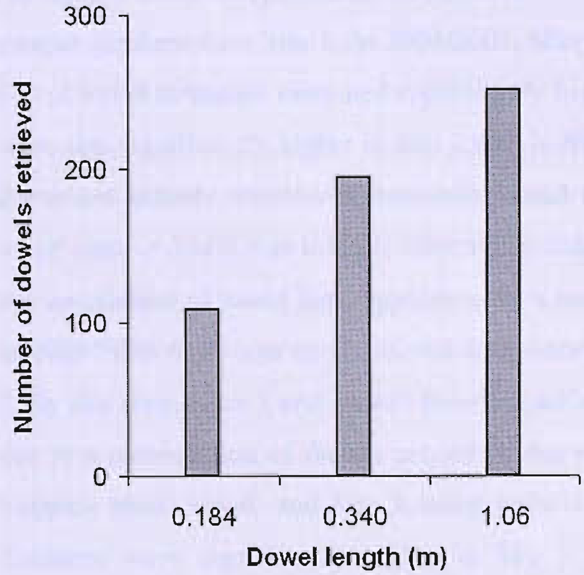


Figure 8.7 Number of dowels retrieved according to length.

8.6 Discussion

The results show an increase in dowel travel distance post restoration at Site 1 (although a significant difference only occurred between 2004/2005 and 2005/2006). There was no obvious change in channel morphology between 2004/2005 and 2005/2006 that could account for this significant difference. There was, however, a notably higher maximum discharge in 2005/2006 (0.98 $m^3 s^{-1}$) than in 2004/2005 (0.30 $m^3 s^{-1}$). The decrease in retention could also be due to burial of trapping sites (e.g. wood jams and pools) during the restoration. At Site 2, transport distances decreased throughout the years, with 2005/2006 having significantly lower transport distances than both 2003/2004 and 2004/2005. This result is unexpected: small wood transport did *not* decrease significantly immediately after restoration, even though the number of jams/100 m increased from 0.17 before the restoration to 0.31 after the restoration. This is possibly due to a large proportion of dowels being retained on the floodplain in 2005/2006 (Table 8.7) due to high channel-floodplain connectivity. Finally, at Site 3, transport distances decreased significantly from 2003/2004 to 2004/2005. This decrease could either be due to lower flows in 2004/2005 than during 2003/2004 (Table 8.4), or it could be a direct result of the addition of a large wood jam approximately 50 m downstream from the start of the reach during the restoration. This trapped a large proportion of the dowels (74 % of those retrieved).

The results also show significantly higher transport distances in Site 2 than in Site 1 before the restoration. This is likely to be due to differences in channel morphology (Table 8.1), with Site 2 (i) having fewer potential trapping sites such as wood jams, pools, and meander bends, and

(ii) being a reach that promoted wood movement, being considerably deeper, wider and with a steeper gradient than Site 1. In 2004/2005, after the restoration and contrary to expectations, dowel travel distances remained significantly higher in Site 2 than in Site 1. Travel distances were also significantly higher in Site 2 than in Site 3. This indicates that the restoration at Site 2 was not initially effective at decreasing small wood transport. In contrast, the installation of wood jams at Site 3 was initially effective at reducing the transport of small wood. Therefore, the installation of wood jams appears to be a more immediately effective measure. However, in 2005/2006 there was no significant difference in small wood transport between Sites 1 and 2. By this time, Sites 1 and 2 were therefore acting similarly, a convergence that is likely to be due to a combination of factors caused by the restoration, with Site 1 being less effective at trapping small wood, and Site 2 being more effective. In 2005/2006 small-wood transport distances were significantly higher in Site 3 than in Site 2. This could imply that the restoration at Site 2 was becoming more effective. It also implies that the restoration at Site 3 was less effective at trapping small wood in 2005/2006 than it had been the previous year. Therefore, the morphological modifications within Site 2 appear to be increasingly effective at trapping small wood; whereas the addition of wood jams in Site 3 was only temporarily effective.

The results show that wood jams were particularly effective at trapping small wood, and that the large numbers of dowels retrieved from wood jams were not simply due to a high abundance of wood jams but also to their high trapping efficiency. Restoration involving planform re-meandering and the addition of wood jams increased the frequency of wood jams, but restoration involving channel in-filling resulted in a reduction of wood jams. However, the number of pools per 100 m (also an important trapping location) decreased in the two sites where the bed morphology was changed, but not in Site 3. This could be because the 2005 survey was conducted immediately post-restoration, and therefore pools and wood jams had not had sufficient time to develop but are likely to return in subsequent years. The restoration (in Sites 2 and 3) therefore increased the occurrence of some trapping locations (e.g. wood jams) and the effectiveness of others (e.g. increased floodplain connectivity) but not all (e.g. pools). Therefore, because jams were more effective at trapping dowels than pools were, this type of restoration was effective at increasing the type and frequency of small-wood trapping sites.

Distances travelled by the individual dowels in this study ranged from 0 to 1183 m, and the average ranged from 48 to 400 m. These distances are comparable with results from Bilby (1984), who traced natural wood in a fourth-order stream in the Coastal Range of Washington, USA, over one winter, and found that pieces of length 0 - 2.5 m moved an average distance of

129 m. Other studies have traced dowels over much shorter periods (minutes), resulting in shorter transport distances: e.g., James and Henderson (2005), 71 m for 0.1 m length dowels and 55 m for 0.2 m length; Larrañaga *et al.* (2003), 18.3 m for plastic strips 3 cm x 10 cm in first-order reaches, 20.7 m in second-order reaches and 32.9 m in third-order reaches. However, Webster *et al.* (1994) conducted a similar experiment in streams in the southern Appalachian Mountains in western North Carolina, USA, using dowel tracers of a similar size to this study, which they left in place for one year. They found that the dowels were efficiently retained where they were input, and only travelled between 0.4 and 80 m. These distances are much shorter than our results from a low-gradient stream. Other authors (e.g. Larrañaga *et al.*, 2003; Daniels, 2006) have suggested that wood is more stable in many high-gradient systems due to smaller channel width relative to wood size and higher frequencies of roughness elements, e.g. boulders. Our results provide further evidence that wood is indeed more mobile in small low-gradient systems.

In this study wood jams were the most important trapping site, trapping a total of 157 dowels (31.2% of the total retrieved within the study reaches) (Table 8.7). Many other studies have also demonstrated that retention of organic material is related to the abundance of large wood in streams (e.g. Naiman and Sibert, 1978; Bilby and Likens, 1980; Bilby, 1981; Smock *et al.*, 1989; Webster *et al.,* 1994) and that in the absence of major wood structures wood may become very mobile (e.g. Gurnell and Sweet, 1998; Daniels, 2006). In a third-order stream in Palmerston North, New Zealand, James and Henderson (2005) also found that vegetation and wood were more important than rocks and eddies as retention locations. In contrast, Larrañaga *et al.* (2003) traced plastic strips (3 cm x 10 cm) in streams of the Agüera basin, northern Spain, and found that cobbles and boulders were more important retention sites than wood. In streams in the Appalachian Mountains, Webster *et al.* (1994) also found that rocks were the most important trapping site, trapping 44% of dowels, followed by boulders (28%), sticks (9.4%), logs (7.7%), 'other' (including eddies, weeds, roots and bank) (6%) and leaves (3%), and wood jams only trapped 1%. The small percentage of dowels retrieved from wood jams was not due to a low frequency of wood jams, as they were more frequent in these streams than in the Highland Water (approximately 2.8 wood jams per 100 m compared with an average of 0.7 in the Highland Water), but rather to a high frequency of rocks and boulders (which were absent from the Highland Water). A further reason for the disparity in results could be that 'wood jams' may be defined differently in each study; for example, a single log spanning the channel on the Highland Water is termed a 'wood jam', whereas this may have been defined as a 'log' in the study by Webster *et al.* (1994). The observed increase in travel distance post-restoration at Site 1 is therefore likely to be due to the burial of wood jams during the restoration, which represents a loss of large-roughness structures.

Various authors have suggested that retentive structures (such as wood jams or boulders) are more important than discharge and stream power in determining stream retention (Naiman, 1982; Gurnell *et al.,* 2000; James and Henderson, 2005). The results presented above lend some support to this concept because jams were the primary retention location. However, the results also show that stream discharge can play an important part in controlling trapping locations of small wood because, during overbank flows, more than 10% of wood was trapped on the floodplain.

Indeed, although most wood transport takes place during large events (see e.g. Bilby, 1984; Webster *et al.,* 1994), dowel tracing experiments are rarely conducted during overbank flows. Hence, the importance of the floodplain as a wood trapping site and as a long-term storage site has probably been underestimated during tracing experiments (although other research records natural wood rafted onto the floodplain, e.g. Piégay and Gurnell, 1997; Piégay and Marston, 1998). This study showed the floodplain to be an important trapping site post-restoration, with 10.7% of dowels being rafted onto the floodplain during overbank flows (during the 2003/2004 trials, before the restoration, dowels were not retrieved from the main floodplain). Therefore, the restoration increased connectivity between the channel and floodplain, and facilitated energy exchange, which is important in promoting high biodiversity (Ward *et al.,* 1999). Jeffries *et al.* (2003) demonstrated that this exchange is particularly significant upstream of wood jams, as these structures dramatically increase the frequency and duration of overbank flows (see Chapter 6).

This work has also shown that more short dowels were not recovered and travelled out of the reaches than longer dowels. Other researchers have also found that shorter pieces of wood travelled further than long pieces (see e.g. Bilby, 1984; Lienkaemper and Swanson, 1987; James and Henderson, 2005; Daniels, 2006). However, it needs to be kept in mind that the dowels were not perfect surrogates for natural wood as they were firmer and had no irregularities, such as protruding branches, possibly reducing trapping potential and resulting in longer travel distances compared with natural wood.

The geomorphological and ecological benefits of high organic material retention are generally recognised (see e.g. Harmon *et al.*, 1986), although few projects have specifically monitored the impacts of restoration on organic material retention. The results in this chapter indicate that different types of restoration had different affects on small-wood retention: adding wood jams was the most effective method of retaining small wood; re-meandering the channel planform also increased small-wood retention; but small-wood retention was reduced by channel infilling. Although this is a first attempt at monitoring the effects of different types of restoration on small-wood retention, the results are only based on three years monitoring: one year before and two years after the restoration. Longer-term monitoring, particularly of wood jam formation and the morphological changes that naturally develop post-restoration (e.g. pool development), is required to gauge the lasting effects of restoration measures on small-wood dynamics.

8.7 Conclusion

In conclusion, this chapter has demonstrated that: (i) different types of restoration had different affects on the frequency and type of small-wood trapping mechanisms, and hence also on small-wood transport; (ii) wood jams were the most effective structures for trapping small wood in this environment; (iii) shorter pieces of wood travelled further than long pieces. Channel-floodplain interactions were also found to be important, allowing the floodplain to function as a trapping site.

Chapter 9. Evaluating restoration of floodplain processes

To evaluate the restoration it was first necessary to understand natural floodplain processes. This was done initially through the development of a conceptual model of floodplain processes based on the literature, which was updated through observations and surveys of semi-natural New Forest floodplains. Results from the monitoring were then used to construct a conceptual model of restored floodplain processes, and the restoration design, construction, and the monitoring programme, where evaluated. The evaluation can be used to inform future restoration projects involving forested floodplains. The thesis therefore contributes to the evolution of restoration design and monitoring techniques, as well as to our understanding of geomorphological processes operating in forested floodplains.

9.1 Natural floodplain processes

9.1.1 Natural floodplain processes based on the scientific literature

This research set out to monitor the dynamics of the floodplain geomorphology in reaches of the Highland Water in the New Forest, in response to the LIFE 3 restoration project. Focus was placed on monitoring *processes* rather than *features* due to the short-term nature of a PhD, and due to the lack of scientific understanding of how these types of floodplain systems function.

The geomorphological processes on forested floodplains are greatly complicated by the presence of live and dead vegetation that create a suite of processes that do not occur on unforested floodplains (Gurnell, 1997; Piégay, 1997). Our understanding of these processes is limited but it has been rapidly increasing since the 1980s (Gurnell, 1997), for example Hupp (1996), Hupp and Osterkamp (1996), Hughes (1997), Piégay (1997) and Hughes *et al.* (2001). Much of this research, however, is limited to large, piedmont rivers, for example the Fiume Tagliamento, a high-energy piedmont river in Italy (Gurnell *et al.*, 2001). There is very limited research on low order, temperate, lowland floodplains such as those found in the New Forest, even though they occur widely in the UK, Europe and North America (although see McKenney *et al.*, 1995; Brown, 1997; Jeffries *et al.*, 2003). Consequently, information reported in the literature from other systems was used to construct a conceptual model of how the geomorphological processes on the floodplain in this system are likely to function 'naturally' (Figure 9.1).

Figure 9.1 demonstrates how in-channel wood jams are important in promoting interactions between the channel and floodplain environments (channel-floodplain connectivity) through promoting overbank flow (Gregory *et al.,* 1985; Brown, 1997; Jeffries *et al.,* 2003) and long residence times of organic and inorganic material (e.g. Bilby and Likens, 1980; Megahan, 1982; Nakamura and Swanson, 1993; Smith *et al.,* 1993; Keller *et al.,* 1995) both in the channel and on the floodplain. Wood jams promote overbank flow (Jeffries *et al.,* 2003) and this locally increases residence times of material on the floodplain. Thus sediment and organics are locally deposited overbank at a greater rate than is likely to occur in unforested systems of a similar size, slope and geology. Wood that is trapped in the channel in the form of wood jams may remain in situ for long periods (e.g. for more than 200 years (Keller *et al.,* 1995)), and may trap other pieces of wood and organics, further increasing residence times of organic material. Wood jams may also prolong residence times of inorganic material in the channel by promoting upstream sediment accumulation (Megahan, 1982; Nakamura and Swanson, 1993; Smith *et al.,* 1993; Keller *et al.,* 1995).

Once on the floodplain, overbank flow is concentrated by topography and by obstacles created by vegetation, leading to floodplain scour and deposition, and the creation of diverse floodplain geomorphology (Brown, 1997; Piégay, 1997; Jeffries *et al.,* 2003). This, together with long residence times of organic and inorganic material, forms a mosaic of physical habitats supporting diverse vegetation and ecology (e.g. Naiman and Decamps, 1990; Amoros and Petts, 1993; Malanson, 1993; Naiman *et al.,* 1993; Marston *et al.,* 1995; Ward, 1998; Ward *et al.,* 2002), which in turn promotes geomorphological diversity.

Long residence times of organic and inorganic material in the channel promote interactions between vegetation and geomorphological processes (e.g. bank scour around wood jams (Zimmerman *et al.,* 1967; Swanson *et al.,* 1976)), promoting habitat and ecological diversity. Diverse channel geomorphology increases the potential for wood jams to establish (Gurnell *et al.,* 2000), which consequently further promotes abiotic and biotic interactions.

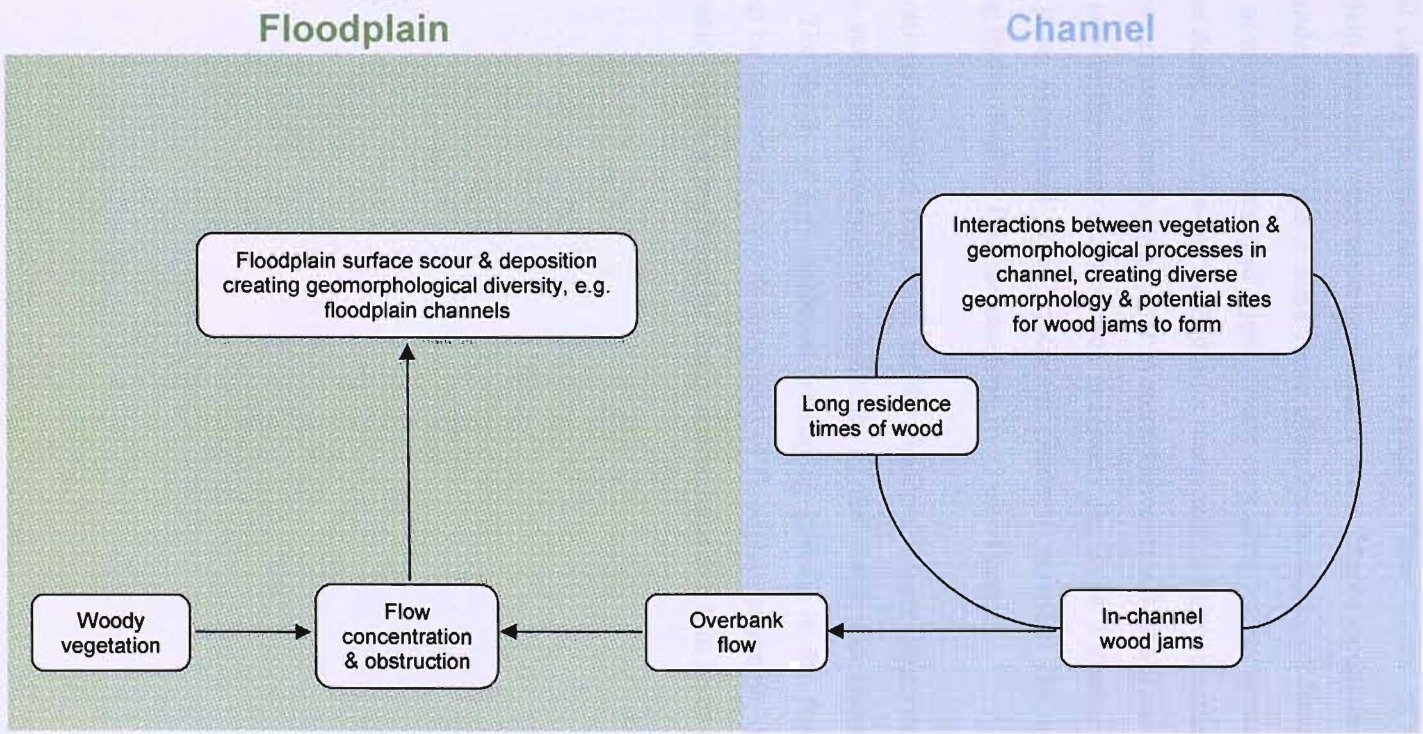


Figure 9.1 Conceptual model of interactions between vegetation and geomorphology in a lowland, temperate semi-natural forested floodplain based on the literature.

9.1.2 Natural floodplain processes based on field observations

Field observations of semi-natural floodplains in the study area (Chapter 5) enabled the conceptual model of floodplain processes that was based on the literature (Figure 9.1) to be adapted to represent processes in semi-natural floodplains in the New Forest (Figure 9.2). Floodplain channels were found to be particularly important geomorphological features, and their reach and catchment-scale distributions were investigated. At the catchment-scale, floodplain channels were associated with high floodplain-channel connectivity, minimal channel modification, high frequencies of wood jams, high channel sinuosity, and low channel capacity (particularly low bank height). Three 'types' of reach-scale distributions of floodplain channels were observed: Type 1 were single floodplain channels across the inside of meander bends; Type 2 were more complex networks of floodplain channels across the inside of meander bends; and Type 3 were very complex networks of floodplain channels of variable depth, which were located on a reach with a tight meander bend (e.g. Millyford), or on a less sinuous reach (e.g. Ober Water). However a hydraulically effective and long-lived wood jam in the main channel was necessary for Type 3 channels to develop. Analysis of wood jams associated with floodplain channels revealed the importance of living trees forming hydraulically effective and long lived wood jams.

Observations revealed that roots on the floodplain were important in inhibiting floodplain surface scour by reducing the erodibility of the floodplain material (e.g. De Baets *et al.*, 2006). The depth of fine sediment overlaying gravels in the floodplain material was also likely to be important in the development of floodplain channels; deep channels may develop more easily where gravels can be easily reached due to a thin layer of overlying fine material.

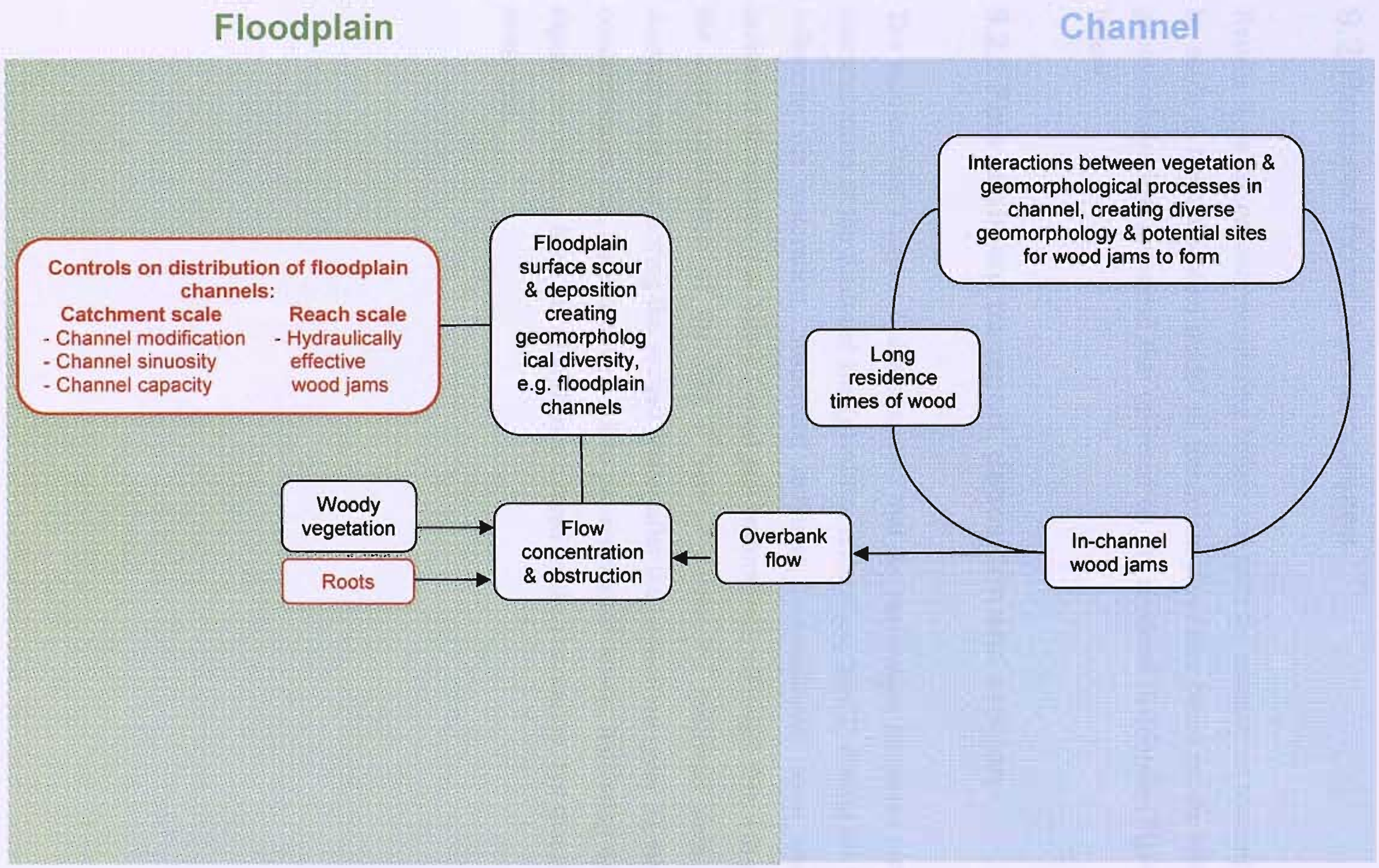


Figure 9.2 Conceptual model of interactions between vegetation and geomorphology in a lowland, temperate semi-natural forested floodplain **improved through field observations (red outline).**

Based on the conceptual model of how geomorphological processes operated in a lowland, temperate, semi-natural forested floodplains, the following processes were identified to monitor before and after the restoration in order to identify the impact of the restoration on the floodplain geomorphology: (i) changes in channel sinuosity, channel capacity and overbank flow frequency; (ii) fine sediment transport, hence the potential *supply* of fine sediment to the floodplain; (iii) patterns and rates of overbank sediment deposition; (iv) patterns and rates of overbank sediment erosion; and (v) retention of wood.

9.2 Restored floodplain processes

Results from the process monitoring before and after the restoration enabled improvements to be made to the conceptual model of floodplain processes based on an understanding of the geomorphological processes that operated on the restored floodplain (Figure 9.3), discussed below.

9.2.1 Fine sediment transport, deposition and erosion

The results from Chapter 6 demonstrated that the restoration increased suspended sediment concentrations at the Restored site (planform restoration, Site 2) during the first flood season following the restoration. Suspended sediment concentrations were also likely to have increased downstream at Site 3 (wood jam restoration), although this was not certain due to the poor calibration of the Site 3 year 1 suspended sediment data. The monitoring demonstrated that during the second winter after the restoration (year 3), suspended sediment concentrations fell, but not quite back to pre-restoration levels, indicating that the system was rapidly recovering from the disturbance caused by the restoration, but that it had not yet fully recovered.

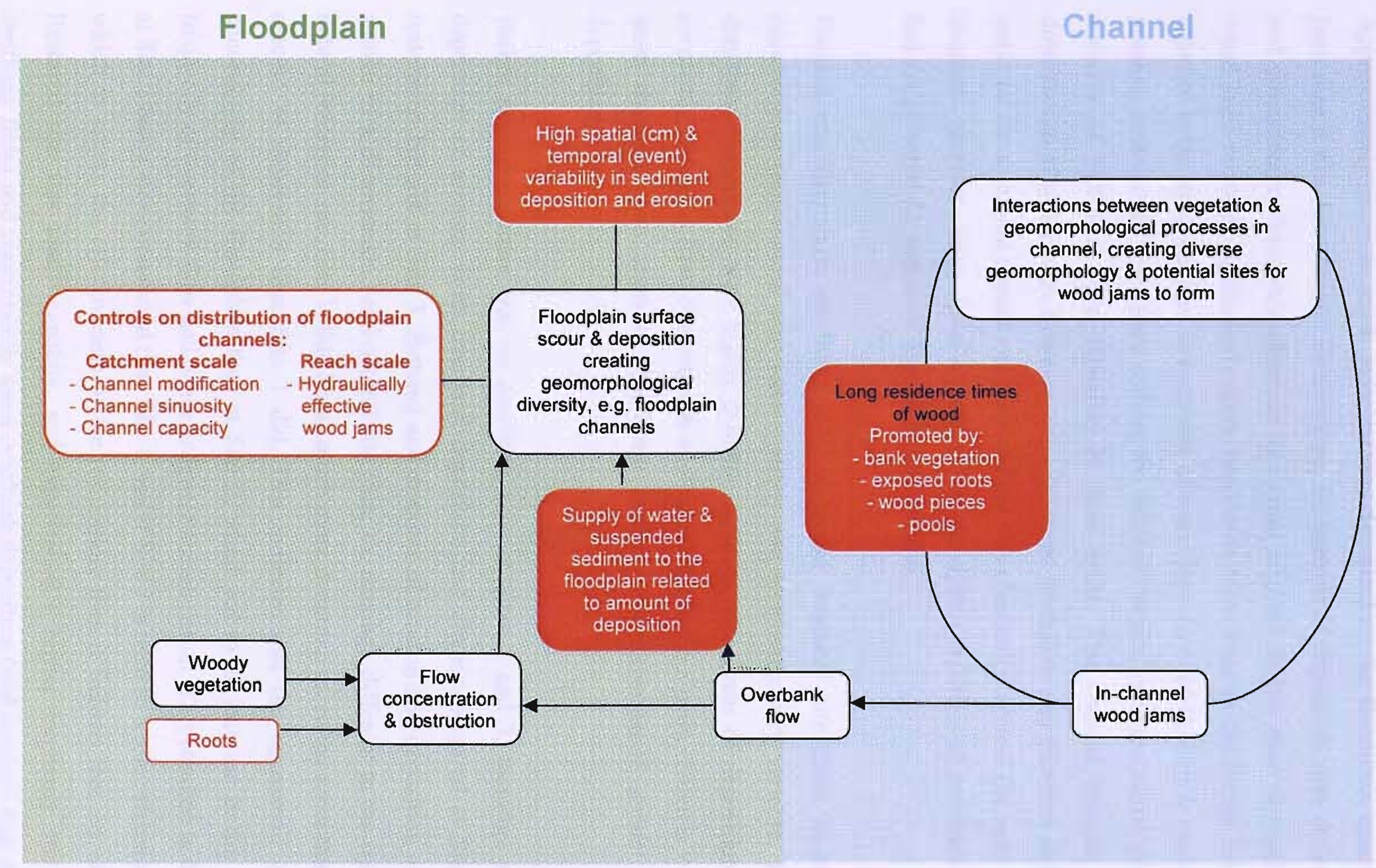


Figure 9.3 Conceptual model of interactions between vegetation and geomorphology in a lowland, temperate semi-natural forested floodplain improved through field observations (red outline) and through **monitoring processes post restoration (red background).**

High suspended sediment concentrations at the Restored site also meant a large supply of fine sediment to the floodplain. The amount of inorganic sediment deposition on the floodplain, at the event scale, was closely related to the supply of water and suspended sediment to the floodplain; the distribution across the floodplain, however, was strongly controlled by a combination of wood jams and floodplain channels.

Approximately twice as much sediment was deposited on the floodplain upstream of wood jams than it was downstream. Furthermore, the patterns of deposition were different upstream and downstream: floodplain channels and areas adjacent to the main channel upstream of wood jams received significantly more deposition than areas of floodplain surface or areas adjacent to the main channel downstream of wood jams ($p < 0.01$). This is explained by flow ponding upstream of wood jams causing the channel margins to be inundated, and hence large amounts of sediment were deposited in these areas. The channel margins immediately downstream of wood jams, however, were sheltered from flow and therefore did not have the potential for sediment deposition; instead flow was channelled around the jams in floodplain channels, therefore more distal regions of the floodplain experienced overbank flow and so had the potential for sediment deposition and erosion.

Erosion and deposition on the floodplain at the Restored site (Site 2) and at Site 4 (downstream semi-natural site) were spatially and temporally very variable. This indicates that these floodplains were highly dynamic surfaces, with areas of deposition and erosion constantly changing from one event to another, although floodplain channels were generally more dynamic than areas of floodplain surface, and experienced greater erosion and deposition.

Before restoration there was no overbank flow at Sites 2 and 3, therefore there was no deposition or erosion. Both overbank deposition and erosion occurred at Site 2 after the restoration but not at Site 3. Patterns and amounts of erosion and deposition at Site 2 were similar to a downstream semi-natural site (Site 4), although different to the upstream semi-natural reference site, Site 1. Site 2 was much more dynamic, receiving more than 7 times the amount of deposition than Site 1 did. This indicates that the restoration increased the connectivity of the floodplain than at Site 2, which led to an increase in the duration and frequency of overbank flow and hence sediment accumulation. This resulted in the floodplain at Site 2 being *more* connected than Site 1, and if Site 1 is used as a true reference site against which to assess the effectiveness of the restoration, then it follows that the channel at the Restored site was *under* capacity, and experienced a higher frequency and duration of overbank flows and consequently more overbank deposition (and erosion) than the Reference site did. The creation of a low-capacity channel was part of the restoration design, partly due to the importance placed on re-connecting the floodplain, and also because a smaller capacity focuses much of the available energy within a smaller channel cross-section which effectively provides excess stream power that the channel could use for self-adjustment to a stable regime. Therefore, longer term monitoring is required to determine if the channel does self-adjust or if it remains under-fit.

The lack of overbank flow and deposition experienced on the floodplain at Site 3 (restored with wood jams) post-restoration indicates that the addition of wood jams alone was not effective at promoting floodplain connectivity and dynamic floodplain geomorphology. However, the wood jams were effective at increasing retention of small wood, particularly during the first flood season after restoration (Chapter 8).

The type of 'vegetation trap' was found to influence the amount of overbank deposition, with more deposition on Astroturf and Bracken traps than on 'Long Grass' and Plain traps. This has implications for restoration, as different types of vegetation on the floodplain are likely to trap different amounts of sediment. Large amounts of sediment (and potentially seed propagule) deposition may be promoted by establishing dense, low-level vegetation on the floodplain, rather than open, bare surfaces, or surfaces with higher level, sparse vegetation.

9.2.2 Wood retention

The dowel tracing experiments showed that the planform restoration (Site 2) and wood jam restoration (Site 3) generally reduced small wood travel distances; however, travel distances increased at Site 1 after restoration that involved channel infilling due to wood jam burial. Wood jams were the most important trapping location, trapping 31.2% of the total dowels retrieved within the study reaches. Other important trapping locations were pieces of natural wood in the channel (14%); bank vegetation (12.5%); pools (12.3%); the main floodplain (as apposed to more lower-lying, incipient floodplain) (10.7%); and exposed roots in the channel banks (10.5%). The results from this experiment indicate that the floodplain was an important store of small wood, highlighting the importance of channel-floodplain connectivity for long residence times of organic material.

Thus the process monitoring results have improved our understanding of the geomorphological processes operating in these forested floodplains, and have enabled further improvement of the conceptual model (Figure 9.3). One aspect of the floodplain geomorphological processes that was not recognised before the monitoring was the extremely high spatial (10^{-1} m) and temporal (event scale) variability in sediment deposition and erosion that was found on the floodplain in some reaches (particularly those associated with Type 3 floodplain channels and hydraulically effective wood jams in the main channel). Furthermore, it has been established that both deposition and erosion occurred in floodplain channels, although they are fundamentally erosional features. A close association between the supply of water and suspended sediment to the floodplain and floodplain deposition at the event scale was observed. This work has also identified the most important mechanisms that retain small wood, namely wood jams, the floodplain (through floodplain-channel connectivity), pools, wood, exposed roots in channel banks, and bank vegetation.

9.3 Scientific context

This section places the findings of the research into a broader context by viewing the floodplain as a shifting mosaic of processes, features and physical habitats that operate over a range of scales and support high geomorphological and ecological diversity (e.g. Naiman and Decamps, 1990; Amoros and Petts, 1993; Malanson, 1993; Naiman *et al.,* 1993; Marston, *et al.,* 1995; Ward, 1998; Ward *et al.,* 2002; Steiger *et al.,* 2005; Thoms, 2006). Different species favour different habitats, so diverse habitats create the potential for a wide range of species to exist on the floodplain. Regular disturbances (e.g. flooding) ensure that the habitats constantly change and inhibit vegetation succession leading to one dominant species (Salo *et al.,* 1986; Naiman *et al.,* 1993).

This work has focused on identifying physical habitats and processes in the riparian zone at the patch, feature, reach, segment and catchment scales (Frissell *et al.,* 1986) (Table 9.1), and understanding the processes that are responsible for their formation. Many researchers have found high levels of biodiversity associated with diverse habitat mosaics (e.g. Salo *et al.,* 1986; Naiman *et al.,* 1993; Gilvear and Willby, 2006) but unfortunately, monitoring the biodiversity resulting from these diverse habitats was beyond the scope of this thesis.

Table 9.1 Features observed on New Forest floodplains scaled according to Frissell *et al.*'s (1986) model of physical habitats.

Scale	Feature
Patch / Micro (10^{-1} - 10^{0} m)	Topographic variations in the floodplain surface resulting from overbank erosion and deposition.
Meso / Feature (10^{0}- 10^{1} m)	Wood jams, wood accumulations and scattered wood on the floodplain, scour hollows, trees, bushes, herbaceous vegetation, exposed roots, floodplain channels.
Reach (10^{1} – 10^{2} m)	Floodplain channels, areas of floodplain surface (islands between floodplain channels).
Segment (10^{2} – 10^{3} m)	Semi-natural and modified stretches of channel.
Catchment (10^{3} m)	Distribution of reaches where floodplain channels were present and absent.

Diverse physical habitats were found in semi-natural reaches throughout the catchment, and were identified and mapped at the reach-scale. They consisted of floodplain channels of different dimensions, ranging from a few centimetres deep and 10 cm wide, to more than 1 m deep and 2 m wide, but most commonly they were approximately 10 cm deep and 50 cm wide. The distribution of floodplain channels was mapped at the catchment-scale, and the following characteristics were identified as being important controlling factors of floodplain channel development: floodplain connectivity, channel sinuosity, bank height, and the presence of hydraulically effective wood jams; floodplain width and floodplain vegetation type were not found to be important.

Other physical habitats observed in semi-natural reaches included areas of floodplain surface at a higher elevation than the floodplain channels, floodplain scour hollows (varying in size but approximately 1 m deep and 1 m diameter), trees, bushes and herbaceous vegetation, exposed tree roots, and single wood pieces and accumulations of wood. These diverse physical habitats were created by (and also influenced) processes of scour and deposition that were characterised by their extremely high spatial and temporal variability.

The research findings addressed key concepts identified within the literature that help to describe and explain the shifting mosaic of habitats observed on the floodplains of semi-natural streams in the New Forest. The following concepts identified within the literature are addressed within this thesis: (i) the importance of lateral floodplain-channel connectivity to support a dynamic floodplain (e.g. Ward and Stanford, 1993; Hughes, 1997; Ward *et al.*, 1999; Ward *et al.*, 2002; Amoros and Bornette, 2002); (ii) patterns and processes of floodplain sediment deposition (e.g. James, 1985; Pizzuto, 1987; Asselman and Middelkoop, 1995; Marriott, 1998) and how it is complicated by topography (e.g. Nicholas and Walling, 1997a; Middelkoop and Asselman, 1998; Walling and He, 1998; Steiger *et al.*, 2001b) and vegetation (e.g. Zwolinski, 1992; Harwood and Brown, 1993; Piégay, 1997: Piégay *et al.*, 1998; Jeffries *et al.*, 2003); (iii) wood retention and the mechanisms that influence its retention (e.g. Swanson and Lienkaemper, 1978; Bilby, 1984; Gregory *et al.*, 1991; Gregory, 1992; Fetherston *et al.*, 1995; Gurnell *et al.*, 2000; Gurnell *et al.*, 2002); and (iv) magnitude and frequency of flows that shape the floodplain (e.g. Wolman and Miller, 1960; Pickup and Warner, 1976; Nanson, 1986; Costa and O'Connor, 1995; Warner, 1997).

9.3.1 The importance of lateral channel–floodplain connectivity to support a dynamic floodplain

The importance of channel-floodplain connectivity to support dynamic floodplain habitats has been widely recognised (Steiger *et al.,* 2005). Channel-floodplain connectivity provides pathways for the transfer of energy and the migration of organisms between the main channel and the floodplain, and maintains high habitat diversity and hence biodiversity (Ward and Stanford, 1993). In areas of high channel-floodplain connectivity, overbank flows deposit nutrients, seed propagules (Hughes, 1997; Goodson *et al.,* 2001) and other vegetative particles (Gurnell, 2007) onto the floodplain, promoting vegetation regeneration and the production of more organic material through photosynthesis; therefore organic matter cycling continues, and there is a turnover of vegetation that influences, and is influenced by, physical processes. Furthermore, overbank flows erode inorganic sediment and remove wood from the floodplain, and deposit inorganic sediment and wood onto the floodplain. Thus channel-floodplain connectivity promotes the development of diverse physical habitats on the floodplain.

This study has found that lateral channel-floodplain connectivity was promoted by in-channel wood jams, high channel sinuosity, and small channel dimensions in relation to discharge; floodplain channels were observed more frequently in reaches with these characteristics. Additionally, overbank flows were observed more frequently upstream of in-channel wood jams than downstream of them (as found by Jeffries *et al.,* 2003), and at the Restored site (Site 2) they only occurred after the restoration, when channel dimensions were reduced.

9.3.2 Patterns and processes of floodplain sediment deposition complicated by vegetation

Diverse physical habitats on the floodplain were created by floodplain deposition and erosion. Rates and patterns of deposition were monitored and found to differ significantly from traditional diffusion models of floodplain sedimentation on non-forested floodplains, but were similar to those found by Jeffries *et al.* (2003). According to the diffusion models of James (1985) and Pizzuto (1987), the majority of sediment is transported by turbulent eddies at the interface between the channel and floodplain, and these eddies detach themselves and diffuse away toward calmer areas of the floodplain. Floodplain flows are often incapable of transporting much sediment due to their shallow depths and high flow resistance and therefore low competence, hence sediment is deposited near the interface between the channel and floodplain, with coarser grains deposited first (James, 1985; Pizzuto, 1987; Asselman and

Middelkoop, 1995; Marriott, 1998). The thickness of overbank deposits and the calibre of sediment deposited therefore decreases exponentially with distance from the channel (Pizzuto, 1987; Marriott and Alexander, 1999; Zwolinski, 1992).

These simple diffusion models of floodplain deposition fail to replicate fully the spatial variability in deposits, grain size, and hence physical habitat, as they do not take into account local variations in topography or vegetation that exist on natural floodplains. Nicholas and Walling (1997a) propose a model for floodplain inundation sequences and patterns of deposition that incorporates floodplain topographic complexity. From their predictive model and from field data, they found that suspended sediment transport processes within the channel belt were dominated by longitudinal convective currents resulting in high concentrations of suspended sediment and high rates of overbank deposition in this area. Outside the channel belt convective currents were perpendicular to the channel and weaker, therefore suspended sediment transport was dominated by diffusive mechanisms. Sediment concentrations and deposition rates were highly spatially variable, with patterns controlled by local and distant floodplain topography.

Although the inclusion of topographic variations renders Nicholas and Walling's (1997a) model more physically realistic than early diffusion models, it is still does not explain patterns of deposition in the forested floodplains studied here, where overbank deposition was found to be influenced by vegetation in the channel and on the floodplain. For example, different amounts and patterns of sediment deposition were observed upstream and downstream of wood jams due to flow ponding upstream and the development of floodplain channels, and flow sheltering immediately downstream; different types of vegetation on the floodplain (represented by different types of sediment trap) were found to trap significantly different amounts of sediment (e.g. as found by Brown, 1996).

The very high spatial and temporal variability of deposition and erosion on the floodplain demonstrated the processes involved in the creation of the diverse shifting habitat mosaic observed at the patch scale (10^{-1} - 10^{0} m) on semi-natural floodplains in the New Forest.

9.3.3 Retention of small wood

Retention of organic material is important for nutrient cycling, habitat diversity and biodiversity. High retention allows organic matter to accumulate and to be processed to small particles and dissolved organic carbon (DOC) before it is transported downstream (Bilby and

Likens, 1980; Bilby, 1981; Naiman, 1982; Allan, 1995), leading to hotspots of biological activity (Allan, 1995). For example "shredders", who feed on coarse particulate organic matter (CPOM), appear in greater abundance in streams or reaches that have long residence times of organic material (Winterbourn and Townsend, 1980).

Retention of wood plays an important role in the shifting mosaic of habitats on the floodplain. When it is retained in the channel it may form in-channel wood jams that promote overbank flow and hence sediment deposition and erosion; it also forms accumulations on the floodplain that affect the pathway of flow. Wood on the floodplain is dynamic (Piégay, 1997), changing in orientation and position, and hence its influence on flow pathways and patterns of sediment deposition and erosion changes, affecting the shifting habitat mosaic. Wood pieces themselves also form important habitats for invertebrates and fish (e.g. Harmon *et al.*, 1986).

Some variables that control wood retention have been identified within the literature, e.g. habitat heterogeneity, stream power and location within the catchment (Gregory *et al.*, 1991). This work has identified wood jams and channel-floodplain connectivity to be particularly important in retaining small wood in the study sites, further demonstrating the importance of lateral channel-floodplain connectivity for the proper functioning of the river-floodplain system.

Quinn *et al.* (2007) argue that the relative importance of different factors at retaining CPOM vary with region and landuse. Similarly, the importance of different mechanisms at retaining wood is likely to be a function of the size of wood pieces and the size and nature of the river and its riparian zone. For example, on rivers with fewer wood jams (perhaps due to the width of the river being larger than the average height of the trees in the riparian corridor, or due to the absence of trees on the floodplain, or, more often, due to river management), bank vegetation may be more important than wood jams in retaining wood pieces.

9.3.4 Magnitude and frequency of floodplain forming flows

Within the literature there is much discussion concerning the magnitude and frequency of events that shape the landscape. In some environments the landscape is shaped predominantly by relatively frequent events of fairly low magnitude (e.g. bankfull flow, occurring once every year or two years, is often thought to be the most important flow for shaping alluvial channels (Wolman and Leopold, 1957; Wolman and Miller, 1960; Dunne and Leopold, 1978)). Friedman *et al.* (2005), for example, describe floodplain development on the Rio Puerco, New

Mexico as taking place during brief overbank flows that occur every few years. In other environments, rare events of a catastrophic magnitude are more important. In rivers in confining bed-rock valleys, for example, erosion only occurs during high-magnitude, low-frequency events, but accretion occurs more gradually during less extreme conditions (Nanson, 1986; Nanson and Croke, 1992).

Warner (1997) suggests that rivers in southeast Australia are subject to changing regimes between flood dominated (FDR) and drought dominated (DDR), that can last for periods of up to 50 years. The author argues that floodplains on these rivers only experience significant erosion and deposition during FDRs; during DDRs the main floodplain is inundated very infrequently, and becomes isolated from the channel and therefore can be considered a terrace. Incipient floodplain may form in the channel during DDRs.

Lowland cohesive floodplains (as found in the New Forest) are predominantly formed by vertical accretion of overbank deposits (Nanson and Croke, 1992) and experience very slow rates of lateral migration (as observed by Jeffries *et al.,* 2003). Therefore overbank flows are the most important flows controlling the processes that form these floodplains, resulting in the shifting habitat mosaic already discussed. Consequently, the magnitude and frequency of these flows is important in understanding the development of the floodplain.

Flow data from the Restored site (Site 2) have only been collected since the winter of 2003/2004, however, flow records dating back to 1960 were available from the Environment Agency for a gauging station 15 km downstream at Brockenhurst. Therefore a flow duration curve was constructed from the Brockenhurst gauging station data from 1960 to 2006 (Figure 9.4). Since restoration, overbank flow at the Restored site was initiated at a discharge of approximately 0.33 m^3s^{-1} (upstream of the wood jam), which corresponded to a discharge of 6.43 m^3s^{-1} at Brockenhurst if a constant relationship between catchment area and discharge is assumed (e.g. Gurnell *et al.,* 2000).

From Figure 9.4 it can be seen that since 1960, flows that could influence the floodplain at the Restored site (based on its dimensions since restoration) occurred on average three percent of the time (or 11 days a year). Flows of this magnitude have a recurrence interval of 0.13 years, which is considerably lower than average recurrence intervals of overbank flows recorded within the literature (e.g. 1-2 years (Leopold *et al.,* 1964), 1.5 years (Mosley, 1981), and 1.2-2.7 years (Woodyer, 1968)), highlighting the importance of wood jams at promoting overbank flow, and the fact that the channel was undersized and so overbank flow occurred at a lower discharge and hence higher frequency than would normally be expected.

Before restoration, a discharge of approximately 7.35 m^3s^{-1} was required at the Restored site for overbank flow - this corresponds to a discharge of 158 m^3 s^{-1} at Brockenhurst, which is nearly five times larger than the highest average daily flow recorded since 1960. Therefore, one can be confident that overbank flow would not have been experienced at Site 2 since the channel was modified (between 1960 and 1970). It needs to be kept in mind that the flow duration curve represents average daily flow, and individual flood events may have reached higher peaks, particularly as the river had such a flashy hydrological regime. However, it is still highly unlikely that such high discharges would have occurred. Furthermore, no evidence of floodplain flow at Site 2 had been observed prior to the restoration despite there being two separate surveys that focused on floodplain connectivity (Jeffries, 2002 and GeoData, 2003). Thus, all the available evidence indicates that before restoration the floodplain was disconnected from the channel and did not receive overbank flow.

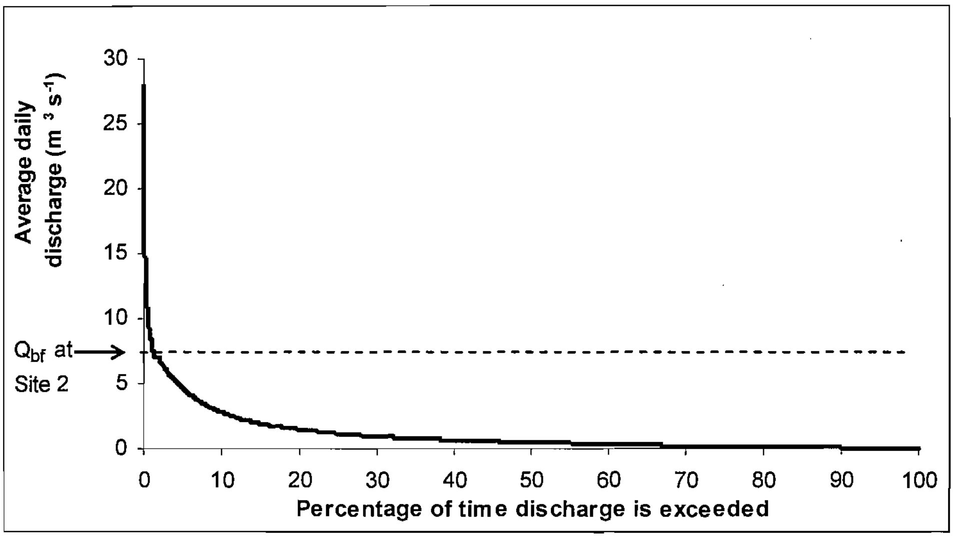


Figure 9.4 Flow duration curve from Brockenhurst gauging station data from 1960 to 2006, indicating discharge at which overbank flow is initiated at the Restored site (Site 2).

To put the two flood seasons that have been monitored after the restoration into context, the peak average daily discharge recorded at the Brockenhurst gauging station during 2004/2005 was 13.4 m^3s^{-1}, and during 2005/2006 it was 14.3 m^3s^{-1}, compared with a maximum average daily discharge of 28 m^3s^{-1} since 1960. Therefore, in extreme cases the discharge may reach twice that recorded during the two flood seasons after the restoration. Based on an understanding of floodplain processes gained from this thesis, together with research carried out on the Highland Water by Jeffries *et al.* (2003) during the 2000 floods, it is proposed that under such extremely wet conditions, floodplain geomorphological processes (particularly overbank deposition and erosion) would be likely to increase significantly (e.g. see rates of deposition recorded by Jeffries *et al.* (2003) at Millyford for 2000/2001 in Table 6.9).

9.3.5 Summary of scientific context

In floodplain forests, water, sediment and vegetation interact to form a suite of processes distinct from those observed in non-forested floodplains (Gurnell, 1997; Piégay, 1997). Within this general concept lie detailed and varied interactions, some of which differ according the size of the river in relation to the height of the trees within the riparian corridor. In 'large' rivers, e.g. the Queets River, Washington state; the McKenzie River, Oregon; the Drome, France; and the Tagliamento, Italy, where the channel width is greater than the average tree height, wood is generally mobile unless it is anchored at the margin of the channel or in a complex accumulation of other pieces of wood (Gurnell *at al.,* 2002). In 'small' rivers, where channel width is less than the average tree height, however, large wood mobility is very limited, and trees that fall into the channel are more likely to block the entire width of the channel, and remain in place (unless removed by humans) until they are broken down into smaller, more mobile pieces of wood, or decompose. Consequently, in small rivers the effect of vegetation on channels may be overwhelming (Hickin, 1984), and in such a small, lowland system as the New Forest, where wood pieces are frequently much longer than the channel width, vegetation has the potential to control, rather than respond to, the hydrological and geomorphological characteristics of the river (Gurnell *et al.,* 2002). Furthermore, tree roots play an important role in hindering erosion through reducing the erodibility of the floodplain surface (De Baets *et al.,* 2006).

The majority of rivers where floodplain habitats and processes arising from interactions between vegetation, water and sediment, have been studied, are much larger than the systems studied in this research, e.g. the Tagliamento (Gurnell *et al.,* 2001), with floodplains that are hundreds of metres wide. The habitats and processes observed along New Forest streams were very different to those found in larger systems. For example, Gurnell *et al.* (2000) report extensive destruction and establishment of wooded islands (of up to 1 km^2 in size) over a period of seven years between 1984 and 1991 on the Tagliamento, Italy. In contrast, this work and research by Jeffries *et al.* (2003) has demonstrated that semi-natural New Forest streams are generally much less dynamic over this length of time, and are laterally very stable (Jeffries, 2002). However, this work has shown that semi-natural and restored floodplains are dynamic at the scale of 10^{-1} to 10^{1} m, particularly in the vicinity of hydraulically effective wood jams, where floodplains may experience depths of erosion and deposition in the order of centimetres over one flood season.

This section has demonstrated that floodplain forming flows at the Restored site after the restoration are likely to be of fairly low magnitude (0.33 m^3s^{-1}) and high frequency (over approximately 11 days a year). If the restored channel increases its capacity over time through self-adjustment processes, then larger, less frequent flows may be required to influence the floodplain. However, the discharge required for overbank flow is not only dependent upon channel capacity but also on the presence of in-channel hydraulically effective wood jams, as demonstrated by this thesis and by Jeffries *et al.* (2003). Therefore, even if the channel does increase its capacity, if hydraulically effective wood jams establish then the discharge required for overbank flow may remain low.

9.4 Evaluation of restoration: constraints and recommendations

This intensive monitoring programme, which was undertaken as part of the LIFE 3 New Forest Restoration project, provides an opportunity to identify constraints and recommendations of the restoration design, construction, and the monitoring programme that can be used to inform future restoration projects involving forested floodplains. The thesis therefore contributes to the evolution of restoration design and monitoring techniques.

9.4.1 Restoration design

The LIFE 3 restoration project involved re-meandering a total of 10 km of stream length and was one of the largest restoration projects in the UK (New Forest LIFE 3 Final Technical Report, 2006). As the restoration covered such a large area, the restoration design was particularly important. Furthermore, even though it was a large project (£2.9 million), resources were still limited, and the restoration design had to take into account that not all modified areas could be restored through channel re-meandering.

The restoration design that was undertaken was an integrated, catchment-scale approach, that involved river channel restoration (primarily focusing on reconnecting the floodplain), felling conifers and removing non-native species (e.g. rhododendron), and opening up selected areas of inclosure to grazing. The principal method by which the floodplain was reconnected was through channel infilling and the re-occupation of former meander bends that were still visible on the floodplain. In a few instances it was not possible to re-connect former meander bends (e.g. when old meanders could not be located) in which case new meanders were cut. Channel re-meandering was undertaken in reaches where this level of restoration was anticipated to be the most effective, for example in the most degraded (heavily incised) reaches, and in upstream reaches to halt headward migration of incision. Less intensive restoration measures were undertaken in less severely modified reaches, in the form of wood jam emplacement.

The restoration design benefited by being informed by extensive baseline data, including research into the interaction of wood with channel and floodplain processes (e.g. Gregory *et al.,* 1985; Gurnell and Sweet, 1998; Jeffries *et al.,* 2003); and catchment-wide characterisation of the channel and floodplain geomorphology (GeoData, 2003).

The process monitoring described in this thesis indicates that the re-meandered channel (at Site 2) was under-sized in relation to an upstream semi-natural reference site, resulting in higher frequencies and durations of overbank flows and consequently high erosion and deposition rates. However, the channel was designed to have a small capacity to allow flows to have adequate energy to re-shape it. If the channel remains undersized, prolonged periods of flooding and exaggerated floodplain erosion and deposition may occur, however these outcomes can only be determined through an extended monitoring period.

Locations where former meander bends could not be re-connected and new channels were cut were not monitored in detail, but after the restoration there was less evidence of overbank flow (e.g. trashlines) in these reaches than in reaches where old meander bends were re-connected. This is likely to be due to the newly-cut channels having larger dimensions, and therefore requiring higher discharges for overbank flow, than the re-occupied old meander bends.

Observations discussed within this thesis have highlighted that it may have been beneficial to consider the depth of fine material overlying gravel when selecting the exact locations of the new meander bends during the restoration design. Observations have shown that, other than hydraulic effectiveness and wood jam age, the development of floodplain channels into channels that function like the main channel (e.g. have a gravel bed and bars), is also likely to be related to the depth of fine material above the gravels in the floodplain. In some places this was not very deep (+/- 30 cm), so floodplain channels could easily scour down to gravel, creating deep floodplain channels; in other places, fines were deeper (+/- 1 m), rendering floodplain scour more difficult. Obviously the ease with which floodplain scour can penetrate to gravel also depends upon characteristics of the main channel (e.g. discharge, bed slope, channel width and depth). Furthermore, fine deposits may build up from overbank flow, instigating positive feedback, whereby it becomes still more difficult for flows to scour into gravels as the depth of fines increases.

These observations have implications for the restoration. It has already been noted that the principal method of channel change was through channel cut-offs (Jeffries *et al.*, 2003), and for cut-offs to form, the floodplain needs to be scoured down to the same depth as the former main channel (i.e. to gravel). Therefore, if a new channel is cut during restoration in a position where the depth of fine sediment it is too deep for scour to reach gravel, the development of channel cut-offs may not be possible, limiting the effectiveness of the restoration.

The monitoring results have shown that restoration that only involved the addition of wood jams was ineffective at re-connecting the floodplain. This could be due to the wood jams being 'complete' rather than 'hydraulically effective', and discussions within this thesis have demonstrated the importance of hydraulically effective wood jams (particularly those based on living trees) for promoting floodplain connectivity, and using such jams to re-connect the floodplain could be a useful measure in future restoration projects. However, the wood jams were effective at reducing transport distances of small wood, particularly during the first flood season after their emplacement.

9.4.2 Restoration construction

The restoration construction work was carefully planned in order to cause minimal damage to the channel and floodplain physical and ecological habitats. The work was scheduled to be undertaken during the summer months when flows were at their lowest. This ensured that detrimental impacts of downstream transport of large quantities of fine sediment (e.g. smothering gravels) were kept to a minimum. It also meant that the floodplain was as dry as possible when heavy machinery crossed it, and so avoided excessive damage to the floodplain material (New Forest LIFE 3 Final Technical Report, 2006). Wherever possible, vehicles kept to the same routes to reduce the area impacted.

Details of the dates of the restoration works were reported in Table 4.3. The restoration works were unavoidably delayed for several reasons: firstly a freshwater mud snail (*Lymnaea glabra*) was observed in a former meander bend on the Blackwater, and this meant that the meander could not be re-connected until other populations of the snail were identified; and secondly DEFRA (Department for Environment, Food and Rural Affairs) requested an

Environmental Impact Assessment to be undertaken, which delayed some of the channel restoration works.

Despite the unavoidable delays in the restoration works, prolonged detrimental impacts from the construction work itself were not observed. For example, although suspended sediment concentrations were raised during the flood season immediately following the bulk of the restoration at Site 2, by the second flood season they had fallen almost back to pre-restoration levels. Additionally, the heavy machinery did not cause lasting damage to the floodplain, and vegetation already started to re-establish during the summer after the main restoration works (New Forest LIFE 3 Final Technical Report, 2006).

9.4.3 Restoration monitoring

Lessons learned from restoration monitoring

The positive and negative elements of the New Forest restoration monitoring programme can be used to inform future restoration projects.

The restoration monitoring enables a contribution to be made to defining reference conditions for forested headwater channel/floodplains. Table 9.2 updates reference conditions that were identified within the literature (Section 3.6) based on the research findings presented in this thesis.

Table 9.2 Reference conditions identified from the literature and updated from the research findings

Reference conditions identified from the literature	Modifications to reference conditions based on research findings
Geomorphologically diverse channels with wood jams present.	Reference conditions identified from the literature plus the following: sinuous channel planform; different types of wood jams present in the channel; living trees that form hydraulically effective and long-lived wood jams; diverse channel geomorphology and channel-floodplain connectivity providing small wood trapping sites.
Long residence time of organic material promoting high nutrient processing and diverse ecology.	Long residence times of small and large wood is important for processes but nutrient processing and ecology were not monitored.
Frequent overbank flow, particularly in the presence of wood jams.	Overbank flow is not ubiquitous but is locally frequent upstream of hydraulically effective wood jams.
Diverse floodplain geomorphological processes (overbank sediment deposition and erosion) creating complex floodplain geomorphology (e.g. floodplain channels).	Reference conditions identified from the literature plus the following: both deposition and erosion occur in floodplain channels; processes occur at a small temporal (event) and spatial (cm) scale, and are more dynamic in floodplain channels than on the floodplain surface. More sediment deposition occurs on the floodplain upstream of hydraulically effective wood jams than downstream of them.
Diverse vegetation on the floodplain linked to geomorphological processes, e.g. seedlings established in sediment deposits.	Different types of low-level vegetation on the floodplain trap different amounts of sediment, with rough low-level vegetation (e.g. short grass) trapping more than taller herbs (e.g. Juncus sp.). A proportion of the overbank deposition is organic (approx. 10% by dry weight). The influence of processes on vegetation was not monitored.
	Sediment deposition on the floodplain is closely related to the supply of water and fine sediment to the floodplain which is in turn related to hydraulically effective wood jams (see above).
	Fine sediment transport is largely restricted to storm flow, and compared with other UK rivers the annual yield per unit catchment area is low (see Figure 6.11).

Other positive elements of the monitoring were that; (i) it was an integral part of the wider restoration project, and so it was allocated time and resources, which meant that monitoring was undertaken before and after the restoration, and therefore the effects of the restoration could be clearly identified; (ii) extensive baseline data were available which helped identify appropriate sites and variables to monitor; (iii) it was designed to be multidisciplinary, incorporating geomorphology (Sear *et al.,* 2006; Millington and Sear, 2007; this thesis); hydrology and hydraulics (Sear *et al.,* 2006; Kitts, in prep.); and ecology, including macro-invertebrates, fisheries, wading birds, and vegetation communities (New Forest LIFE 3 Final Technical Report, 2006); (iv) it covered the spatial scales that rivers function within, ranging from the patch-scale to the catchment-scale (e.g. Frissell *et al.,* 1986); and it covered as wide a range of temporal scales as possible, from one event to one flood season; (v) it was undertaken at multiple sites, including the Restored site (Site 2), a Reference site (Site 1), a Control site (Site 3 which later became a site restored with wood jams), and a particularly dynamic semi-natural site with a hydraulically effective wood jam (Site 4). This ensured that differences in processes recorded at the Restored site before and after restoration that were not recorded at the Reference site could be attributed the restoration measures rather than to the natural variability in conditions. Monitoring multiple sites also provided a better understanding of how semi-natural floodplains in the New Forest functioned, which enabled the Restored site to be contextualised within a range of more or less dynamic floodplains (dependent on the level of floodplain connectivity); and (vi) an adaptive monitoring strategy using an approach focused at different scales within the nested spatial and temporal hierarchy displayed by river systems (Frissell *et al.,* 1986) provided robust monitoring. This approach was also flexible (e.g. monitoring overbank deposition at the event scale in years 1 and 2, and then reducing this to the flood season in year 3), which maximised the scientific knowledge gained from monitoring a complex natural system using finite resources.

A distinct challenge at the outset of the restoration monitoring was the limited existing scientific understanding of the geomorphological processes functioning on New Forest floodplains, despite the extensive baseline data that was available. This was a challenge for restoration monitoring, because it meant that an experimental / research aspect was necessary as part of the monitoring programme. More positively, however, this represented a good opportunity for scientific research.

Constraints upon the restoration monitoring were the short time scales available for monitoring. The funding time scale meant that restoration work was scheduled for completion less than a year before the project end, which only permitted limited post-restoration monitoring. Longer term monitoring would have been useful, for example to determine if fine sediment concentrations fell back to pre-restoration levels, and to identify the effects of a wetter flood season on floodplain processes.

A further constraint of the monitoring programme was that wood jams were emplaced in the Control site (Site 3), turning it into a Restored site rather than a Control site. However, this was beyond the control of the monitoring personnel, and it meant that the effects of wood jam restoration alone could be monitored.

Constraints and recommendations associated with specific monitoring techniques

Stage and turbidity data

Stage and turbidity data were considerably more reliable from year 2 than from years 1 and 3, when more 'bad' data had to be deleted during data 'cleaning' (Chapter 6). This was because a very rigorous maintenance regime was in place during year 2, whereby probes were cleaned and equipment was checked often as frequently as once a week. Such a high level of maintenance was not possible during years 1 and 3, when equipment was checked approximately once every fortnight. The improved quality of data obtained during year 2 compared with years 1 and 3 highlights the benefits of regular equipment maintenance, however, the extra time spent maintaining equipment needs to be taken into account when designing a monitoring programme.

Further constraints with the stage and turbidity data were associated with the challenge of obtaining sufficient water samples to calibrate the turbidity record, particularly during large floods due to the flashy nature of the hydrological regime. Manual and automatic water samples were obtained whenever possible in an attempt to overcome this constraint. Measuring discharge (in order to calculate stage-discharge relationships) during high flows of short duration at more than one site was also a challenge, as flows often started to recede before discharges could be measured at all sites. However, even though the stage-discharge relationships did not cover the entire range of flows experienced, they were sufficient to effectively demonstrate catchment-scale effects of the restoration on fine sediment transport. Difficulties encountered while measuring discharge in more than one site could be overcome by increasing the numbers of monitoring personnel, or by increasing the period over which monitoring is undertaken, and so increasing the opportunities to measure high discharges at each site.

Astroturf sediment mats

Advantages of using Astroturf sediment traps were that they effectively monitored floodplain deposition at a high spatial and temporal resolution at multiple sites. The use of Astroturf mats has become a standard technique to monitor floodplain deposition, therefore it was possible to compare the results with other published data and so contextualise them. However, various constraints were associated with the use of Astroturf mats. Firstly, changing the mats in the field was time consuming and it was not always possible to change them at all of the sites between every overbank event. Laboratory processing of the samples collected on the mats was also time consuming. Secondly, results from the 'vegetation' mat experiments indicated that the Astroturf mats may have been over sampling deposition, leading to higher rates of deposition recorded than if other types of sediment trap had been used instead. However, although this may influence the total deposition recorded, reliable comparisons can still be made of relative deposition between sites and upstream and downstream of wood jams.

Erosion pins

Vertical erosion pins in the floodplain surface were effective for monitoring short term changes in floodplain surface elevation, hence depths of erosion and deposition over a flood season. However, the erosion pins were not useful for monitoring longer term changes in the floodplain surface (over the whole flood season of 2005/2006) as very few could be re-located at the end of the flood season, largely due to vegetation covering them. Floodplain clearing and digging was necessary to locate them, which disturbed the pins and so removed the potential to use them to measure changes in floodplain surface elevation.

Dowel tracers

The use of in-channel dowel tracers at multiple sites before and after the restoration allowed the identification of important trapping locations for small wood, and confirmed the association between high wood retention and high geomorphological diversity. The dowels were both quick to deploy (one day for all three sites) and quick to retrieve (two days from all three sites). Constraints associated with using the dowels were that: (i) dowels did not replicate natural wood exactly as they were firmer and had no irregularities; (ii) dowel retrieval was fairly low during some trials (e.g. 36% at Site 2 during year 1); and (iii) public tampering was a possibility.

9.5 Summary

This chapter initially identified important geomorphological processes and interactions operating on forested floodplains based on the scientific literature. In-channel wood jams and floodplain vegetation were identified as particularly important elements promoting diverse floodplain geomorphology and long residence times of organic and inorganic material in channels and on forested floodplains. Field observations allowed the conceptual model of forested floodplain processes to be improved, and reach and catchment-scale controls on the distribution of floodplain channels (an important geomorphological feature observed on semi-natural forested floodplains in the New Forest) were identified. The importance of hydraulically effective wood jams for promoting overbank flow and hence the development of networks of floodplain channels was highlighted. Further improvements to the conceptual model were then made based on process monitoring before and after restoration. The monitoring identified high spatial and temporal variability in sediment deposition and erosion on floodplains, and a close association between the supply of water and sediment to the floodplain from overbank flow and floodplain deposition at the event-scale. Wood trapping sites that promoted small-wood retention were identified; the most important sites included in-channel wood jams, wood pieces, pools, floodplain connectivity, bank vegetation, and exposed roots in channel banks.

An evaluation of the restoration design, construction and monitoring can be used to improve future restoration projects. The restoration design focused on re-connecting floodplains and providing channels with energy that could be used for future self-adjustment. The monitoring revealed that channel-planform restoration was successful at re-connecting the floodplain, although channels may have been under-sized (and further monitoring is required to identify whether this action helps with self-adjustment); the re-introduction of wood jams alone was unsuccessful at re-connecting the floodplain. Although the restoration construction work faced unavoidable delays, it was successful in causing minimal damage to channel and floodplain physical and ecological habitats. Restoration monitoring faced challenges from an initial lack of understanding of geomorphological processes operating in forested floodplains in the New Forest, and from tight timescales, particularly post-restoration; however, it benefited from the availability of extensive baseline data, and from monitoring multiple variables at a range of sites at different scales before and after restoration.

This research has used a variety of robust methods for monitoring river/floodplain restoration. It would be impractical to continue implementing all of these techniques; however, certain techniques could be implemented as part of an on-going monitoring programme. Fine sediment transport could be monitored at just one site downstream of the restoration (Site 3) to determine the longer term influence of the restoration on fine sediment transport; rapid walk through surveys could monitor the development and chronology of wood jams in restored reaches; in order to identify the longer term development of floodplain channels, a topographic survey of the Restored Site (Site 2) could be undertaken every two to three years, and it would also be useful to identify the longer term adjustment of floodplain processes to the restoration by repeating the use of overbank sediment traps at the Restored Site at approximately the same interval; finally, as this study was carried out during a dry period, it would be useful to observe the system response to a wet period using some or all of the techniques identified above.

Chapter 10. Conclusions and recommendations for further work

10.1 Conclusions

The primary goal of this research was to monitor the geomorphological dynamics of a restored forested floodplain. This has been undertaken, and the results have demonstrated that before restoration the floodplain was disconnected from the channel and it did not receive overbank flow, hence there was no potential for geomorphological dynamism; during the two flood seasons that were monitored after the restoration, however, overbank flow did occur, and the floodplain demonstrated both spatial and temporal dynamism in terms of sediment deposition and erosion. Therefore it can be concluded that, over the time scale monitored, the increase in channel-floodplain connectivity indicates that the restoration was successful. However, the restored floodplain was considerably more connected and consequently more dynamic than an upstream semi-natural reference reach, indicating that the restored channel was undersized, the impact of which will require further monitoring to assess. Another impact of the restoration was to alter the dynamics of small-wood retention: adding wood jams was the most effective method of retaining small wood; re-meandering the channel planform also increased small wood retention; but wood retention was reduced by channel-infilling.

The second goal was to use the monitoring to further scientific understanding of the processes that arise from the interactions between water, sediment and vegetation, in a low order, temperate, lowland, semi-natural forested floodplain. This research has demonstrated that floodplain erosion and deposition were both spatially (from the patch to the reach scale) and temporally (event-scale) extremely dynamic, with vegetation playing an important role in influencing the geomorphological processes in forested floodplains. In-channel wood jams forced flow overbank and were important features for connecting floodplains. The formation of in-channel wood jams relies on the accumulation of wood. Experiments to investigate transport of small wood demonstrated that shorter transport distances were associated with higher in-channel geomorphological diversity, particularly the presence of wood jams, pieces of natural wood in the channel, bank vegetation, pools, channel-floodplain connectivity (wood was rafted onto the floodplain), and exposed roots in the channel banks.

Geomorphological complexity increases the retention of wood and is likely to promote the formation of wood jams, which result in overbank flow and increased floodplain connectivity. Observations showed that, on connected floodplains, floodplain channels were most frequent and well developed around hydraulically effective wood jams, with overbank flow being channelled between obstacles (particularly trees, accumulations of wood and topographic variations). Experiments into sedimentation and erosion showed that overbank flow scoured the surface and distributed sediment, and rates of erosion and deposition were higher within floodplain channels than elsewhere on the floodplain surface. These channels were therefore a major control over the spatial distribution of energy and materials on the floodplain surface at the patch, feature and reach scale (10^{-1} to 10^{2} m). At the catchment scale, the floodplain channels were not clearly related to catchment area; instead their distribution was influenced by channel-floodplain connectivity, which in turn was related to in-channel wood jams, channel dimensions, channel sinuosity and channel modifications.

Overbank deposition patterns on this forested floodplain therefore differed, both from traditional models of overbank sedimentation (e.g. James, 1985; Pizzuto, 1987), and from more refined models that take into account variations in topography (e.g. Nicholas and Walling, 1997a and b), as the models do not include the effects of vegetation, which had a great influence on floodplain geomorphology in this environment. A new model of forested floodplain geomorphology was therefore proposed, which included the role of wood and vegetation in controlling floodplain processes.

10.2 Recommendations for further work

A number of ideas have emerged from this thesis that are beyond its scope, but could potentially further scientific understanding of the geomorphological dynamics of a restored forested floodplain.

High rates of sediment deposition and erosion were observed on floodplains, particularly in floodplain channels, that were associated with hydraulically effective or 'active' (Gregory *et al.,* 1985) wood jams. High discharges forced flow onto the floodplain that provided the potential for floodplain deposition and erosion, however, high discharges also potentially remove in-channel wood jams, therefore reducing the potential for overbank flow and floodplain sediment deposition and erosion. This highlights the importance of wood jams that are constructed around living trees for floodplain processes – even if high discharges remove some of the organic material built up around a living tree, they is less likely to remove the living tree itself, unless the tree becomes uprooted or decays over time. Therefore, more material can build up around the tree in the future, re-building the wood jam.

The following questions therefore arise: are all hydraulically effective wood jams constructed around living trees? If not, how does the geomorphological diversity of floodplains associated with hydraulically effective wood jams that are constructed around living trees compare with the geomorphological diversity of floodplains associated with hydraulically effective wood jams that are not constructed around living trees? How do the ages of the jams compare? It is suggested that wood jams that are constructed around living trees will be older than those that are not, and therefore will be associated with move diverse floodplains. Also, human intervention occurs in most rivers in the UK, so what impact does woodland management have on the type of jams that are likely to form and, therefore, on floodplain geomorphology?

Given the relatively cohesive nature of the floodplain surface, and the fact that within the timescale of this thesis the formation of the largest floodplain channels could not be observed, longer-term monitoring of their formation to verify whether they do indeed need long-lived and hydraulically effective wood jams to form is recommended.

Further research into the mobility of wood, taking into account the roughness of the wood itself (e.g. multiple branches) could also refine our understanding of wood dynamics. Undertaking tracing experiments in a wider variety of rivers of different sizes and types (semi-natural, modified and restored) could provide a greater understanding both of wood dynamics (are New Forest streams typical of other lowland rivers) and of the likelihood of wood jam formation and, therefore, of how possible it is to re-connect (restore) floodplain processes using wood jams.

Increasingly it is being recognised that biotic and abiotic interactions are circular and developmentally intertwined (Stallins, 2006). For example, Chapter 6 demonstrated that different types of low-level floodplain vegetation are likely to trap significantly different amounts of sediment; what influence does this process have on the type of vegetation that subsequently develops and therefore on future sediment deposition? It would therefore be valuable to investigate the impact of floodplain geomorphology on vegetation dynamics, with the ultimate aim of exploring the full cycle of feedback between biotic and abiotic processes.

Research into ecological dynamics would also provide information on whether dynamic areas of the floodplain support different floral or faunal assemblages to stable areas that rarely experience overbank flows. For example, do fish use the floodplain channels to by-pass large wood jams during floods? Furthermore, do the floodplain channels support different invertebrate assemblages to those found in the main channel environments or in areas of stagnant water on the floodplain? Are variations in floodplain geomorphology important for birds, reptiles or mammals?

Finally, longer term monitoring of the restoration site itself is recommended, particularly as the flood seasons monitored after the restoration were dry years, and it would therefore be valuable to monitor how the restored system responds to a very wet flood season; this could have a crucial impact on the stability and processes associated with the under-sized channel.

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