**UNIVERSITY OF SOUTHAMPTON**
Faculty of Engineering, Science and Mathematics
School of Geography

# The Hydraulic and Hydrological Performance of Large Wood Accumulation in a Low-order Forest Stream

**By**

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# ABSTRACT

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
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THE HYDRAULIC AND HYDROLOGICAL PERFORMANCE OF LARGE WOOD ACCUMULATIONS IN A LOW-ORDER FORESTED STREAM

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Large wood and its accumulations are poorly understood despite being an important feature in the functioning of forested river channels and floodplains. Large wood has previously been removed from rivers in order to reduce flow resistance and increase channel conveyance. However, recently there has been an appreciation of the role of large wood accumulations in creating important aquatic habitat, increasing geomorphic diversity, re-connecting river channels to their floodplains and in the development of multi-channel anastomosed river patterns. This thesis examines the role that large wood plays at a range of scales in a low-order forested stream in the New Forest, Southern England. The study river was subject to restoration measures, involving the addition of large wood to the river channel, as part of an EU LIFE III project.

An empirical and Froude-scaled flume approach is taken to determine the role of large wood accumulations upon the reach-scale flow resistance values. Large wood accumulations from a variety of environments are assessed to determine the hydraulic effects of accumulations of different architecture in different environments. Field data from the study catchment is used to show the role of large wood in increasing the frequency and duration of reach-scale, floodplain inundation. Hydrological data shows the impact the restoration has upon both flood peak magnitude and flood peak travel time highlighting the potential benefits of large wood to downstream flood risk. A 2-Dimensional model is produced which simulates the effect of a range of large wood accumulations upon the inundation extent. An approach using spatial diversity metrics, widely used in ecological sciences, is conducted in an attempt to quantify the flow depth and flow velocity diversity, which can influence flow habitat diversity. Results show that large wood can initiate an anastomosing flow pattern which allows increases flow depth diversity by up to 49% and flow velocity diversity by up to 48%.

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# DECLARATION OF AUTHORSHIP

I, **DUNCAN RENFIELD KITTS**, declare that the thesis entitled '***THE HYDRAULIC AND HYDROLOGICAL PERFORMANCE OF LARGE WOOD ACCUMULATIONS IN A LOW-ORDER FORESTED STREAM***' and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
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- I have acknowledged all main sources of help;
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**Signed:** ……Duncan Kitts…………………………………………………..

**Date:**……… 9th...August 2010……………..………………………………

**This thesis is dedicated to my parents and grandparents who instilled in me my inquisitive nature and the desire to succeed.**

*Fortunately science, like that nature to which it belongs, is neither limited by time nor by space. It belongs to the world, and is of no country and of no age. The more we know, the more we feel our ignorance; the more we feel how much remains unknown.*

***Sir Humphry Davy, discourse delivered to the Royal Society (30th November, 1825)***

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# 1. Introduction

Recent widespread flooding in England and Wales in 2000, 2007 and 2008 (EA, 2001; EA, 2007) together with recent EU policy drivers such as the Floods Directive (EU, 2007), the Water Framework Directive (EU, 2000) and the Habitats Directive (EU, 1992) has put the focus on sustainable river management practices within the UK as well as the wider European Community. This is demonstrated through the recent increase in river restoration as a means of restoring the quality of previously damaged water bodies (Palmer *et al.*, 2005) allowing integration of the river channel with its surrounding floodplain (Brookes *et al.*, 1996) which, in turn, can assist in the management of flood risk (Defra, 2004). It is estimated that by 2080, £30 billion could be saved by using a combination of engineering and non-engineering flood risk management measures rather than relying on hard-engineered defences such as building higher defences with the same reduction in flood risk (Evans *et al.*, 2004).

It is also possible to combine flood risk management measures with the ecological drivers of restoration. As part of an EU LIFE 3 river catchment restoration scheme, designed to recreate riverine woodland in the New Forest, Southern England, there is an experimental aspect that aims to use large wood accumulations to recreate the processes favourable for the development of riverine woodland, which is the natural character of many river channels within the UK (Gregory, 1992). Although deforestation has reduced the amount of large wood present within UK rivers, 52% of lowland rivers still have some large wood (Raven *et al.*, 1998). Brookes (1995) suggests that a pragmatic approach for widespread restoration of floodplains is to allow natural recovery to occur wherever practical and, where the process is slow, to install low-cost devices to enhance recovery. In this way, many kilometres of watercourses could be improved in relatively short time periods (1-150 years Brookes, 1992). One such low-cost device is the use of large wood (often called large woody debris or snags in the academic literature). The use of large wood as a restoration tool is on the increase (Shields *et al.*, 2004) and it is particularly useful for providing new habitats (Gippel, 1995; Lehane *et al.*, 2002; Brookes *et al.*, 2004), protecting against bank erosion (Shields *et al.*, 2001; Shields *et al.*, 2004), and attenuating floodwaves (Gregory *et al.*, 1985; Gregory, 1992). The presence of large wood can assist in the creation of conditions favourable for the development of riverine woodland (Fetherston *et al.*, 1995). Large wood is also seen to be an important feature in the functioning of floodplain forests and riverine woodland (Piégay, 1997), is known to have an important role in providing regeneration sites for riverine woodland species (Hughes and Rood, 2003) and can help maintain the highly complex nature of woodland by encouraging the natural flood pulse (Tockner *et al.*, 2000; Tockner and Stanford, 2002). Riverine woodland is a key source of large wood and, as a result, large wood accumulations are prevalent in channels that flow through wooded areas (Piégay and Gurnell, 1997). Large wood also plays a key role in influencing the functioning of forested streams (Robison and Beschta, 1990; Harwood and Brown, 1993; Lisle, 1995; Gurnell and Sweet, 1998).

The hydraulic and hydrological role of large wood and especially accumulations in forested floodplain river systems, are poorly understood, with many claims unsubstantiated with supporting data (Gippel *et al.*, 1992). Although it is known that large wood, as a roughness element, can lead to some improvement of the channel-floodplain link (Gippel *et al.*, 1996; Jefferies *et al.*, 2003) it is not known how well it provides this link. Large wood is both dynamic and mobile and thus complex in nature (Braudrick and Grant, 2000). It often forms accumulations that can affect channel hydraulics in a number of ways depending on their architecture and locations (Abbe and Montgomery, 1996; Wallerstein *et al.*, 1997). Hydraulically, there has been some work that focuses on the role of in-channel large wood in affecting the reach-scale roughness and how this feeds into the inundation of the floodplain is currently unknown.

The EU Life 3 restoration project provides an opportunity to study the hydraulic and hydrologic effect of large wood and how floodplain inundation is influenced by the presence of large wood accumulations. The basis of this research will seek to assess the role of large wood at a range of scales from single large wood accumulations, through reach to catchment scale in order to assess the range of processes, which may have an impact upon the role of large wood and its accumulations in a forested river system. A number of techniques were used including field monitoring, field measurement and hydraulic models to determine the role of large wood. This is framed against a backdrop of the use of large wood as a restoration tool and also as an alternative flood management tool in natural and semi-natural river catchments.

In addition, this research will build upon recent research from north-west European rivers, including the UK, by Gregory *et al.* (1985), Gregory (1992) and Gurnell and Sweet (1998). This will add to the understanding of large wood that has traditionally been focused on North American streams (Shields and Smith, 1992; Abbe and Montgomery, 1996) with some work carried out in Australia (Gippel *et al.*, 1996).

# 2. Literature Review

## *2.1. Riverine Woodland and Floodplain Forests*

Human interventions have historically involved disconnecting river channels from their floodplains in order to control localised flooding and for land drainage. This has led to the fragmentation and isolation of floodplains and the loss of important wetland habitats, which support high levels of biodiversity (Richards *et al.*, 1996; Tockner *et al.*, 1998; Tockner and Stanford, 2002). This, together with the influence of human encroachment onto the floodplain, means that only 250km$^2$ of riverine woodland is currently present within Europe (UNEP, 2000). The natural vegetation of many river floodplains is a highly complex and variable mosaic of woodland types which provide a corridor of high species diversity along a river channel (Sterba *et al.*, 1997; Peterken and Hughes, 1998; Hughes *et al.*, 2001). Such woodland typically contains tree species such as Oak (*quercus robur*), ash (*Fraxinus excelsior*), beech (*Fagus sylvatica*), alder (A*lnus glutinosa*), sallows (*Salix spp*.) and black and grey poplar (P*opulas nigra* and P*opulus canescens*) (Brown *et al.*, 1997 and Peterken and Hughes, 1998). Floodplain forests have a number of benefits including the attenuation of flood waters (Brown *et al.*, 1997; Piégay, 1997; Sterba *et al.*, 1997), improvement of water quality (Peterken and Hughes, 1998), the retention of suspended sediments (Jeffries *et al.,* 2003) and the provision of an ecotone of high biodiversity which is an important type of wetland habitat (Brown *et al.*, 1997; Peterken and Hughes, 1998) and a priority habitat type (Type 91EO) under the EU habitat directive (EU, 1992).

As valuable and rare ecosystems, especially in the British Isles it is not surprising that there have been calls for their restoration (Brown, 1997; Peterken and Hughes, 1998). Furthermore, the protection and enhancement of such ecosystems is required under the EU Water Framework Directive (WFD). For surface waters Article 4 section (ii) states:-

"*Member states shall protect, enhance and restore all bodies of surface water…with the aim of achieving good surface water status…in accordance with the provisions laid down in Annex V…*" (EU Water Framework Directive, 2000).

Where Annex V gives the definitions of high and good ecological status of rivers which require a move towards the conditions of hydromorphological, biological and physico-chemical elements that are approaching the conditions "*…totally or nearly totally to undisturbed conditions.*" (EU Water Framework Directive, Annex V, page 41.)

Another driver to restore floodplain forests is the EU Habitats Directive under which floodplain forests, as priority habitat types, are required to be restored to a favourable conservation status (EU, 1992).

The scientific case for restoration is well established and underpins these legislative requirements. For example, Everard (1998) argues that floodplain restoration provides five key benefits:-

- Storage of flood waters on the floodplain reducing the 'flashiness' of a river system
- Dispersal of river energy which in turn leads to a reduced chance of bank erosion
- Buffering of flows and storage of water by vegetation that leads to stability of river flows throughout the year offering potential for more water abstraction.
- Trapping of sediment on the floodplain aiding flood defences, water quality and the potential to enrich floodplain soils.
- Acting as a buffer for nutrients thus reducing nutrient loading from diffuse sources.

Enhanced channel-floodplain connectivity also has ecological benefits, as inundation of the floodplain is essential for the development of wetland and other habitats (Brookes, 1996, Tockner *et al.*, 1998; Richards *et al.*, 2002), while the geomorphic diversity on the floodplain is directly influenced by inundation (Lewin and Hughes, 1980; Zwolinski, 1992).

## Conservation of Riverine Woodland

Unfortunately, opportunities for restoration of large tracts of riverine woodland, especially within the British Isles, are limited and Peterken and Hughes (1998) claim that the first objective is to conserve those stands of riverine woodlands that have survived. Examples of existing riverine woodland in the British Isles are those within lowland river systems such as the Beauliea river and Highland Water in the New Forest in the south of England and the River Spey in northern Scotland, and the more common upland examples of the River Tay and the Derwent in northern England and the midlands, respectively (Brown *et al.*, 1997).

Peterken and Hughes (1998) highlight two essential measures which are required to protect existing riverine woodland forests and even restore them to a near-natural state. The first is to minimise management of river channels both upstream and within the riverine woodland. The natural flood pulse should be maintained and the importance of high and low flows must be considered (see Brookes, 1995). The management of dead wood in channels should be minimal in order to create those processes that encourage floodplain inundation (Gregory *et al.*, 1988; Jefferies *et al.*, 2003). There is a dearth of wood in rivers throughout many forested regions due to management guidelines and channel modification for development, navigation and flood control (Abbe and Montgomery, 2003) although the importance of large wood is now widely recognised (Robison and Beschta, 1990; Gregory and Davis, 1992; Abbe and Montgomery, 1996; Gurnell *et al.*, 2002). Channels should also be free to migrate laterally creating a dynamic mosaic of floodplain habitats (Peterken and Hughes, 1998).

The second measure required to protect riverine woodland is the requirement that forest management be kept to a minimum. This allows trees to grow, die and regenerate naturally (Peterken and Hughes, 1998). Occasionally it is not possible for this requirement to be met due to the pressures of grazing but in these locations it is necessary for the grazing to be kept as low as possible (Peterken and

Hughes, 1998). These measures are necessary to ensure that the limited stands of riverine woodland that do exist are protected from further degradation and can serve as a reference condition for restoration projects. However, there is more difficulty in restoring areas that have not survived the impact of humankind and have been replaced by meadows, pasture or arable land (Peterken and Hughes, 1998).

## The Restoration of Riverine Woodland Functioning

The key issue in the restoration of floodplains forests is that it requires a multi-faceted approach, which seeks to restore the high biodiversity associated with the riverine woodland, as well as restoring natural geomorphological heterogeneity (Brown *et al.*, 1997) and the hydrological processes that underpin the functioning of riverine woodlands (Gurnell, 1997; Bendix and Hupp, 2000). It is for these reasons that any approach must try to renew those processes that formed riverine woodlands in the first place. The physical nature of the riverine woodland is strongly influenced by the hydrological and geomorphological processes that occur and consequently can directly feedback into these processes (Gurnell, 1997; Piégay, 1997). Loftin *et al.* (1990) reported on work conducted on the Kissimmee River in Florida in which the project aimed to restore the floodplain using the natural energy of the river system. This was achieved by restoring the annual variability in water levels needed to restore conditions favourable to the increase of native species. This involved the restoration of the natural flood pulse to the flood plain thus restoring seasonal flows, overbank inundation frequencies, duration and extent, and flow velocities. It is these factors that are important in creating the vegetation patterns that are present in such riverine woodlands (Hupp and Osterkamp, 1996).

The restoration of such processes can be achieved in a number of ways from re-shaping the channel form, recreating meander belts and the amelioration of any river bed lowering. Petts (1998) argued that, when considering floodplains, restoration should be focused upon processes and functions rather than on the restoration of structures and forms. In particular, Petts (1998) stated that the aim should be to restore ‘ecological integrity’, which recognises that floodplains are essentially a mosaic of patches and that the functional relationship of these patches and their biological communities depend on hydrological connectivity with the river and the underlying aquifer.  These approaches to floodplain restoration raise the issue of sustainability (Brookes *et al.*, 1996). Sustainability is a term that is commonly used when specifying restoration objectives that refer to the capacity of a river restoration project to continue to enhance recovery (Gore, 1985).  Sustainability is inversely proportional to the amount of maintenance required to keep the rehabilitation functioning as was intended (Brookes and Shields, 1996) and is seen as an ideal approach in returning floodplains to their natural functioning (Holmes, 1998; Petts, 1998; Tockner *et al.*, 1998).  Brookes *et al.* (1996) highlighted five general approaches to floodplain restoration that aim to re-establish and sustain ecological functioning.  These are:-

1. The restoration of riparian buffer strips,
2. The intensive restoration of small but ecologically valuable patches,
3. Less intensive restoration of larger floodplain areas,
4. Restoration of original hydrograph, and
5. Relaxation of constraints on lateral river channel migration.

The first is often the only restoration option available, especially in urban areas and within developed floodplains.  Riparian strips on the floodplain can lead to the buffering of agricultural discharges (Petersen *et al.*, 1987; Petersen *et al.*, 1992) and can create conditions favourable for detritus break down, fish spawning and other ecological processes (Zalewski *et al.*, 1998).  Such measures restore the ecological integrity of the river corridor and increase its resilience to the pressures of humankind (Zalewski *et al.*, 1998).  Riparian buffer strips have also been identified as a key component in the stabilization of river banks, which is vital if channel restoration measures are to be maintained (Petersen *et al.*, 1992). The optimal width of a buffer strip is not known, but Doyle *et al*. (1977) measured the amount of nitrogen reduction in varying sizes of buffers strips and found that there was a curvilinear decline in nitrogen as buffer size increased with the curve reaching a plateau at a width of 10m.  However, whilst this option may provide riparian habitat, stabilise banks and buffer nutrients, its influence is spatially limited and does not allow the restoration of entire floodplains or provide connectivity between the channel and its adjacent floodplain.

The intensive restoration of small patches is used where there are prime examples of aquatic and floodplain habitat (Galat and Rasmussen, 1995). In these cases habitat diversity is the first priority and little other work aimed at restoring sustainability is undertaken. It is argued that larger scale restoration based upon the ‘flood pulse effect’ can have the same effect and be more cost-effective than restoring smaller, disjointed, patches along a river (Bayley, 1991). The following quote summarises the advantages of the use of the flood pulse effect.

*“Restoration based on the ‘natural pulse’ will permit us to win back the system functions that provide high productivity, flood control and an aesthetic setting, with nature paying a much larger proportion of the bill than taxpayers in the long term.”* (Bayley, 1991, p84).

The key to accomplishing floodplain restoration using the flood pulse effect is to allow floodwaters to inundate larger areas of the floodplain than are inundated under the disturbed regime. These pulses of floodwater lead to the establishment of disturbance-dominated ecosystems with the high habitat heterogeneity characteristic of floodplain environments (Tockner *et al.*, 2000; Tockner and Stanford, 2002). The practicalities involved in allowing floodplain inundation usually involve the removal of flood defence structures such as embankments and levees, together with the creation of artificial openings at low elevations that allow flow to spill onto the floodplain (see Tockner *et al.*, 1998 and Scheimer *et al.*, 1999). Another measure involves the use of secondary channels to create permanently flowing channels in the floodplain, which allow a high hydrological connectivity with diverse morphological processes that support the formation of diverse habitats (Schropp and Bakker, 1998; Simons *et al.*, 2001).

In some rivers, allowing floodwaters to inundate the floodplain by removing flood defence structures will not have the desired outcome because of artificial regulation of the hydrograph. For example, dams alter the timing, magnitude and duration of not only flood pulses but also other flows (Bayley, 1991; Brookes *et al.*, 1996). To manage the flux of water and facilitate its most efficient use by society, dams have led to fractured river systems, which are in need for restoration (Graf, 1996). In the case where a dam is controlling the flow regime, it may be necessary to remove the dam, or modify its operation to restore the natural hydrograph and allow the natural flood pulse to function and re-establish inundation of the floodplain (Brookes *et al.*, 1996). Bayley (1991) stated that the implementation of a 'natural flood pulse' is dependent on the hydrograph and that once a dam is removed or modified, costs per unit area would be relatively low. The restoration of the natural hydrograph could, in many cases, lead to a conflict with the need for flood control, riverine navigation and water supply and therefore may not be the right option for the restoration of floodplains. This needs to be assessed on a case-by-case basis with stakeholder input so that restoration does not adversely impact upon the needs of the local community.

The final approach to floodplain restoration described by Brookes *et al.* (1996) is that of relaxing the constraints of lateral migration of the channel, effectively restoring the meandering nature of a river. In this approach a corridor is provided to allow lateral migration of a river channel termed the 'streamway concept' by Palmer (1976) or the 'Channel Migration Zone'. Palmer (1976) claimed that although the meander belt may take thousands of years to shift across an entire floodplain, it only takes a few decades for the shifting of individual meander bends and thus attempts to confine a channel to strict limits in order to reduce bank erosion and meander migration will fragment habitats and lead to erratic responses by the river channel. Palmer (1976) concluded by stating:-

"*The rewards of preserving the natural channel are many, including the natural accommodation of floods and saving of habitat and aesthetic values*." (Palmer, 1976, p345).

This kind of approach is akin to the approach suggested by Brookes (1995) in which the river is left to its own devices with no restoration works taking place. It has been argued that this approach may require a large amount of time in order to produce the desired objectives, whilst others wonder whether natural recovery without intervention can occur in less dynamic systems such as lowland streams (Kern, 1992).

## Improving Channel-Floodplain Connectivity

What is clear about most of these restoration measures is the desire to reconnect the river with its floodplain to restore the natural processes by which the floodplain was formed in the first place (Gurnell, 1998). Reconnection leads to a range of floodplain processes that both erode and deposit the floodplain surface (Schmudde, 1963; Zwolinski, 1992; Sear *et al.*, 2010). This gives rise to complex floodplain topography and geomorphic forms that influence future inundation events (Lewin and Hughes, 1980; Zwolinski, 1992) and encourage ecological habitat diversity (Tockner *et al.*, 1998; Tockner *et al.*, 2000; Tockner and Stanford, 2002).

Although the connectivity of the channel to the floodplain is an important aspect in preserving, and in some cases recreating, riverine woodlands there is often the need for further action such as the introduction of native species and the removal of non-native species. Such actions were reported by Peterken and Hughes (1998) who illustrated the work of the Black Poplar action plan, which sought to reintroduce black poplar (P*opulus nigra* var. *betulifolia)* into lowland floodplain systems. It may also be necessary to partition the floodplain into certain areas of wetlands and drylands to increase habitat diversity. Brown *et al.* (1997) claimed that the optimum amount of forest in order to create a mosaic of habitats would be no more than 30% of the land thus avoiding homogenous ecosystems although this would vary through the length of river. Hughes *et al.*, (2001) described the three different spatial scales of processes that must be considered when restoring floodplain woodlands: the site scale, the reach scale and the catchment scale. At the site-scale, factors such as the development of vegetation in response to hydrological and sedimentological regimes are key, whilst at the reach scale it is the channel dynamics and hydrological regime that condition the processes that allow regeneration of riverine woodlands. At the catchment scale, the management of water and the flow regime is important. Once riverine woodlands are present on a floodplain, they have significant positive impacts upon floodwave attenuation, ecological diversity and sediment retention. Piégay (1997) noted that forested margins were effective at slowing flow through a reach due to the considerable roughness of rigid vegetation. This can assist in laterally reducing overbank flow depths and also control the erosive capabilities of the overbank flow (Piégay, 1997). However, Neumeister *et al.* (1997) argued that 'artificial' flooding of riverine woodlands could increase the leaching of heavy metals and other atmospheric pollutants into the groundwater.

## The Role of Large Wood in Forested Floodplains

An important contribution to ecosystem processes associated with forested floodplains is the presence of large wood (Piégay, 1997). Forests upon floodplains have been known to contribute large quantities of large wood to the river system flowing through them (Abbe and Montgomery, 1996). Originally removed in order to increase flow conveyance, the presence of large wood is now seen as important for ecological (O'Connor, 1991), hydraulic (Shields and Gippel, 1995; Gippel *et al.*, 1996; Manga and Kirchner, 2000; Shields *et al.*, 2001), hydrologic (Gregory, *et al.*, 1985) and geomorphological reasons (Keller and Swanson, 1979; Hupp and Osterkamp, 1996; Piégay and Gurnell, 1997). There has also been a recent move to use large wood as a tool for river restoration (Shields *et al.*, 2001; Lehane *et al.*, 2002; Brooks *et al.*, 2004). One area large wood may be useful is in the reconnection of the channel with its floodplain to recreate the conditions favourable for the development of riverine woodland environments, as it has been shown that its presence in a lowland stream can improve the connectivity between the channel and the floodplain (Gurnell, 1997; Jefferies *et al.*, 2003).

## Use of Large Wood in Floodplain Restoration

Large wood accumulations are increasingly being seen as a multi-faceted restoration option with potential benefits for stabilizing incising rivers (Shields *et al.*, 2004, www.ELWDsystems.com ), enhancing ecological performance (Lehane *et al.*, 2002 and Brookes *et al.*, 2004) and increasing hydraulic diversity (Shields *et al.*, 2001 and Shields *et al.*, 2004). They hold considerable potential as low cost measures for rehabilitating small sand bed streams damaged by channel incision (Shields *et al.*, 2001 and Shields *et al.*, 2004). Typical costs are estimated to be \$80 $m^{-1}$ (£45 $m^{-1}$) compared to \$750 $m^{-1}$ (£400 $m^{-1}$) for bank and in-channel structures (Shields *et al.*, 2001). Although a cheaper option, large wood may also be preferred because it is an important aspect of the aquatic habitat (Brooks *et al.*, 2004) and creates higher levels of physical habitat due to the complex flow fields around such structures (Gippel, 1995 and Abbe and Montgomery, 1996). Large wood in the active channel or on the floodplain creates low velocity zones where transported sediment and organic matter collect, which can influence the local geomorphologic, processes (Fetherston *et al.*, 1995). Large wood was previously thought of as detrimental to flood control measures, erosion control and river navigation and so was frequently removed in order to reduce flow resistance and increase the conveyance of the channel. Accordingly, the removal of large wood became the most commonly practiced stream modification throughout many managed fluvial systems (Shields and Smith, 1992). However, routine clearance of wood from river channels is no longer an environmentally acceptable management practice (Shields and Nunnally, 1984 and Piégay and Gurnell, 1997) and efforts have been taken to actively increase the amount of large wood present in rivers, whilst guidelines have been produced on their use as a restoration tool (e.g. Oregon Department of Forestry Guide, 1995).

Introduction of large wood is likely to increase flow resistance and reduce the channel cross-sectional area, which may retard flow, and in some high flow events lead to the inundation of the floodplain. Fetherston *et al.* (1995) produced a conceptual model of montane forest development and found that there was a positive feedback system in which the introduction of large wood can create conditions favourable for the development of riverine woodlands, which can thus result in increased loadings of large wood in the river system (see Figure 2.1.1). In this model, the presence of large wood creates the transport and deposition of sediment creating incipient floodplain. The presence of the large wood provides low velocity areas where seeds can propagate and thus colonisation occurs.

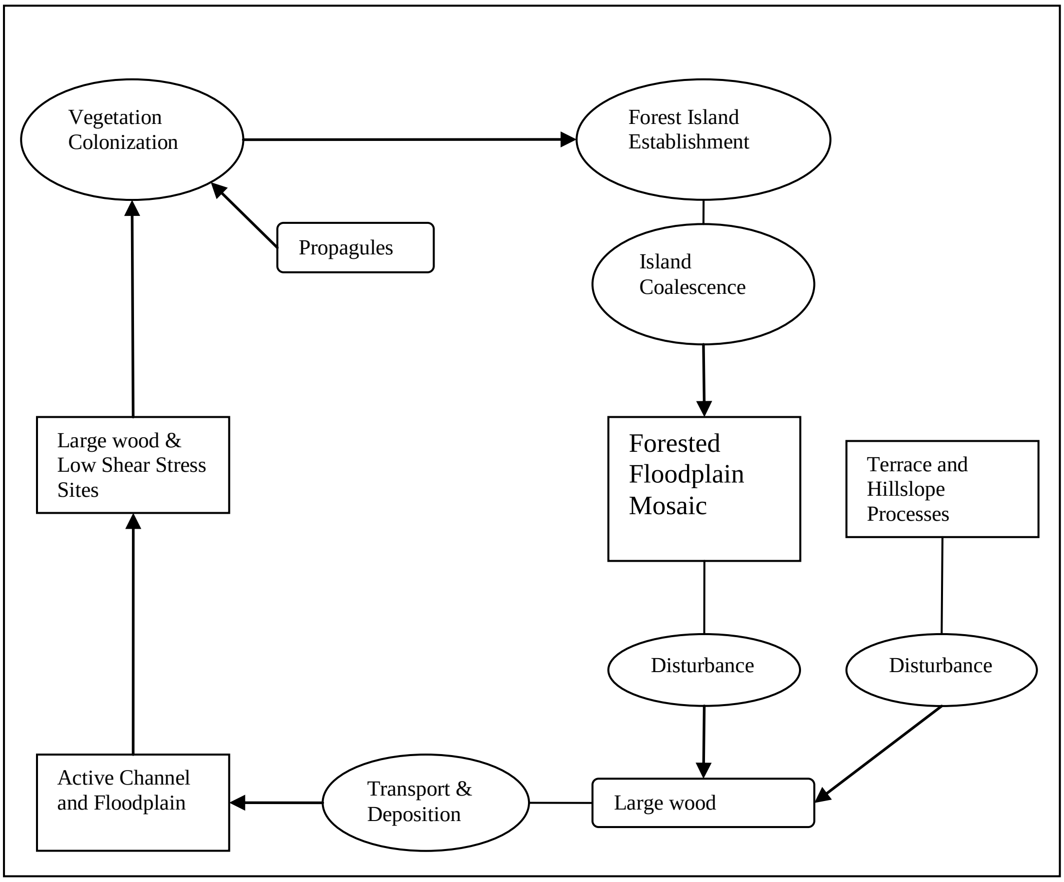



**Figure 2.1.1 :-Conceptual Model of montane riparian forest development (from Fetherston *et al.*, 1995).**

This process creates a number of vegetated islands within the floodplain that can locally slow floodplain flow leading to further deposition and growth of the islands. These vegetation islands can coalesce creating a floodplain vegetation mosaic displaying the complexity and biodiversity associated with riverine woodland. The riverine woodland can then act as a source of large wood during flood events to further propagate the process. Large wood accumulations can cause the backing up of flows, which lead to the development of floodplain channels (Keller and Swanson, 1979; Harwood and Brown, 1993; Piégay, 1997; Jefferies *et al.*, 2003). Understanding how the introduction of large wood affects local flow hydraulics is imperative to assess its impact upon local floodplain inundation, the conveyance of flow and the catchment hydrology. Furthermore, large wood is likely to have differing effects depending on its arrangement and structure, it is necessary to assess the differing classifications of large wood structures, and how each type of structure can affect the local flow hydraulics.

Despite this new found appreciation of the important implications of large wood to hydrological, geomorphological and ecological processes in forested catchments, the role of large wood is poorly understood (Abbe and Montgomery, 1996). There has been an increase in the number of publications on large wood in the last two decades focused on particular aspects such as the channel hydraulics (Young, 1991; Harwood and Brown, 1993; Gippel, 1995; Manga and Kirchner, 2000), catchment hydrology (Gregory *et al*., 1985), the geomorphic influence of large wood (Keller and Swanson, 1979; Brookes, 1988; Montgomery *et al.*, 1995; Webb and Erskine, 2003; Brooks *et al.*, 2004) and the ecological habitats provided by large wood (Smock *et al.*, 1985; Smock *et al.*, 1989). However, there are still some questions regarding the use of large wood as a restoration tool, especially in the context of restoring the processes favourable to the development of riverine woodlands. At present, few studies have attempted to assess the performance of the input of large wood upon frequency and extent of floodplain inundation, which is a major requirement for the restoration of riverine woodland functioning. Furthermore, it is not yet fully understood how the input of large wood alters the catchment flood hydrology and subsequent flooding downstream. These issues need to be resolved if there is to be a continued use of large wood as a restoration tool for recreating conditions favourable for riverine woodland development.

## *2.2. Floodplains*

Although channel dynamics and hydraulics have been often been the focus of fluvial geomorphology in recent times there has been renewed interest in floodplains and their processes (Anderson *et al.*, 1996). It has been recognised that the floodplain landform assemblage has a complex sedimentological background (Brown, 1997) with highly variable three-dimensional flow hydraulics (Knight and Shiono, 1996; Nicholas and McLelland, 1999) influenced by complex topography (Nicholas and Walling, 1997; Sweet *et al.*, 2003), which in turn create intricate patterns of overbank deposition (Nicholas and Walling, 1997; Nicholas and Walling, 1998; Sweet *et al.*, 2003; Jeffries *et al.*, 2003). Despite the undoubted complexity, it is imperative that hydrologists and hydraulic engineers understand floodplain processes and their implications because the floodplain is the interface between human activity and the fluvial system (Marriott, 1998).

Firstly, it is useful to define a floodplain so that the processes occurring upon it can be identified. Nanson and Croke, (1992) used a number of floodplain definitions comprising a *hydraulic* floodplain:-

'*…the surface next to the channel that is inundated once during a given return period regardless of whether this surface is alluvial or not.*' (p460)

to a *genetic* floodplain which is defined as the:-

*'…largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow regime.*' (p460).

The former does not however distinguish the sedimentary nature of the floodplain nor the processes by which it is formed, whilst the latter does not account for the geomorphic history of the floodplain (Marriott, 1998). Marriott (1998) introduces a number of floodplain definitions before settling on one given by Schmudde (1968) which defines the floodplain in the following manner.

*'…as a topographic category, it is quite flat and lies adjacent to a stream; geomorphologically, it is a land form composed primarily of unconsolidated depositional material derived from sediments being transported by the related stream; hydrologically, it is perhaps best-defined as a land form subject to periodic flooding by the parent stream'.*

However, this definition gives the impression of an area of uniform topography and discriminates against those floodplains studied by Nicholas and Walling (1997) and the forested ones studied by Jeffries *et al.* (2003) which show more complex topography. Perhaps in this context, it is inaccurate to think of the floodplain as a flood*plain* as sometimes the topography has little akin to a plain surface. Despite this omission, the definition of a floodplain by Schmudde (1968) is broadly sufficient to be used within this review with the caveat that the floodplain is not necessarily planar. Nonetheless, the floodplain is part of the fluvial system and is subject to the same basic processes that occur in a classic uniformly trapezoidal river channel, although as explained in the following sections these processes can show increased diversity. To begin with, floodplain hydrology will be discussed, as it is the hydrology that is important in making the floodplain functional.

## Floodplain Hydrology

Floodplain inundation arises when there is an increasing discharge with a corresponding rise in stage, which results in the channel capacity being overwhelmed and flow spilling onto the floodplain. The change in cross section from one that is essentially a trapezoidal channel-shape to one that incorporates a complex floodplain, leads to a change in the stage-discharge relationship, which can affect the storm hydrograph and also means that the prediction of inundation extent is difficult (Kiely, 1990; Wark *et al*., 1990). For flows that are just greater than bankfull, the large surface area and high roughness contributed by the floodplain reduce the velocity of flow across the floodplain surface. As the flood magnitude increases the effectiveness of floodplains to store water is reduced and floodplain velocities begin to approach channel velocities (Bhowmik and Demissie, 1982). This changes the nature of the floodplain from one that predominantly stores flow to one that predominantly conveys flow (Bhowmik and Demissie, 1982). The flooding of the floodplain is the main driver of the floodplain geomorphology such that the topography reflects the different flow, sediment and, in forested floodplain, the large wood accumulation types to which it is subjected (O'Connor *et al.,* 2003).

This complex topography of natural floodplains coupled with the complex stage-discharge relationship can give intricate patterns of floodplain inundation, which affect flood routing, and erosional and depositional processes (Hughes, 1980; Lewin and Hughes, 1980; Nicholas and Mitchell, 2003). Numerous attempts have been made to identify and chronologically place different flood phases. An evaluation of the processes that occur in each phase is shown in Figure 2.2.1 (Lewin and Hughes, 1980; Zwolinski, 1992).

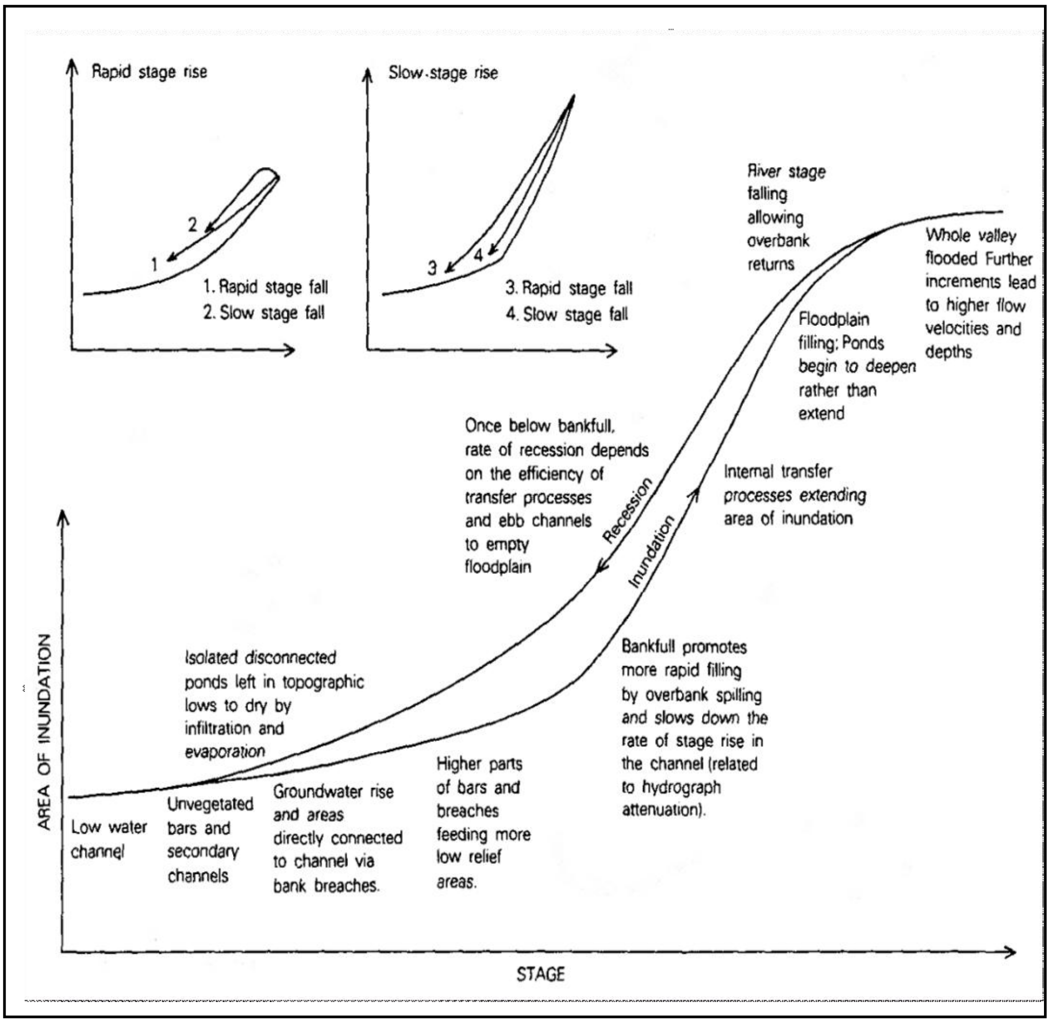



**Figure 2.2.1:-Inundation-stage relationship and characteristics (from Lewin and Hughes, 1980).**

Although these studies have been largely empirical, they still provide a representation of inundation phasing which has been reinforced by observations of geomorphic architecture (Zwolinski, 1992). Nicholas and Walling (1998) simulated floodplain flows and found that there is a general two-phase model of flooding. In phase one the flow inundates areas close to the channel such as abandoned channel features or point bars. In the second phase, areas remote from the channel where topographical features, such as abandoned channels, control water conveyance and overbank flood distributary channels become inundated (Nicholas and Walling, 1998 and Jeffries *et al.*, 2003). This two-phase model gives an indication of the complex behaviour of overbank hydraulics and reflects the influence of topography upon the routing of overbank flows (Nicholas and Walling, 1998). The complications involved in representing a generic floodplain inundation model arise because of the complex topography and the various geomorphic forms which may be found in a fluvial environment, together with the hydrologic and hydraulic variations with which they are associated (Zwolinski, 1992). Past work has attempted to simulate floodplain inundation at a range of scales using hydrodynamic models (Bates *et al.*, 1996 and Nicholas and Walling, 1997) although there still is a need to better represent floodplain flow processes (Anderson *et al.*, 1996).

The inundation of the floodplain leads to floodplain storage, which can result in an attenuation of flood peak, thus forming a link between the floodplain and catchment scale hydrology (Bates *et al.*, 1996). The storage and delay in the passage of the flood wave produces flood hydrographs that are low and broad compared to similar systems that lack floodplain storage (Archer, 1989; Woltemade and Potter, 1994). Not only does the presence of a floodplain lead to attenuation but the roughness of the floodplain can also influence the amount of flood wave attenuation and suppress flood growth downstream (Archer, 1989). Diehl (1990; cited in Woltemade and Potter, 1994) simulated the effect of changing floodplain roughness upon peak flood discharge and found that an increase in Manning's n from 0.053 to 0.1 reduced the peak discharge of a moderate flood event (4-50 years recurrence interval) by up to 27%. Such an attenuation changes the nature of a downstream flood event and can lead to a reduction in the flood risk for the downstream channel. Therefore, it is necessary to assess the influence of any floodplain restoration schemes upon catchment hydrology including the attenuation of flood waves. The input of large wood and the increase in floodplain attenuation may however reduce the occurrence of inundation at sites downstream of the large wood. This may be detrimental as it contrasts with the goals of floodplain restoration, or in the case where the floodplain is developed and needs flood protection, it may be beneficial. However, whether detrimental or beneficial, the effect of any changes in floodplain functioning upon catchment hydrology needs to be assessed. The floodplain hydrology varies little over short time scales; the real difficulty arises from the determination of the hydraulics, which can vary at minute spatial and temporal scales.

## Floodplain Hydraulics

'*Whereas inbank flows may be treated as if they were predominantly one-dimensional flows in the streambank direction…overbank flows must be treated differently as certain three-dimensional processes begin to be especially important, particularly the main channel/floodplain interaction. It is this interaction among others that makes the analysis of floodplain flows inherently difficult'* (Knight and Shiono, 1996, p139.)

What is obvious from the above statement is the inherent complexity that is present within the study of floodplain hydraulics. It is this and the relatively sparse nature of data describing flood events which have meant that floodplain processes have, until relatively recently, rarely been studied. Research into overbank hydraulics has since taken on two main approaches, those that use field based investigations (Lewin and Hughes, 1980 and Babaeyan-Koopaei *et al.*, 2002) and those that use numerical and/or physical models to examine the largely steady-state flow hydraulics (Shiono and Knight, 1991; Knight and Shiono, 1996 and Nicholas and Walling, 1997). Floodplain flows are a natural consequence of the hydrological regime and, despite larger discharges than in-channel flows and a different cross section to the channel, can still be treated as an open channel albeit with a more complicated geometry, roughness and planform (Knight and Shiono, 1996). As such, the same concepts that are present in channel hydraulics can be applied to floodplain hydraulics with some alterations for the complex patterns of inundation, the interactions involved at the channel-floodplain interface, and the floodplain roughness coefficients.

Under flood conditions when the discharge increases so does the flow depth and stage according to a relatively simple stage-discharge relationship. However once stage is commensurate with bank height then the river is considered to be at bankfull level. It is at this level that interaction with the floodplain is initiated and the once relatively simple stage-discharge relationship becomes more complicated as the cross sectional area and flow resistance changes.

The interaction between the channel flow and a treeless floodplain is best summarised by the conceptual model produced by Shiono and Knight (1991) as shown in Figure 2.2.2. The interface is dominated by a highly sheared zone between the faster flowing channel flow and the slower floodplain flow, which is subject to increased resistance. This shear zone gives rise to vertical interface vortices that were first observed and identified by Sellin (1964). These interface vortices convect the faster flowing channel flow from the channel onto the floodplain (as shown in Figure 2.2.3) and can therefore act as a major source of momentum transfer between the channel and the floodplain (Knight, 1989). These interface vortices were observed across a range of relative (dimensionless) flow depths (ratio of floodplain flow depth to main channel flow depth = 0.05 to 0.5) although the maximum interaction between the channel and floodplain was found to be at relative depths between 0.1 and 0.3 (Knight and Shiono, 1996).

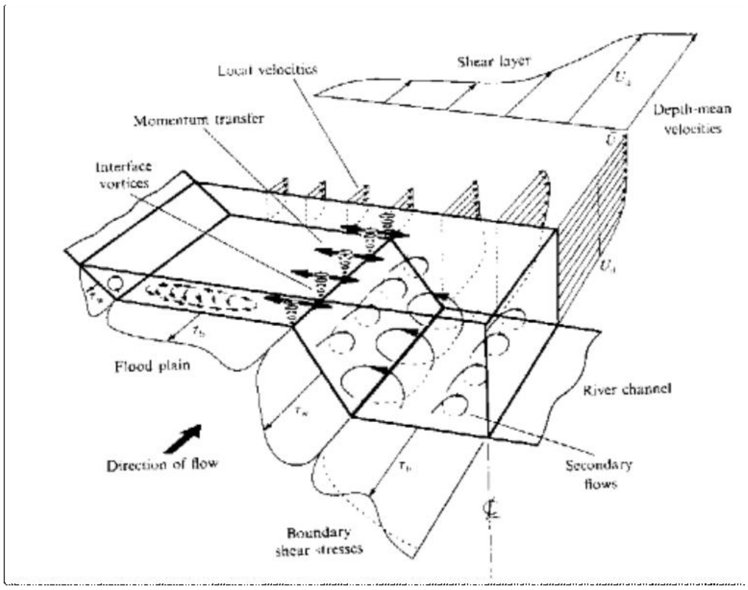



**Figure 2.2.2:- Conceptual model of the channel-floodplain interface (from Shiono and Knight, 1991).**

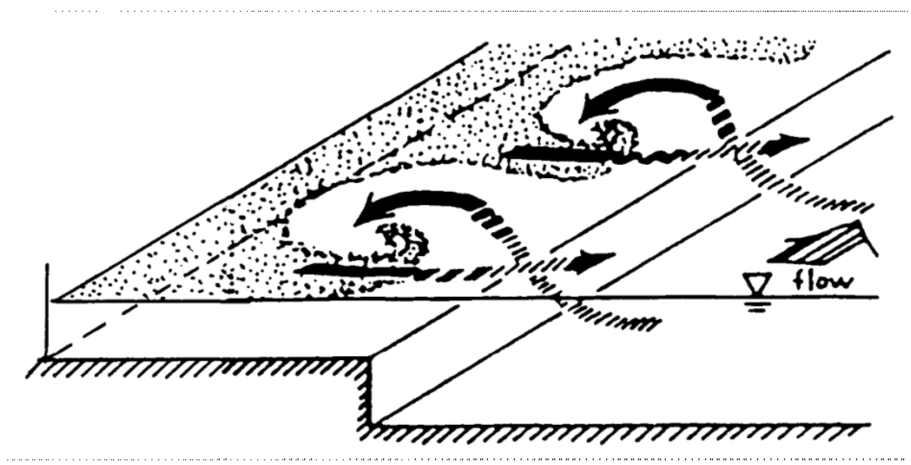



**Figure 2.2.3:-Lateral momentum transfer by large-scale vortices associated with the channel-floodplain interface (from Knight and Shiono, 1996)**

Flume studies into overbank flow in meandering channels have also identified that the direction of floodplain flow is essentially longitudinal (i.e. parallel with the floodplain walls) apart from during periods of low overbank depth when flow is almost parallel with the channel walls, indicating the existence of horizontal shearing at the interface between the channel and the floodplain flows (Kiely, 1990). This shearing nature of the flow gives rise to secondary circulations which transfer momentum longitudinally and emphasises the three dimensional nature of floodplain flows. These vortices and secondary flows can also be significant in the transfer of sediment overbank from the main channel flow. Theoretical and flume based studies have been applied to simulate suspended sediment transport at the channel-floodplain interface (see James, 1985; Pizzuto, 1987) although these have been developed in relatively simple topography (Nicholas and Walling, 1998) and in the absence of vegetation (Jeffries *et al.*, 2003). However, these studies have emphasised the role played by the sediment advection driven by the turbulent vortices shown in figure 2.2.3. These conclusions concur with those obtained by Nicholas (2003) who showed through a numerical simulation that suspended sediment transport on natural floodplains with complex topography is dominated by advection with some diffusion in ponded sites that are detached from the main channel flow by a well-developed shear layer.

Away from the channel/floodplain interaction zone the flow structure is less complex and as Figure 2.2.4 shows for a plane bed floodplain, seems almost uniform in nature. Such flow patterns follow the general floodplain relief and are steered by the channel planform (Kiely, 1990). Although the flows shown in Figure 2.2.4 were observed in a flume experiment, the same general flow pattern has been found in the field with some variation due to topographical effects as shown in Figure 2.2.5 (Nicholas and Walling, 1998; Siggers *et al.*, 1999).

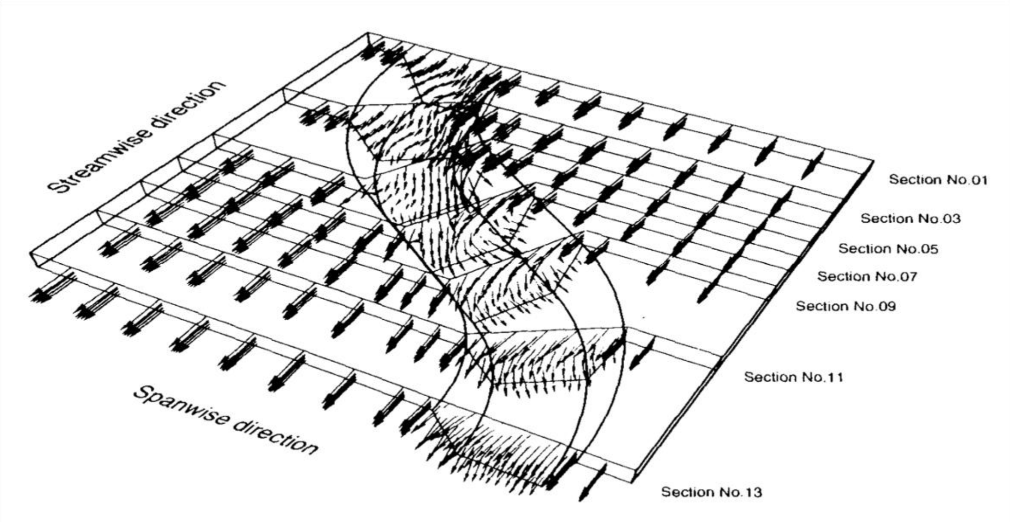



**Figure 2.2.4:- Velocity Vectors for Overbank Flows (from Knight and Shiono, 1996).**

## Processes on Forested Floodplains

Where the floodplain is vegetated, it is possible that the uniform flow patterns on these treeless floodplains are disrupted and instead diverse flow fields are generated. Little work has actually looked at the flow patterns present on vegetated floodplains (Harwood and Brown, 1993 and Brown *et al.*, 1995) although some work has been performed in flumes and with hydrodynamic models (Klaassen and Van Der Zwaard, 1974; Cobby *et al.*, 2003; Mason *et al.*, 2003). It is well known that vegetation can affect the roughness values for floodplains and its influence upon roughness values has been widely studied

(Chow, 1959; Li and Shen, 1973; Arcement and Schneider, 1989; Sellin *et al.*, 2003).

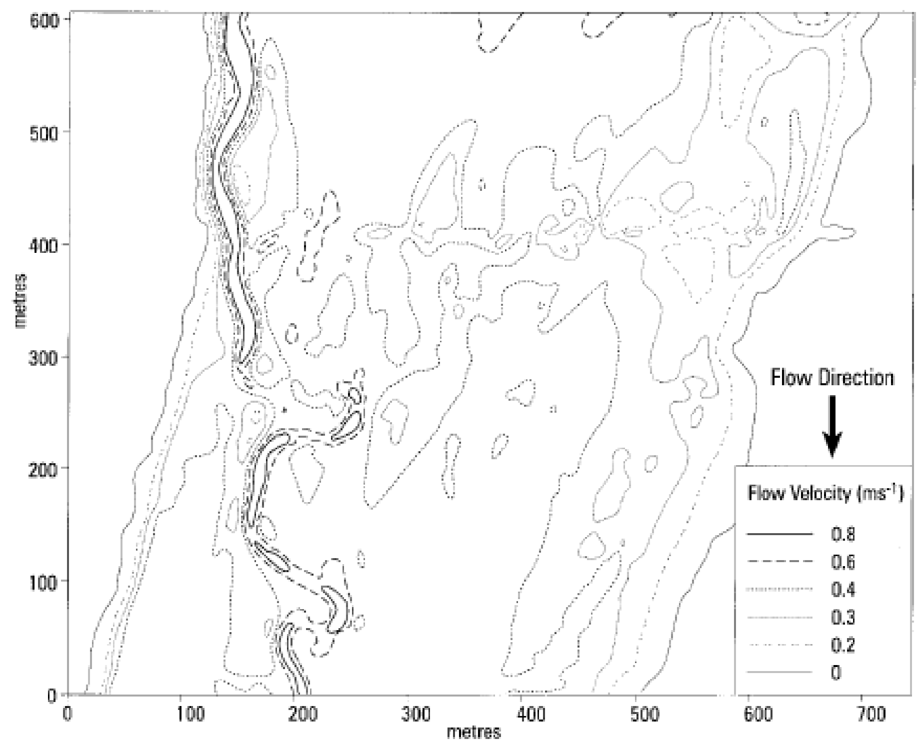



**Figure 2.2.5:-Predicted pattern of velocity magnitude ($m^3s^{-1}$) for an upstream water level of 2.6m on the River Culm, Devon, UK (from Nicholas and Walling, 1998).**

This increase in roughness can have significant impact upon the floodplain dynamics and can create recirculation zones and low flow areas as shown in a flume study by Sellin *et al.* (2003) (see Figure 2.2.6) and simulated and observed in the field by Nicholas and McLelland (1999). However, these studies investigated the effects of non-rigid flexible vegetation upon the flow as in many cases the floodplain is often covered by short flexible vegetation such as grass. However, riverine woodlands normally have more rigid vegetation that protrude through the water surface and act as elements of considerable roughness. To date very little work has investigated the role of rigid vegetation upon floodplain flow dynamics (see Li and Shen, 1973; Harwood and Brown, 1993). Harwood and Brown (1993) found that biotic components such as large wood accumulations and trees played a key role in the partitioning of flow which caused diverse channel and overbank velocities (see Figure 2.2.7). They found that overbank flow was predominantly in the downstream direction but was disrupted and deflected by both trees and topography. Thus, riparian and riverine woodlands are often described as environments of multi-directional flow (Piégay, 1997).

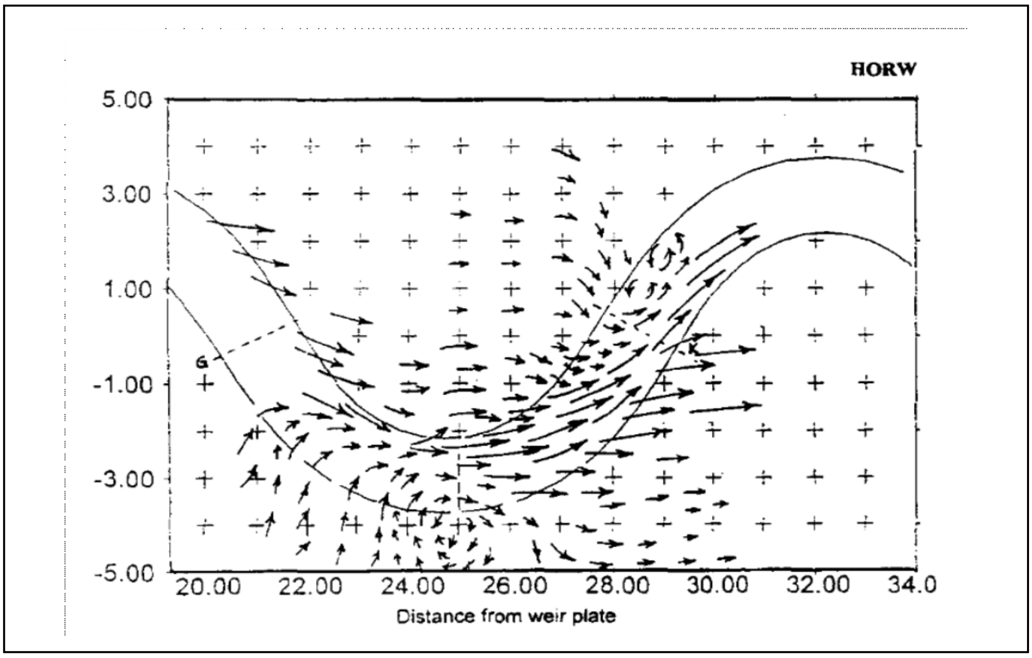



**Figure 2.2.6:- Floodplain flow vectors on artificially (using metal strips) roughened floodplain in a flume environment (from Sellin *et al.*, 2003).**

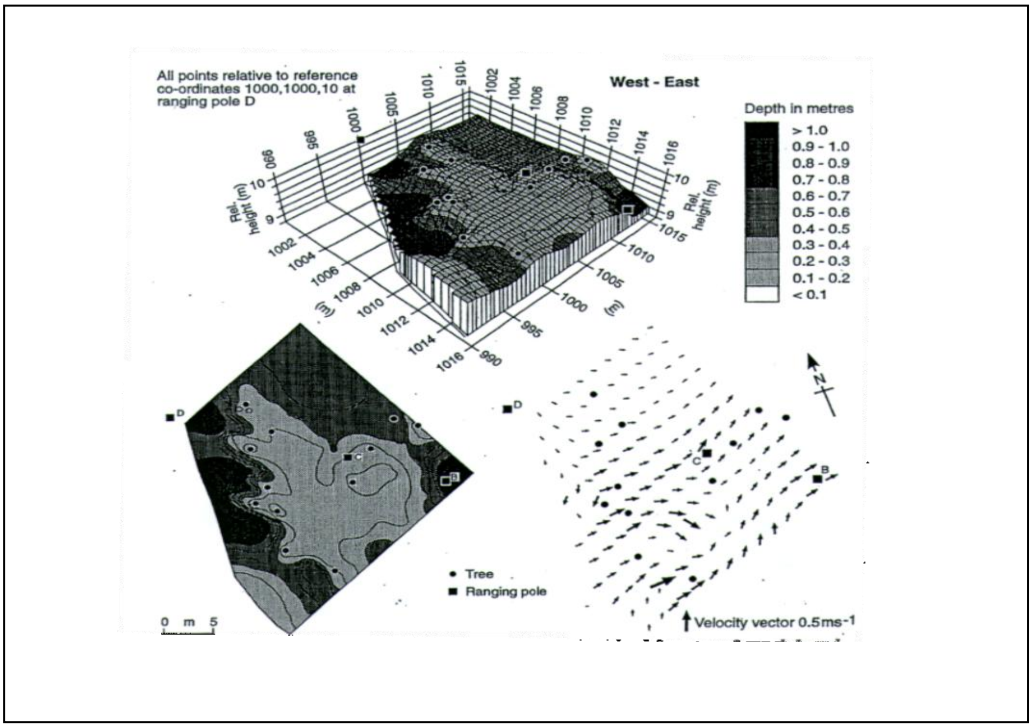



**Figure 2.2.7:- Floodplain flows in the presence of riverine woodland vegetation (From Brown *et al.*, 1995).**

The presence of biotic matter is also likely to give rise to increased hydraulic diversity and shear layers that can significantly alter deposition mechanisms. Wake deposits may form behind vegetation and create a micro-scale intricate floodplain surface, which is indicative of the local flow directions (Zwolinski, 1992) and created by deformation of the flow field by the vegetation (Tsujimoto, 1999). Vegetation such as that found in riverine woodlands can play a key role in controlling the spatial distribution of suspended sediment and in retarding flow (Jefferies *et al.*, 2003). Large trees create form drag, which leads to a wake effect downstream and a reduction in shear stress, which can result in the deposition of transported suspended sediment (Li and Shen, 1973; Tsujimoto, 1999).

The work by Jeffries *et al.* (2003) found that in a forested floodplain environment the main sediment depositional mechanism was diffusion in areas between slow ponded and faster flowing zones, but that this was significantly more complex than other examples due to the presence of vegetation and large wood. What these overbank sedimentation studies show is that despite the fairly uniform nature of floodplain flow, it is subject to high levels of shearing that lead to rapid energy loss and sediment deposition. Furthermore, observations of distributary channels indicate that vegetation may deflect flow into preferential pathways of high velocity that may cause scour of the floodplain surface (Jeffries *et al.*, 2003). Any large wood or other vegetative matter that is present can only compound these processes, give rise to more complex flow structures, and affect flow resistance. The role that large wood plays in interacting with the channel-floodplain interface and wider floodplain is important to understand since these are the processes that are important in shaping the topography and sedimentological nature of a riverine woodland reach. Piégay (1997) claimed that "*…more quantitative analysis of data is needed to define clearly relationships between overbank flows, floodplain morphology and vegetation dynamics.*" (Piégay, 1997. p.187).

## *2.3. Large Wood and fluvial processes*

It has been known for some time that vegetation exerts considerable control over fluvio-geomorphological processes (Hickin, 1984; Hupp and Osterkamp, 1996;

Gurnell *et al.*, 2002). There is little doubt that rivers prior to human disturbance were influenced by vegetation within their corridors, with vegetation affecting the geomorphological processes (Gregory, 1992; Gurnell, 1997; Montgomery and Piégay, 2003; Francis *et al.*, 2008). One type of vegetation that is often overlooked when assessing fluvial processes is large wood, which can have significant impact upon river landscapes (Francis *et al.*, 2008). It is this large wood that is the focus of this research.

## The Classification of Large Wood

An important consideration in large wood investigations is the need to classify the nature of large wood as a basis for developing a systematic synthesis of the role of large wood in differing contexts. Perhaps the most basic is the definition of large wood which is widely accepted as being wood over 1 metre in length and larger than 0.1 metre in diameter (Platts *et al.*, 1987; Fetherston *et al.*, 1995; Gurnell, 2003) although threshold dimensions can vary between studies (Wohl *et al.*, 2010). This definition does not account for the fine wood that can form accumulations that may significantly impede the passage of flow. These fine wood accumulations have been observed by Shields and Gippel (1995) who used their presence to justify treating large wood accumulations as simple blockages with no seepage, without accounting for the permeability of the large wood accumulation. The effect of such fine wood is largely ignored but it is possible that such accumulations will alter flow patterns and lead to the transmission of flow through the large wood accumulation. Shields and Gippel (1995), however, used the presence of fine wood to justify the use of a drag coefficient for solid obstacles approach to estimate roughness contributed by large wood. In practice, this may create difficulties as the porous nature of large wood and fine wood means that the assumption that the drag coefficient for solid obstacles is not entirely justified (see Chapter 7).

## Large Wood Accumulations

A large wood accumulation is a collection of large wood that can span partially or completely across a channel, although it is also specified as a minimum of ¼ of the channel and that the large wood should be in contact with the bed (Smock *et al.*, 1989). This has important implications for the effect upon flow hydraulics as a large wood accumulation that spans the whole channel dramatically reduces the channel cross-sectional area and may be a significant obstacle to the flow. On the other hand, a large wood accumulation spanning a smaller part of a channel may be less of an impedance and may cause local increases in flow velocity through the part of the channel cross-section, which is constricted by the large wood. In order to assess the impact of large wood accumulations as a tool for restoring the processes favourable for riverine woodland development it is necessary to look at the effect of different accumulations upon the frequency and extent of floodplain inundation (see Chapters 6-8). Therefore, a robust classification of large wood accumulations is required.

There are many different types of large wood accumulation and a range of classification schemes available in order to categorize them. The earliest scheme was that of Gregory *et al.* (1985) which classified accumulations into three types, active, complete and partial (see Figure 2.3.1). An active accumulation is an accumulation that spans the channel completely and creates a step in the water surface profile similar to a complete accumulation, although the latter does not induce a step. As the name suggests a partial accumulation is one that only spans a part of the channel width. A further category, high water accumulations, was added to the classification by Gregory *et al.* (1993) who observed accumulations that only influenced the channel hydraulics near bank full flow. Whereas this classification gives some implication as to the type of accumulation and alludes to some impact upon the water surface profile it is difficult to discriminate between different types of accumulations, some large wood accumulations span the whole channel and so may be classified as complete but are not in contact with the bed over the whole channel width. In addition, it is often difficult to assess whether an accumulation is complete or active as large wood accumulations may behave differently at different discharges (Sear *et al.*, 2010).

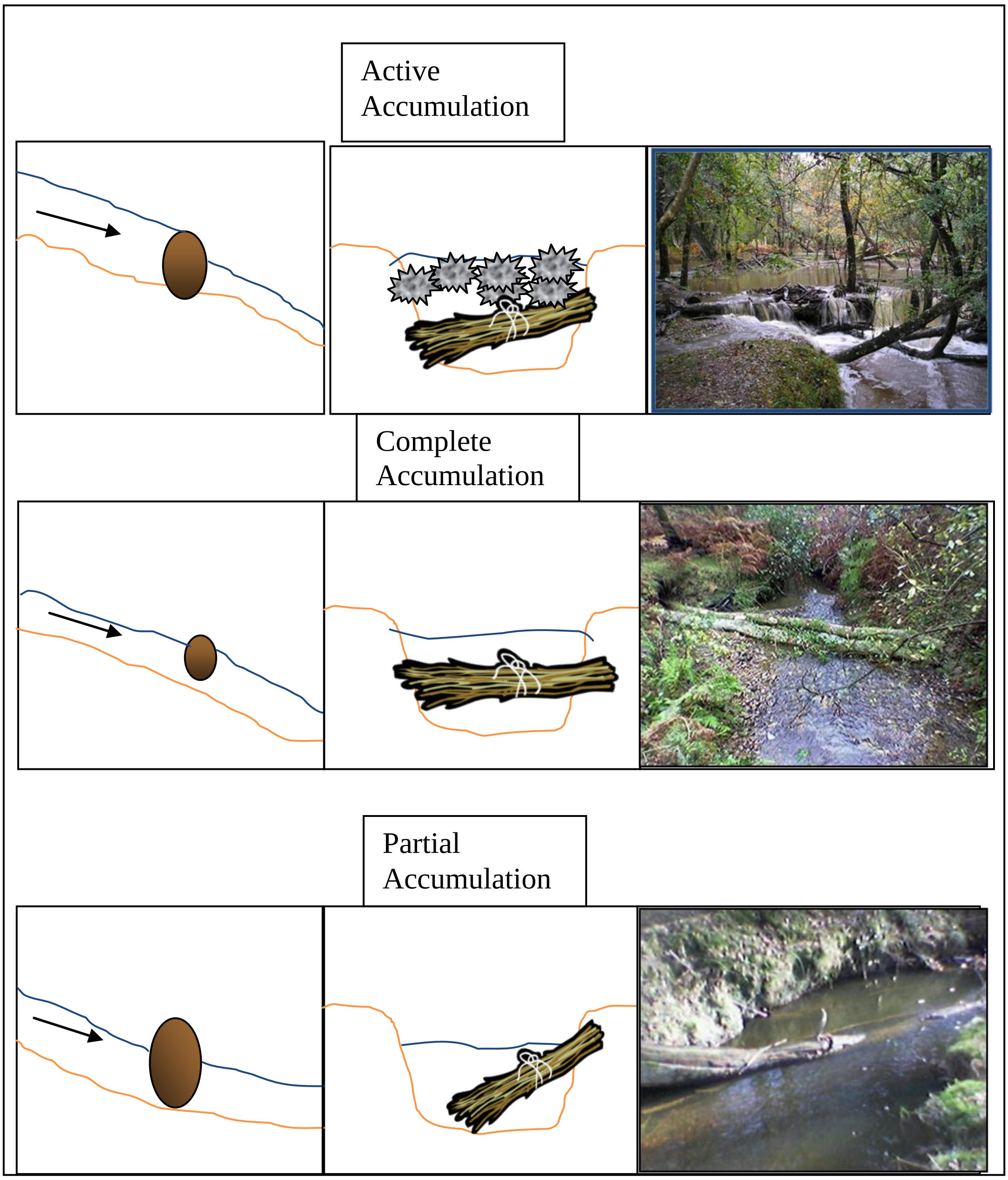



**Figure 2.3.1:-Large Wood Accumulation classification from Gregory *et al.* (1985). Left: Planform Views. Middle: Cross-section views. Right: Photo of Example Accumulation.**

Another of the more basic schemes is that of Smock *et al.* (1989) who classify large wood simply according to the wood diameter of the main structural log. The wood piece size is an important control on whether the wood is likely to become jammed within the channel although this is likely to vary with channel size and it has been suggested that the critical dimension is the ratio of large wood length to channel width (Gurnell *et al.*, 2002). This classification is inappropriate when looking at the impact of large wood accumulations, as it gives no indication as to the true size, nature or location of the large wood accumulation. A large wood accumulation can have distinct architectures that can affect flow in a variety of ways.

One scheme used by Abbe and Montgomery (1996) took account of location as large wood accumulation types were assessed relative to their proximity to channel forms. The work highlighted the notion that there were distinctive structural patterns to large wood accumulations, which varied systematically along a channel network. This gave rise to accumulations such as a bar top jam, bar apex jam and meander jam which are all located on the relevant channel form. A process-based classification is likely to offer a framework by which it is possible to assess the impact of large wood accumulations upon local flow hydraulics such as that of Wallerstein *et al.* (1997) which was adjusted from Robison and Beschta (1990). This classification scheme uses large wood dimensions relative to channel width which itself is scaled on drainage area to categorise the large wood accumulations and describe their functional impact upon flow structure and local morphology. Figure 2.3.2 shows the classification scheme presented by Wallerstein *et al.* (1997).

The different types of large wood accumulations are likely to have different impacts upon flow hydraulics, the local channel morphology and upon the inundation of the floodplain. Table 2.3.1 gives a qualitative evaluation of how each type of accumulation may affect flow hydraulics, channel morphology and floodplain inundation. This is based on assumptions that a high blockage area leads to increased impact upon flow resistance and ponding of water leading to floodplain inundation, whilst the geomorphic impact is linked to steering of flow and either bank or bed scour/deposition.

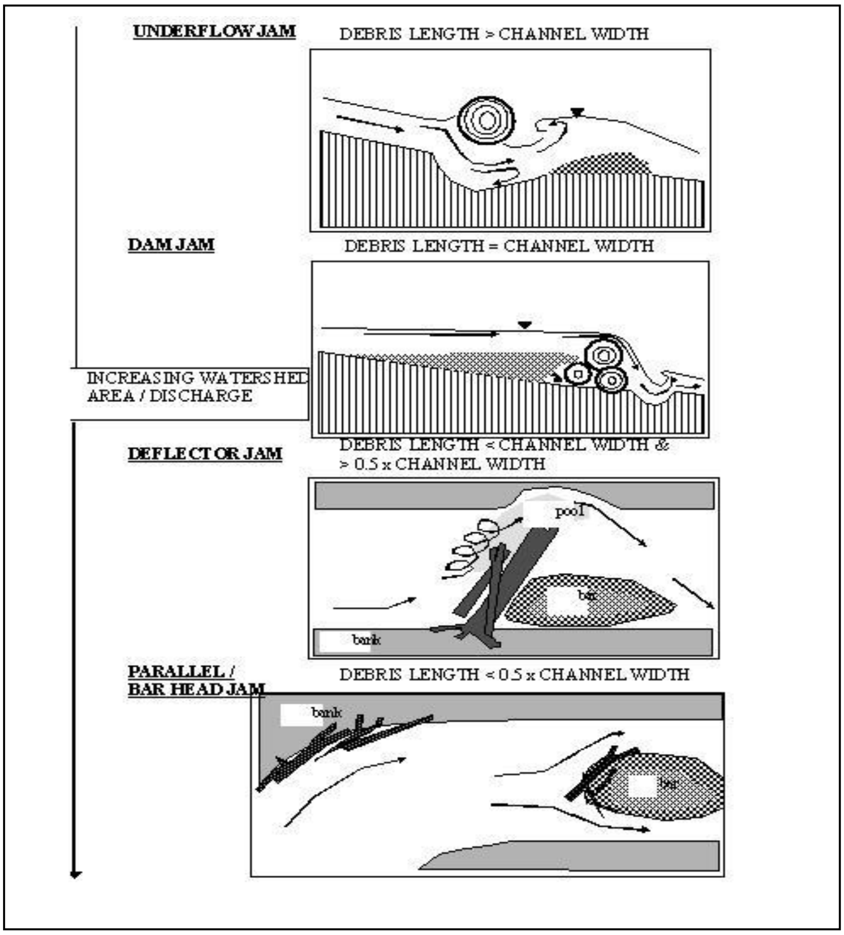



**Figure 2.3.2:-Large Wood accumulation classification from Wallerstein *et al.*, 1997.**

| Accumulation Type | Blockage Area | Relative Impact upon Water Surface | Geomorphic Impact | Influence on floodplain inundation |
|---|---|---|---|---|
| **Deflector Accumulation** | Low | Low | High-Can steer flow towards banks | Low |
| **Underflow Accumulation** | Medium | Low | High-Can lead to bed scour | Low |
| **Overflow Step Accumulation** | High | Very High | High-can create scour pools | High |

**Table 2.3.1:-Predicted impact of different classifications of large wood accumulation (adapted from Wallerstein, 1999)**

The different types of large wood classification proposed by Wallerstein *et al.* (1997) give some indication of the location of the accumulation and some of the potential qualitative impacts of the large wood accumulation. For example the underflow accumulation suggests that some scour may occur underneath the accumulation, whereas the term 'deflector jam' hints at the fact that flows may be deflected towards one of the riverbanks resulting in bank erosional/depositional processes.

Other factors may influence the affect on local flow hydraulics such as the blockage area (the frontal area of large wood relative to channel cross-sectional area) of the wood, which effectively changes the cross-sectional area of the channel (Gippel *et al.*, 1996). The volume of wood is also likely to be important and is usually expressed in a dimensionless density measure that relates wood volume to channel flow volume (Shields and Gippel, 1995). Furthermore, the impact of large wood accumulations upon reach-scale hydraulics is likely to be strongly governed by the flow discharge with the damming effect of large wood accumulations being drowned out by increasing discharges (Gregory *et al.*, 1985)

## The Impact of Large Wood Accumulations on Channel Hydraulics and Flow Processes

An obstruction in a river channel disrupts flow patterns and the presence of large wood can have the same affect (Gippel *et al.*, 1992). What is distinctive about large wood is its porosity which is rarely investigated and thus previous work has tended to conceptualise large wood as solid structures as demonstrated by Manners *et al*. (2007). Large wood can influence the direction and magnitude of flow within and outside of the channel. Swanson and Leinkaemper (1978) produced detailed maps of large wood accumulations indicating flow orientations and showed how large wood can shape flow patterns, which have an immediate impact upon bank erosion and sediment deposition. Abbe and Montgomery (1996) found that log locations affected local flow hydraulics, which subsequently influenced the spatial characteristics of scour and deposition, leading to the pools and bars associated with large wood structures (Robison and Beschta, 1990 see Figure 2.3.3). However, large wood does differ from other river structures by virtue that it is highly mobile and can form semi-permanent accumulations (Braudrick and Grant, 2000).

Qualitative impacts of large wood on river hydraulics are well known (Tabacchi *et al.*, 2000) but what is less well known is the quantitative impact of large wood on flow. Using 2-dimensional velocity measurements, Abbe and Montgomery (1996) discovered that near bed horizontal velocity components directly upstream of a large wood structure are characterised by two null points and an area of flow recirculation. Adjacent to the large wood structure, constriction and subsequent acceleration was observed, whilst flow separation occurs downstream (Shields and Gippel, 1995; Abbe and Montgomery, 1996).

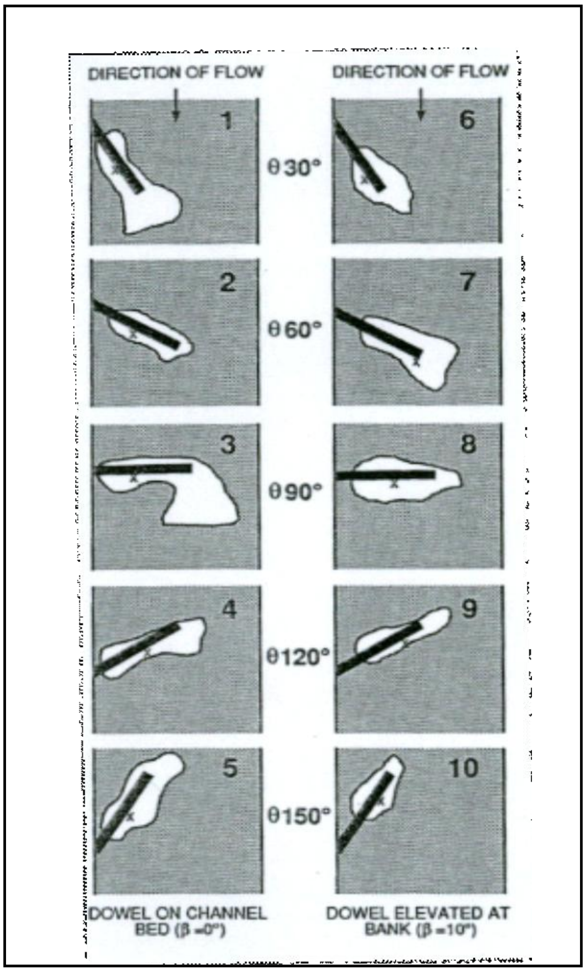



**Figure 2.3.3:-The distribution of scour associated with deflector large wood accumulation (from Robison and Beschta, 1990).**

The downstream acceleration adjacent to the obstruction is strongly associated with the formation of turbulence and is partially responsible for local scour contributing to the formation of a scour pool upstream of an accumulation (Abbe and Montgomery, 1996*)*.

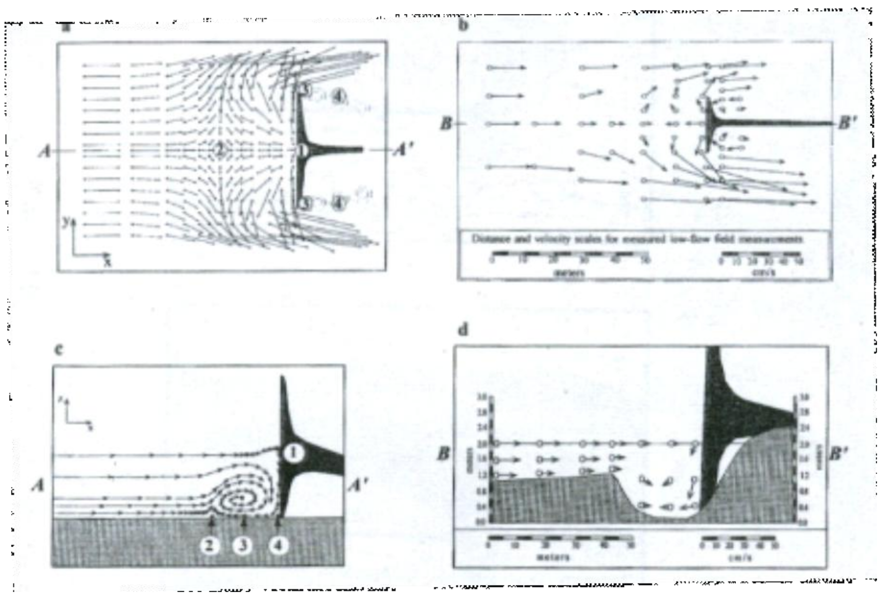



**Figure 2.3.4:- Generalized flow patterns showing flow velocity vectors upstream of a bar apex jam. A). Plan view of the near-bed flow field, (1) is the point of vortex initiation (2) is the null point, (3) the point of flow separation and (4) is the boundary of separation downstream of jam. B). Plan view of measured near-bed velocities during low flow C).Profile of flow field upstream of a bar apex jam. Point (1) is where the development of a downward acceleration in flow initiating vortex flow occurs. Point 2 is the null velocity point and 3 and 4 show the boundaries of the zone of vortex scour D). Profile of measured flow field upstream of a bar apex jam. (From Abbe and Montgomery, 1996).**

It is not only streamwise velocities that are affected by the presence of large wood, Daniels and Rhoads (2003) studied the effect of a large wood obstruction in a meander bend in an Illinois creek and found that the large wood accumulation affected the magnitude of the helical flow structure as steering of flow past the obstruction results in an increase in streamline curvature and enhanced vorticity as the flow contracts and is accelerated through the area adjacent to the obstruction. Shields *et al.* (2001) monitored the influence of large wood structures (Bar apex jams) upon the magnitude of flow velocities and found that for a sand bed river in Mississippi large wood structures were effective in reducing mean storm event velocities from about 150% of channel centreline velocities to values between 3-45% of centreline velocities. The work also showed that maximum velocities were displaced away from the bank toe reducing the potential for bank toe erosion.

These studies have been backed up by evidence that show that reach-scale velocities are faster in sections cleared of large wood than in uncleared reaches of the same river (Shields and Smith, 1992). Macdonald and Keller (1987) also found that there was an increase in reach-scale velocity by up to 250% as a result of large wood removal and a consequent change in the channel sinuosity. Shields and Smith (1992) reported that large wood removal produced more uniform flow with less of the channel subject to eddies or regions of reduced velocity than would occur in the presence of large wood. It is also possible that in some circumstances the presence of large wood can lead to local flow accelerations where the flow is constrained to a small part of the channel cross-section (Curran and Wohl, 2003).

## The Role of Large Wood Accumulations in Ponding Flow

Not only will large wood accumulations affect the flow patterns and velocity but they can back up flow, creating a local region of ponded flow. Gippel *et al.* (1992) suggested that apart from the local disturbance in downstream velocity patterns, the large wood also has an impact in the upstream direction. It is this backwatering effect that makes large wood a viable option as a restoration tool when seeking to reintroduce the functioning of a channel-floodplain system. Daniels and Rhoads (2003) observed that as flow approaches an obstruction (in this case a deflector accumulation) there is a stalling due to the damming effect of the obstruction, and although it was not explicitly measured they thought it was most likely that there was super elevation of the water surface immediately upstream of the large wood structure. The idea of super elevation may not be proven but there is evidence that large wood structures, such as Overflow accumulations, can cause a step in the water surface profile and locally elevate flow stage. Gregory *et al.* (1985) found that large wood accumulations increase the flow depth by locally ponding water upstream of the structure, which, through the decrease in velocity, can influence flood travel times. Ehrman and Lamberti (1992) found that large wood accumulations retained water 1.5 to 1.7 times longer than those reaches with negligible large wood.  Young (1991) conducted a flume study to determine what factors influenced the rise in stage associated with large wood.  The study found that only when large wood formed accumulations were present was there a significant rise in stage that may have an effect on flood levels.  Gippel *et al.* (1996) reiterated this point and further suggested that flooding frequency may also increase at locations upstream of a large wood blockage.    This backing up behind accumulations and the subsequent increase in water surface elevation has led flow avulsion that may contribute to the development of anastomosing rivers (Harwood and Brown, 1993; Sear *et al.*, 2010).  Because of this damming effect, Shields and Nunnally (1984) claimed that obstructions such as large wood accumulations may be incorporated in backwater profile models as geometric elements in the channel boundaries rather than being considered as a roughness component.

Gregory *et al.* (1985) observed that the ponding of the flow, which led to an increase in water depth and a reduction in flow velocity, can decrease the downstream flood peaks by attenuating flood waves.  Such increases in water depth could result in floodplain inundation. This effect was more significant at lower discharges because at higher discharges the damming effect of the large wood accumulations becomes drowned out (Gregory *et al.*, 1985).  Jeffries *et al.* (2003) found that large wood increased the frequency of floodplain inundation with overbank inundation occurring 41.5% of the time during the 2000-2001 flood season at a large wood accumulation compared to 0.2% in an adjacent large wood free zone, although this may have also been due to local variations in channel cross-section.  However, it does highlight the potential of large wood as a tool for restoring conditions favourable for re-establishing the connection between the channel and the floodplain. It would be useful to the understanding of riverine woodlands and the understanding of large wood accumulations as a restoration tool to assess the impact of large wood upon the catchment flood hydrology and to see whether the reduction of flow velocities, the ponding of water and the increase in floodplain inundation associated with these structures attenuates the flood wave in the same manner that has been shown to happen with floodplain storage (Archer, 1989; Woltemade and Potter, 1994).  By increasing the possibility of floodplain inundation there is the possibility that peak discharges can be attenuated by the slower floodplain flow.

## The Impact of Large Wood upon Flow Resistance

In the past, large wood was removed from river channels in order to reduce roughness and increase flow velocities to reduce flow stage for the purpose of flood control. For example, Gregory *et al.* (1985) found that Manning's *n* flow resistance coefficient dropped from 0.516 to 0.292 following large wood removal. The Manning's *n* roughness is a commonly used measure of the total resistance offered by channel boundaries and obstructions to flow. Total flow resistance consists of several components (Bathurst, 1997) including grain resistance, form resistance and spill resistance. Grain resistance is the roughness provided by individual grains and particles on the channel bed (Parker and Peterson, 1980). Form resistance is the flow resistance created by bed forms or other sources of form drag such as vegetation (Wilcox *et al.*, 2006). It arises from pressure drag created by the separation of flow around an object (Chadwick and Moffett, 1999). Spill resistance is generated by sharp velocity reductions due to free surface distortion through waves and turbulence (Leopold *et al.*, 1964).

Originally developed by Manning (1889) as an empirical method of estimating channel velocity, the Manning's *n* equation represents the total flow resistance and is presented below:-

$$n = \frac{1}{v} s^{\frac{1}{2}} R^{\frac{2}{3}} \tag{2.1}$$

Where $v$ is the reach-average velocity, $s$ is the slope of the energy gradient (usually the water surface slope) and $R$ is the hydraulic radius.

Large wood in rivers can be a source of significant roughness and consequently influences flow at local and reach scales (Hygelund and Manga, 2003), as well as promoting deposition over wide areas of the channel (Lisle, 1995). The effect of large wood on total roughness is the principal reason for the reduction in velocity, rise in flow stage and the attenuation of a travelling flood wave. In turn altered flow patterns influence channel morphology adjacent to the large wood accumulation. For these reasons, it is important to develop a reliable and accurate approach for predicting the contribution of different large wood configurations to channel flow resistance. It is useful to first begin by looking at the approaches that have been taken to estimate vegetative roughness in general, before focusing in on large wood roughness.

## Vegetative Roughness

A critical issue in river engineering is the prediction of flow resistance associated with vegetation (Bennett and Simon, 2004). Three types of vegetation can influence flow resistance; tall stable, woody vegetation which is essentially rigid, flexible vegetation such as grasses and rushes and finally large wood which can be thought of as rigid vegetation that can dynamically be reconfigured into altered configurations by flotation and transport (Braudrick and Grant, 2000). It is important from the point of view of restoration to accurately predict roughness coefficients to predict the hydraulic and hydrological performance of the restoration scheme. There have been a number of attempts to address the issue of vegetative roughness. The early methods included vegetation as an additional flow resistance exponent of bed roughness (Chow, 1959) and observed the occurrence of *n-VR* curves that demonstrated there was a relationship between roughness (*n*), vegetation density and the product of velocity and hydraulic radius (*VR*). These relationships found that *n* was inversely proportional to *VR* due to the effect of vegetation bending and submergence (Wu *et al.*, 1999). However, these relationships were not adequately physically based and were inappropriate where slopes were smaller than 5% and where vegetation was short and stiff (Kouwen *et al.*, 1981; Fisher and Dawson, 2001). Subsequently *n-VR* approaches gave way to other methods that determined either the relative roughness height or the drag coefficient of the vegetation, and subsequently converted these to roughness values.

## Relative Roughness Approach

Kouwen and various authors (e.g. Kouwen and Unny, 1973;  Kouwen and Li, 1980) have used the relative roughness approach in which vegetative roughness is treated in a similar manner to widely accepted resistance relationships for rigid roughness elements in channels (Kouwen and Unny, 1973; Kouwen and Li, 1980).  These approaches use a form of the Colebrook-White equation based on the relative submergence:-

$$\frac{1}{\sqrt{f}} = a + b\log_{10}\left(\frac{y}{k}\right) \tag{2.2}$$

where $f$ is the Darcy-Weisbach friction factor, $a$ and $b$ are coefficients dependent upon the degree of vegetation flexibility and extent of bending, $y$ is the flow depth and $k$ is the roughness height.  The vegetation flexibility coefficients take into account the bending of vegetation when subjected to shear and therefore it is possible to estimate the effective roughness height as a function of flow (Kouwen, 1992).  From experimental data, the roughness height was found to vary as a function of the amount of drag exerted upon the flow such that:-

$$k = 0.14h\left[\frac{\left(\frac{MEI}{\tau}\right)^{0.25}}{h}\right]^{1.59} \tag{2.3}$$

Where $MEI$ is a function of vegetation stiffness, $h$ the height of the vegetation and $\tau$ the boundary shear stress.  To simplify the formulation of (2.3) further research has empirically related $MEI$ to $h$ for green and dormant grass (Kouwen, 1988) and for pine and cedar saplings (Fathi-Moghadam and Kouwen, 1997).  Such equations have been widely developed and have been able to recreate *n-VR* curves (Kouwen, 1992) and have been successfully used in a model developed to predict stage-discharge curves (Darby, 1999) and in flood inundation models (Cobby *et al.*, 2003).  However, the method is more commonly used for flexible vegetation such as grasses or reeds and is unsuitable for use in quantifying the resistance offered by large wood.  This is because the method is primarily used for resistance elements that line the channel (i.e., grain resistance) rather than large-scale roughness elements that create form drag and spill resistance.

## Drag Coefficient Approach

For rigid vegetation such as trees, Petryk and Bosmajian (1975) used a drag coefficient approach using the equation of drag force (equation 2.4). They used a Vegetation-Density method that accounts for the vegetation density of the floodplain using:-

$$n = n_o \sqrt{1 + \left( \frac{c_d \sum A_i}{2gAL} \right) \left( \frac{1.49}{n_0} \right)^2 R^{\frac{4}{3}}} \qquad \textbf{(2.4)}$$

where $n_0$ is the Manning's boundary roughness coefficient excluding the effect of vegetation, $c_d$ is the effective drag coefficient for the vegetation in the direction of flow, $\Sigma A_i$ is the total frontal area of vegetation blocking the flow in the reach, $g$ is the gravitational constant, $A$, the cross-sectional area of flow, $L$ the reach length and $R$ the hydraulic radius. The preceding equation uses imperial units. The vegetation density is represented by the term:-

$$\text{Vegetation Density} = \frac{\Sigma \text{A}_\text{i}}{\text{AL}} \qquad \textbf{(2.5)}$$

The density can then be estimated using a sampling procedure using either representative cross sections or representative areas. One area of potential error in equation 2.4 could be the determination of the drag coefficient which is known to vary with the Reynolds number and is also likely to vary with tree type although the drag coefficient varies little with Reynolds number above $10^3$ (see figure 2.3.5 from Tritton, 1988; Wilson *et al.*, 2003) and is approximately unity for rough turbulent flows (Kadlec, 1990). For example, Shields and Gippel (1995) found that drag coefficients were fairly constant and only varied significantly with orientation of the large wood pieces to flow.

The drag coefficient approach has been used in a number of contexts including, coniferous trees along rivers (Kouwen and Fathi-Moghadam, 2000), in channel flexible vegetation (Fathi-Moghadam and Kouwen, 1997; Fischer-Antze *et al.*, 2001; Wilson *et al.*, 2003), floodplain vegetation (Pasche and Rouvé, 1985; Arcement and Schneider, 1989), wetlands (Kadlec, 1990) and in the case of large wood (Shields and Gippel, 1995; Gippel, 1995; Wallerstein *et al.*, 1997).

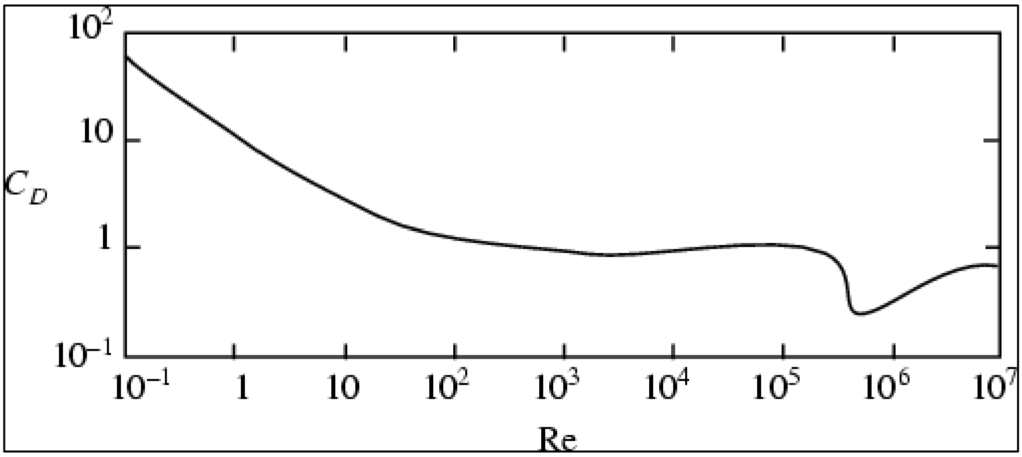



**Figure 2.3.5:-Variation of drag coefficient with Reynolds number for circular cylinders (from Tritton, 1988)**

The drag coefficient is a physically based approach, which takes into account the shape of an object the channel and uses this to estimate the form drag exerted on the flow. Coefficients can be added that take into account the degree of any bending, which can affect the effective blockage area (Fathi-Moghadam and Kouwen, 1997). The blockage ratio is a key component of the drag coefficient approach and has been represented in a number of ways. Shields and Gippel (1995) represented it as the frontal area of blockage that large wood represents to the predominant flow direction. Petryk and Bosmajian (1975) and Arcement and Schneider (1987) used a similar vegetation density approach to assess unsubmerged floodplain vegetation density. The approach takes a representative sample of the floodplain within which the number of trees and trunk diameters were measured to allow the calculation of the total frontage area of vegetation blocking the flow and then divided by the sample area to give a measure of vegetation density as in equation (2.5). Fathi-Moghadam and Kouwen (1997) used a momentum-absorbing area to represent the drag effects of leaves and stems, which are not easily accounted for. They argued that a concept of a fixed frontal area is not valid for flexible vegetation due to the significant deflection associated with high flow velocity.  The momentum-absorbing area also accounts for the foliage hidden behind the frontal areas, which absorbs momentum but cannot be seen by a flow-wise view (Fathi-Moghadem and Kouwen, 1997).  This drag coefficient method is likely to be more useful in assessing the resistance offered by large wood because it is suited for estimating form drag and has been successfully applied to the example of large wood (Shields and Gippel, 1995).  It has also been incorporated into hydrodynamic models, not only to account for roughness, but also to enable the simulation of flow patterns around vegetation (Nepf, 1999). For example, Wilson *et al.* (2003) applied a drag-related sink term within a hydrodynamic model and had some success in recreating velocity profiles observed in flume tests.  These techniques have been applied to a number of environments and some examples of the resulting effect of vegetation upon reach-scale roughness values are given below.

## Rigid, Standing Woody Vegetation

Despite the importance of rigid vegetation in resisting flow, there has been little work to investigate the effect of the presence of trees on river banks and floodplains on hydraulic roughness coefficients.  Petryk and Bosmaijan (1975) showed that, in wooded floodplains, Manning's *n* increases with vegetation density, which can be attributed to the fact that as vegetation density increases so does the frontal blockage area that impedes the flow.  This resulted in roughness values that were an order of magnitude greater than those associated with non-vegetated floodplains.  However, it was also found that Manning's *n* increased with depth and discharge due to a slight increase in vegetation density.  This observation is in contrast to most other findings, which indicate that an increase in discharge effectively drowns out the effect of flexible vegetative resistance (Beven *et al.*, 1979; Lisle, 1986).  Kouwen and Fathi-Maghadam (2000) studied a range of vegetation types and found that Manning's *n* ranged from 0.096 for Cedar trees (*Thuja occidentalis*) in a high velocity flow to 0.208 for Austrian Pines (*Pinus palustris*) in a slow flow.  They concluded that the dominant factor in unsubmerged vegetation is the vegetation density or momentum-absorbing area.  This is as expected as it is this portion of the vegetation that is exposed to the flow and creates the resultant drag.  Li and Shen (1973) found that, for tall vegetation, the pattern of the tree stands had a significant effect on the resistance of flow due to the influence of compound wake effects. Chow (1959) reported on an investigation by the University of Illinois (Pickels, 1931) which concluded that trees of diameters of 6-8 inches (15-20cm) growing on the banks of the river do not impede the flow as much as small bushy plants unless there are overhanging branches which increase the contact of the vegetation with the flow. The effect can also vary with height depending on the stage when flow interacts with the canopy. Antonarakis *et al.*, (2009) used terrestrial LiDAR to parameterise roughness values for planted and natural poplar forests present on floodplains and found that Manning's n was higher for extreme in-canopy flows (0.14-0.33 for planted poplars; 0.202-0.72 for natural poplars) than those flows which were below canopy height (0.037-0.094 for planted poplars; 0.066-0.210 for natural poplar forests). Klaassen and Van der Zwaard (1974) simulated water surface elevations of a high discharge event on the River Maas in The Netherlands and found that orchards and hedgerows appreciably affected the roughness and that their removal would result in lower water surface elevations. Although important, few studies have looked at the roughness due to rigid woody vegetation possibly due to the difficulty in getting data at times when flow is sufficiently large to allow the influence of floodplain vegetation especially tall vegetation to have an effect. More work has been conducted into the effect of flexible vegetation upon flow resistance although the majority of these have been constrained to the flume environment.

## Flexible Vegetation

Flexible vegetation contributes significantly to roughness values and as a result may influence flow stage and flood risk (Darby, 1999; Fischer Antze *et al.*, 2001). A range of studies have looked at the presence of vegetation within the channel (Kouwen, 1992; Wu *et al.*, 1999; Wilson *et al.*, 2003) and on the river bank and the immediately adjacent floodplain (Masterman and Thorne, 1992; Darby, 1999). Flexible vegetation bends when subjected to shear and therefore the roughness height varies as a function of flow strength (Kouwen, 1992). Therefore, there is likely to be a variation in vegetative resistance according to the flow regime and degree of bending. Wu *et al.* (1999) found that for unsubmerged vegetation mean velocity increases with flow therefore leading to a reduction in the resistance. Although a horsehair mattress was used, Wu *et al.* (1999) discovered that once the mattress had been submerged, roughness remained relatively constant with depth, which was attributed to the unchanged flow velocity. Nepf (1999) showed that not only does the additional drag exerted by vegetation reduce the mean flow within vegetated regions, but that it also leads to a variation of turbulence intensity. Wilson *et al.* (2003) concluded that in flume studies canopy layers reduced mean velocities due to the increase in momentum absorbing area of the vegetation. Nepf (1999) also claimed that dense vegetation can reduce the scale of turbulent eddies which subsequently controls the turbulence diffusivity, which may have an impact upon flow resistance. Tsujimoto (1999) observed that the impedance of flow by vegetation led to the concentration of flow and sediment transport into the 'main lane', which gave a mechanism for the scour of channels and the expansion of vegetation.

## Large Wood as a Roughness Element

Large wood is an obstruction in the river interfering with the flow and, like other vegetation, influences flow resistance. Vegetation, especially large wood, represents a large-scale roughness in which form drag is the dominant form of resistance (Petryk and Bosmajian, 1975). At its most obstructive, large wood accumulations can completely block the channel, much like a conventional dam, resulting in the development of a backwater in the water surface profile behind the obstruction until the surrounding floodplain may be inundated. This backwater effect is the important aspect in terms of flood risk (Gippel *et al.*, 1992). However, the flow resistance decreases with increasing discharge as roughness elements become small relative to flow depth (Beven *et al.*, 1979; Shields and Smith, 1992; Curran and Wohl, 2003), although at a certain flow depth it may start to rise as the flow spills onto the floodplain and interacts with riparian and floodplain vegetation (Jarrett, 1984). Any attempts to assess the roughness of accumulations must incorporate a range of flow discharges to account for this effect.

There are a number of methods for ascertaining the roughness coefficients of river reaches with large wood elements. The most commonly used coefficient is the

Manning's equation in which the resistance coefficient represents all sources of resistance within a reach. The resistance coefficient '*n*' is selected from either personal experience, tables presented in Chow (1959) or photographs in Barnes (1967) or, in the case of floodplains, by a guide such as that by Arcement and Schneider (1989). However, Manning's equation was initially developed to describe open channel flows where friction is controlled by surface drag from bed sediments rather than that of form drag by vegetation (Gippel *et al.*, 1996).

Alternative methods use equations to predict Manning's *n* as a function of different factors of channel shape and vegetation density for example those put forward by Petryk and Bosmajian (1975). A similar approach can be taken in order to predict the roughness of large wood from its physical characteristics. The method used by Shields and Gippel (1995) was to derive a relationship between the Darcy-Weisbach friction factor for a reach and the debris density within that reach. One assumption was that the cumulative effect of large wood within a reach can be treated as boundary roughness that is uniformly distributed. In reality, this may not be entirely appropriate due to the contraction and expansion of flow adjacent to the large wood accumulation, which means that resistance, is not uniformly distributed (Shields and Gippel, 1995). Like other vegetation studies, the work of Shields and Gippel (1995) uses a blockage area to estimate the form drag on the large wood.

Using the relationship for the form drag of a solid object in a fluid:-

$$D_i = \frac{C_{d_i} \gamma V_i^2 A_i}{2g} \tag{2.6}$$

where $C_{di}$ is the drag coefficient of the *i*th large wood formation, $A_i$ is the projected area of the *i*th large wood formation that is perpendicular to the flow ($m^2$) and $V_i$ is the approach velocity prior to the *i*th large wood formation ($m\ s^{-1}$). This equation does have one major limitation in that it represents large wood accumulations as solid, impermeable, objects rather than permeable structures of large wood with stems and branches. Likewise flume experiments have used this same approach which represents only the trunks of the large wood and ignores the influence caused by the root wad, branches and other accumulated wood where the blockage may not be impermeable (see Young, 1991; Gippel *et al.*, 1992). Shields and Gippel (1995) observed in the field that spaces between branches are often filled with leaves and sediment, which reduce the permeability of the large wood accumulation, and thus the approach was justified.

Based on the assumption that channel roughness is uniformly distributed along the reach then $V_i = V_{av}$, then Darcy-Weisbach's resistance due to large wood $f_d$ is given by:-

$$f_d = \frac{4}{\alpha}\chi \tag{2.7}$$

where $\chi$ is a dimensionless measure of debris density defined as:-

$$\chi = \frac{\sum_{i=1}^{n} C_{d_i} A_i}{BL} \tag{2.8}$$

To use equation (2.8) the drag coefficient ($C_d$) for the large wood accumulation is required. The drag coefficient is used to calculate the amount of form drag exerted on an object which for a vertical cylinder of diameter *d* in a flume of width *B* is given by an equation of the form (Ranga Raju *et al.*, 1983):-

$$C_d = \frac{C_d^{'}}{a\left[1-\frac{d}{B}\right]^b} \tag{2.9}$$

where $C_d$' is the drag coefficient in a flow of infinite extent (ie with no boundary effects) and a and b are experimentally determined coefficients. $C_d$ is an apparent drag force coefficient because of the finite size of the large wood relative to the flow depth (Manga and Kirchner, 2000). From 50 flume experiments conducted with single and vertically stacked cylinders orientated perpendicular to the flow, a

Froude number of 0.35 and blockage ratios varying between 0.03 and 0.3, a regression analysis resulted in coefficients of *a*=0.997 and *b*=2.06 with an r-squared value of 0.81. Field measurements in the lowland rivers of the Obion River, Tennessee, USA and Tumult River in Victoria, Australia found that large wood orientation is influenced by flow and Gippel *et al.* (1992) found a median angle of 27$^{o}$ to the flow, which corresponds to a flume drag coefficient for model elements of 0.6. Thus, equation (2.9) can be reconfigured to give:-

$$C_d = \frac{0.6}{0.997\left[1-\frac{A_i}{BR}\right]^{2.06}} \qquad \textbf{(2.10)}$$

which can be simplified to:-

$$C_d = \frac{0.6}{\left[1-\frac{A_i}{BR}\right]^{2}} \qquad \textbf{( 2.11)}$$

Resistance due to grain, bar and bends were also considered and when verified with field data, Shields and Gippel (1995) found that estimated values were within 30% of measured lowland straight sand-bed sections of the Obion River, and within 38% of measured values for the meandering, gravel-bed Tumult River. Manga and Kirchner (2000) also used this method in the spring fed, Cultus River, Oregon, USA and found that, once blockage effects were taken into account, large wood drag coefficients of 1.96 ± 0.17 were obtained. Drag coefficients have been found to vary with large wood orientation (Young, 1991) although in the case of more complex large wood accumulations, orientation was found to have little impact upon the drag coefficient (Gippel, 1995). However, despite the potential for estimating roughness coefficients in cases of large-scale accumulations where the flow is either critical or subcritical, the apparent drag coefficient is known to result in abnormally large flow-resistance coefficients (Gippel, 1995). Manga and Kirchner (2000) found that, despite three factors (shown below), converted apparent drag coefficients were consistent with the theoretical drag coefficients of cylinders at similar Reynolds numbers:

- The typical diameters of the large wood are not orders of magnitude larger than the bed roughness
- Velocity in a natural channel varies vertically
- Large wood can protrude above the water surface and thus the free surface can interact with the large wood and flow.

Curran and Wohl (2003) used the same approach in a range of step-pool channels and found that large wood form resistance is not as important in step-pool channels as it is in higher order channels with lower gradients. This suggests that the role played by large wood may vary between environments. However, they did find that large wood had a subsequent impact upon spill resistance, where spill resistance is that resistance resulting from local flow accelerations and decelerations (Leopold *et al.*, 1964) which was found to contribute the dominant component of flow resistance (>90%). Although this is not unusual within the step-pool environment, it has been observed that large wood in other environments can cause a step in the profile and lead to localised accelerations and decelerations of flow, which contribute to spill resistance (Gregory *et al.*, 1985; Wallerstein, 1999).

The drag coefficient approach used by Shields and Gippel (1995) has one limitation in that it treats large wood accumulations as solid objects rather than as a permeable structure of trunks, branches and leaf litter. Many large wood accumulations have a more complex architecture than the simple, single trunk debris experienced in other studies. Currently there is confusion with the use of a blockage area as in some cases the flow blockage area can be greater than the cross-sectional area of the channel (Curran and Wohl, 2003), for example in the case of heavily obstructed channels. Curran and Wohl (2003) used visual estimates of blockage ratios although a more robust approach is needed. Secondly, the blockage ratio is likely to have a large impact upon the resultant drag coefficient and the work of Shields and Gippel (1995) only established a relationship valid up to a blockage ratio of 0.4.

## 2.4. Summary

The restoration and conservation of riverine woodlands within Europe is a statutory requirement as set out by the EU's Water Framework Directive (2000) and the Habitats Directive (1992). However complete restoration is rarely achieved (Osborne *et al.*, 1993; Boon, 1998; Downs and Thorne, 2000) and opportunities within the UK are limited (Peterken and Hughes, 1998). The restoration of riverine woodlands relies on the restoration of the functioning of such systems and in particular the connection of the river with its floodplain. Large wood is a natural component of riverine woodland and contributes to higher flow resistance in the channel and upon the floodplain itself. Therefore, large wood is an important element of any riverine woodland restoration and is useful in recreating the connection between a channel and its floodplain. Large wood is a low-cost restoration measure (Shields *et al.* 2001). Its use has tended to focus upon the geomorphic impact of large wood of reducing bank erosion (Shields *et al.*, 2004) or its role in providing aquatic habitats (Lehane *et al.*, 2002).

However, if it is to be used as a tool for riverine woodland restoration there is a need to assess its ability to recreate the hydraulic and hydrologic conditions that are favourable for the development of riverine woodland. Arguably, large wood can have an impact on flow hydraulics and flow hydrology at three spatial scales. The first is the channel reach scale where the large wood contributes to flow resistance. Although the contribution of large wood to reach-scale roughness values has been studied (see Shields and Gippel, 1996; Curran and Wohl, 2003) there has been little work into the resistance offered by different large wood accumulations. The hydraulic processes of different large wood accumulations are likely to differ and can influence the associated reach-scale roughness offered to the flow. It is suggested that the different processes occurring at the different types of large wood accumulations mean that each are associated with a range of resistance values which best summarise their contribution of reach-scaled roughness. The approach suggested by Shields and Gippel (1995) will be used to predict the roughness of a range of large wood accumulations to evaluate its performance and to assess whether there are any large wood accumulations it is best suited to.

At higher in-bank discharges, large wood accumulations are likely to play a role in elevating water stage until it spills out onto the floodplain. Although there has been a study into the stage rise associated with large wood (see Young, 1991) it did not look at the flood frequency and flood inundation extents, which are important for the local floodplain hydrology and the downstream flood risk. It is likely that different large wood structures have different impacts on the flood frequency and inundation extent, related to the variable resistance of each specific large wood structure. Therefore, a method is required, which allows the investigation of the effect of different types of large wood accumulations upon flood frequency and floodplain inundation. A hydraulic modelling exercise will be required to assess the impact of certain large wood designs upon floodplain inundation and determine which type is most suitable for recreating the complex inundation patterns that allow the development of diverse anastomosing river channel conditions that can assist in the rehabilitation of riverine woodland.

The third scale has links with both the reach scale and the floodplain scale and involves the impact of large wood upon the downstream passage of a flood wave. How large wood influences catchment flood hydrology has been assessed before (see Gregory *et al.*, 1985) but never in the context of restoration. It is not known how the introduction of different types of large wood affects the passage of a flood wave within a small catchment and subsequent incidences of flooding downstream.

These areas are current gaps within the knowledge and understanding of large wood and require attention in order to assess how large wood can be used as a tool for restoring floodplain hydraulic processes and reducing flood risk downstream. No work has been found that explicitly deals with the roughness contribution of large wood accumulations and therefore this study seeks to investigate this.

Therefore, this thesis will seek to address the following questions:-

- Are current methods for assessing flow resistance offered by large wood accumulations appropriate for use for different types of large wood accumulations?
- What is the effect of large wood accumulations upon the reach-scale floodplain inundation frequency?
- Can the presence of large wood accumulations initiate a diverse anastomosing flow pattern?
- How do large wood accumulations affect the attenuation of flood peaks in a small-scale wooded catchment?

In order to seek to address these questions, a multi-faceted approach must be taken that looks at the role of large wood at a range of scales using a range of approaches. This approach uses monitoring, field measurements, physical and numerical hydraulic modelling.

# 3. Modelling fluvial systems

Models have been used since the inception of geomorphology, as illustrated by the conceptual model of Davis' (1899) 'Cycle of Erosion', such that modelling in its broadest sense has now developed into an important philosophical approach to understand processes, responses and landforms (Rhoads and Thorne, 1996). Essentially models can be viewed as representations of real world processes that provide an insight into the functioning of the natural environment and, ultimately, predicting those processes (Kirkby, 1996 and Darby and Van de Wiel, 2003). Modelling represents a methodology to assess a particular understanding of a process and as such can be used to explain outcomes or verify the understanding of those operating processes (Kirkby, 1996). The specific models used in this process can occur in a variety of forms, ranging from simple hardware or physical models, to complete mathematical representations of physical processes, whilst also including statistical and conceptual models (Darby and Van de Wiel, 2003).

## *3.1. Analytical and Numerical Models*

There is a trend of favouring numerical models of fluvial systems and this reflects the desire to view fluvial geomorphology as a branch of applied physics (Rhoads, 1992). Consequently, there has been a move to apply theoretical reasoning to these models (Rhoads, 1992). Two types of abstract models that attempt to do this are analytical models and numerical models. These are similar in some respects as they use mathematical equations to describe those physical processes that are occurring. They differ in the fact that analytical models have exact solutions whereas numerical models use numerical schemes that require some approximations. Physically-based models are derived from a strong theoretical basis, which use the underlying physics and have the potential to generate universal explanations; however, they often include some assumptions and simplifications that make the solving of the governing equations simpler. It is these assumptions that receive the most criticism, as they are difficult to verify in natural systems (Rhoads, 1992). Analytical models applied to the fluvial environment are normally used to predict channel morphology through a variety of approaches, such as tractive force methods (Lane, 1955) and extremal hypothesis approaches (Chang, 1980; Yang *et al.*, 1981; Davies and Sutherland, 1980 and White *et al.*, 1982). In fluvial hydraulics the most commonly used of the numerical models are hydraulic models which are based on fluid mechanics.

## 3.2. Fluid Mechanics

Fluid mechanics are well studied and the fundamental physics behind them are well known and described in mathematical form (White, 1999). Thus using these mathematical forms, a numerical model may be produced in which algorithms can be developed which solve or, at the very least approximate, the mathematical equations over a discretized grid (Lane, 1998). There has been considerable use of numerical flow models in geomorphology and hydrology as they allow improved understanding of key processes across different scales (Lane, 1998). Hydraulic models are available in a range of types depending on the processes to be represented, the level of understanding required and the preferred resolution of detail. The majority of numerical models are based upon the Navier-Stokes equations although some models do use alternatives such as the St Vernant equations to handle more complex topography or for simplified simulations and computational efficiency (Nicholas and Walling, 1998).

### The Navier-Stokes Equations

The Navier-Stokes equations aim to conserve mass and momentum and provide a numerical basis for describing the fluid. Although the Navier-Stokes equations are widely used within a number of engineering contexts and are well thought of as the basis to understanding fluid mechanics they are not directly applicable for simulating natural river channels for a variety of reasons (Nicholas and Walling, 1998; Lane, 1998 and Nelson *et al.,* 2003) and may not be adequately solved in regions of complex topography (Bates *et al.*, 1992). This is because of issues associated with the parameterisation of turbulence, the representation of the domain extents, and the representation of roughness. However, despite these issues computational hydraulic models have been widely used in a variety of environments and are important tools for investigating issues in open-channel flow systems (Lane, 1998; Khatibi, 2001). Computational hydraulics have been used in a number of ways, from predicting water surface elevations and flood extents to the replication of flow structures in complex open-channels (Bates *et al.*, 1992; Lane and Richards, 1998; Hodskinson and Ferguson, 1998 and Nicholas and Sambrook-Smith, 1999). Hydraulic models are generally classified according to how they represent the flow dimensionality: one-dimensional, two-dimensional and three-dimensional models.

## One-dimensional models

One-dimensional models are the most widely used hydraulic models due to their relative simplicity and ease of use, enabling predictions over large areas and over long time scales without much computational time (Nelson *et al.*, 2003). Such models assume that the flow is uniform and does not vary within a cross-section (Nex and Samuels, 1999). These assumptions are rarely met in natural channels and thus the model use is limited to the prediction of the free surface. Indeed, one-dimensional models are most commonly used for predicting water surface elevations from flood hydrographs and using these to predict inundation levels (Wickes *et al.*, 2004). However, they do not model the cross-stream component of the flow and thus are not appropriate for the investigation of complex flow fields or areas where secondary flow patterns are likely to be prevalent. Example one-dimensional hydraulic modelling software include:-

- HEC-RAS (http://www.hec.usace.army.mil),
- ISIS (http://www.wallingfordsoftware.com/products/isis) and,
- MIKE 11 (http://www.dhisoftware.com/mike11/).

## Two-Dimensional Models

Two-dimensional models attempt to overcome the limitations associated with one-dimensional models by using the depth-averaged form of the Navier-Stokes equations (Lane, 1998). These models allow the representation of two-dimensional processes that are present within natural rivers due to a range of curvature-related phenomena such as meander bends and confluences (Hodskinson, 1996; Bradbrook *et al.*, 1998). Two-dimensional models have been shown to provide reasonable estimates of the depth-averaged velocity field (Lane *et al.*, 1995) and have advantages in flood risk studies and in the visualization of floodplain flow, which may be of significance to areas where public awareness is an issue (Wicks *et al.*, 2004). Two types of two dimensional models are available, those that account only for the conservation of mass using diffusion-based methods and those that correctly solve the full St Vernant equations accounting for the conservation of momentum as well as mass. The former are subsequently referred to as hydraulic models (often referred to as quasi-2D) whereas the latter are referred to as hydrodynamic models. Hydrodynamic models are considered superior to hydraulic models in that they represent turbulent processes although this does mean they are more computationally intensive. However, it has been argued whether a two-dimensional velocity field is sufficient for adequate process representation (Lane *et al.*, 1999) with one and two-dimensional models unable to accurately represent flow patterns around structures and the channel-floodplain interaction (Nex and Samuels, 1999). When investigating floodplain flows and large wood accumulations, these three-dimensional processes are likely to be important in steering flow from the channel onto the floodplain. Examples of two-dimensional modelling software include:-

- HYDRO2DE (http://www.fluvial.ch/p/hydro.html),
- MIKE21 (http://www.mikebydhi.com/Products/CoastAndSea/MIKE21.aspx)
- River2D (http://www.river2d.ualberta.ca), and
- TELEMAC2D (http://www.telemacsystem.com/gb).

## Three-dimensional models

Three-dimensional models take into account downstream, cross-stream and vertical variations in velocity using the three-dimensional form of the Navier-Stokes equations. Wilson *et al*. (2000) showed that when applied to a meandering compound channel a three-dimensional code was slightly better in predicting the cross-stream distribution of depth-averaged velocities than a two-dimensional model as well as being able to accurately predict the location and direction of secondary currents. Three-dimensional models have been used to simulate a range of scenarios (see Nex and Samuels, 1999). It must be noted however, that three-dimensional Computational Fluid Dynamics (CFD) modelling is not entirely physically-based as the Reynolds-Averaged Navier-Stokes equations still require the use of two semi-empirical components; a turbulence closure model and a wall function (Nicholas and Sambrook-Smith, 1999). Examples of three-dimensional modelling software are:-

- FLUENT (www.fluent.com),
- TELEMAC3D (http://www.telemacsystem.com/gb),
- Phoenix (http://www.cham.co.uk/), and
- SSIMM (http://www.ntnu.no/~nilsol/ssiimwin/).

## 3.3. The application of hydraulic models

There are a number of hydraulic codes that are available for use in simulating flows in fluvial environments (see Table 3.3.1). These codes occur in a variety of forms and all use the concepts described above but vary them in subtle ways, which may lead to a different representation of processes. As alluded to earlier, computational hydraulic models are not directly applicable to natural river channels (Nicholas and Walling, 1998, Lane, 1998; Nelson *et al.*, 2003). This is because of the difficulties involved in specifying the boundary conditions of any hydraulic model including the representation of roughness, and the representation of turbulence within the model commonly known as the turbulence closure. Therefore, it is necessary to make a number of assumptions that are described in the following sections.

| Hydraulic Code | Applications | Notes | Handle Complex Topography | Represent Turbulence | Discretization |
|---|---|---|---|---|---|
| ISIS (1D) | Mainly large scale flood routing. | -Solves the shallow water St Vernant equations. | No | Yes | Finite difference method |
| HECRAS (1D) | Mainly large scale flood routing. | -Solves the full 1D St Vernant equations for unsteady flow | No | Yes | Finite difference method |
| Mike 11 (1D) | Mainly large scale flood routing. | -Based on shallow water equations<br>-for floodplain studies, requires the floodplain to be broken up into a number of channels (Connell *et al.*, 2001) | No | Yes | Finite difference method |
| STREMR (2D) | Proglacial braided channel (Lane and Richards, 1998) | -Solves depth-averaged Navier-Stokes equations<br>-Makes a rigid lid assumption | Yes | Two-equation model | Finite Volume solution |
| TELEMAC 2d (2D) | Floodplain inundation extents using fractal generated topography-Bates *et al.* (1998)<br><br>-floodplain inundation with high-resolution data (Bates *et al.*, 2003) | -2D shallow-water equations used<br>-Friction calibration seems to be the most important factor (Bates *et al.*, (1998)<br>-Allows free surface representation | Yes | k-Є turbulence model | Finite element mesh |
| HYDRO2DE (2D) (Beffa and Connell, 2001) | Flow and suspended sediment transport in lowland river floodplain environments (Nicholas, 2003)<br><br>-Simulation of overbank processes in topographically complex floodplain environment<br><br>-Rural floodplain (Connell *et al.*, 2001) | -Depth-averaged shallow water form of the Navier-Stokes equations<br>-Can use irregular grids | -Used in New Zealand rural floodplain with complex river topography with many channels | Eddy Viscosity and mixing length models | Finite volume method |

| | | | | | |
|---|---|---|---|---|---|
| River2D (2D) | -Forested Floodplains (Thomas and Nisbet, 2007) | -Depth-averaged shallow water form of the Navier-Stokes equations<br>-Use eddy viscosity | Yes | Eddy Viscosity | Finite Element Method |
| TELEMAC 3d (3D) | Coastal and estuarine environments | -Navier-stokes equations<br>-Developed for coastal and estuarine applications<br>Has a choice of turbulence closure models including k-Є | Yes | k-Є turbulence model | Finite Element Method |
| Fluent (3D) | Meander bends-Hodskinson and Ferguson (1998)<br><br>Floodplain hydraulics and suspended sediment transport and deposition-Nicholas and Walling (1998)<br><br>Boundary roughness in gravel-bed rivers-Nicholas (2001) (used in 2d mode)<br><br>-Three-dimensional flow hydraulics in a braided channel (Nicholas and Sambrook Smith, 1999)<br><br>-Hydrodynamics of a floodplain recirculation zone (Nicholas and McLelland, 1999) | -Navier-stokes equations<br>-Used in zones with separation.<br>-Has choice of K-Є and RNG K-Є turbulence closure models that is recommended for simulating separated and stagnated flows.<br>-Nicholas (2001) used a 'fixed-lid' approach<br>-Can be used in unstructured format to overcome problems with structured meshes (see Nicholas and Sambrook Smith, 1999)-useful in cases of complex topography | Yes | RNG k-Є turbulence model | Finite Element method |
| SSIMM (3D) (Olsen, 1996) | Simulation of flow dynamics in a river with large roughness elements (Olsen and Stokseth, 1995) | -Navier-Stokes equation with a K-Є<br>Turbulence closure model.<br>-Includes a free surface approach | Yes | k-Є turbulence models | Finite Volume Method |

| | | | | | |
|---|---|---|---|---|---|
| | Pool-Riffle sequences (Booker, 2000 and Booker *et al.*, 2001) | -Can be used in a two-dimensional depth-averaged form | | | |
| Phoenics (3D) | Secondary Circulation controls in simple confluence geometry- Bradbrook *et al.*, (1998)<br><br>-High-resolution modelling over complex river bed topography (Lane *et al.*, 2002). | -Can use free surface approach<br>-Used unsteady turbulence model | -Verified in channels with smooth beds and banks | k-Є and RNG k-Є turbulence models | Finite Volume method |

**Table 3.3.1:-Different examples of hydraulic software**

## 3.4. Boundary Conditions

In order to simulate the flow within an area of interest the Navier-Stokes equations are discretized over a representation of this specified area and whereas the equations are generally applicable to the whole flow domain, they need special treatment at the boundaries of the domain.

These boundaries are summarised by Lane *et al.* (1999) as:-

1. The Water Surface,
2. The Bed Surface,
3. The Domain Extent, and
4. The Inflow Characteristics.

### The Free Surface Boundary

The water surface, or free surface as it is known, is the only boundary that can significantly shift within small time scales as it does around large wood accumulations (Gippel, 1995). It is known to be a crucial control on the formation of flow structures in river channels (Bridge, 1992) and as such, there is a need to accurately define and represent this boundary within a model. There are a number of methods that attempt to deal with the free surface of which perhaps the most simple is the 'rigid lid' approach (Lane *et al.*, 1999). This considers the free surface as a fixed lid that is used to define a pressure that is allowed to vary according to the expected changes in water surface elevations from stage-discharge relationships that would occur if the lid was not fixed (Bradbrook *et al.*, 1998). The pressure effects are then dealt with in the momentum equations although their absence from the mass equation has led to overestimates of velocity in places where the water surface is subject to super-elevation (Weerakoon *et al.*, 1991). This might be the case when considering large wood, as large wood accumulations can locally elevate the water surface However, it is unknown whether this is significant enough to preclude the use of the 'fixed lid' approach, although some studies of channel flows have used this approach in areas of super-elevation (e.g., Hodskinson and Ferguson, 1998).

One solution to this problem, which can cope with the displacement of the free surface, is a porous-lid method applied by Lane *et al.* (1999) and Bradbrook *et al.* (1998). In this approach, a porosity value is defined for the free surface cells and the flux across any cell is set equal to the porosity multiplied by the area of the cell and the velocity component of the cell (Lane *et al.*, 1999; Bradbrook *et al.*, 1998). The deviation of the porosity from one represents a change in the height of the surface layer. Thus, the porosity is calculated so that the deviation in pressure is satisfied by a change in the height of the cell layer according to the following equation (Bradbrook *et al.*, 1998; Lane *et al.*, 1999).

$$porosity = 1 + \frac{p}{\rho g h_c} \tag{3.1}$$

Where $\rho$ is the density of water and $p$ the pressure, $g$ the gravitational constant, $h_c$ is the height of the cell. This correction allows the free surface effects to be represented in the mass equation through changing the effective discharge within a water surface cell where the surface layer is either depressed or elevated (Lane *et al.*, 1999). However, this approach is empirical in nature and, in any case where significant free surface variation is expected, it is necessary to use a full model of the boundary between the flow and air.

Other approaches that have been developed are the use of the hydrostatic assumption and the volume-of-fluid method. The former arises when codes assume that water pressure varies linearly with depth, thus ignoring vertical transfers. It is for this reason that these models are described as pseudo-3D or layered (Nex and Samuels, 1999). The momentum conservation equation can then be integrated through the depth to give an estimate for the pressure, which in turn is used to update the position of the free surface. However, this approach is best suited to cases where the free surface is not subject to sharp changes such as those that may occur at weirs, crests and active large wood accumulations where vertical transfers of mass and momentum are important (Nex and Samuels, 1999).

An alternative is the volume-of-fluid (VoF) approach. This method calculates velocities and volume fractions for both water and air at a given location by taking into account the position of the water surface of neighbouring cells. By increasing the complexity of the model this method requires more grid cells and increased computational power (Wright, 2001). It may be appropriate however, as it is one approach that can give solutions for simulation of flow where there may be sharp variations in water surface elevations as is often the case around large wood accumulations where topographic changes are steep.

### Topography

Topographic variations within a river reach and the gradients associated with such variations are the main drivers of fluid flow. As such, there is a requirement for the topography to be accurately defined in order that the Navier-Stokes equations can be adequately approximated for the region of interest. Large-scale topographic variations are represented by creating a grid or mesh of topography of the domain extent over which the Navier-Stokes equations are approximated.

### Domain Extent

The domain is the extent over which the passage of flow is simulated. For three-dimensional models, topographic variation must correspond closely with the grid-cell size. The topographic data is discretized into a grid or mesh over which the computational simulations are made. The choice of grid used, and its resolution, has the potential to have as large an influence as the chosen equations and is largely unbounded (Hardy *et al.*, 1999). Grids can vary in a number of ways, for example, they may employ different co-ordinate systems, be of varying dimensionality and contain different grid cell shapes (Darby and Van de Wiel, 2003). These variations are often outside the users control as the grid attributes are often determined by the numerical techniques used, the user can however determine the type of technique in which the chosen flow equations are used. The most common techniques used to solve the flow equations are the finite difference, finite element or finite volume techniques. Finite difference methods (FDM) employ a rectangular grid that is described using Cartesian co-ordinates although it can also be manipulated into a computational plane. The method of the FDM approach is to approximate the partial differentials in an equation by differences between values at nodes spaced a finite distance apart (White, 1999). In general, FDM are usually easier to solve than the finite element technique (Darby and Van de Wiel, 2003) however, their use is reducing, perhaps due to their geometric inflexibility, which may lead to numerical instabilities arising in the simulation (Alcrudo, 2002). Finite element methods (FEM) use an unstructured grid that uses a number of triangular or quadrilateral cells to describe the area of interest. These regions are partitioned by a number of finite nodes where the calculations take place (White, 1999). The finite element technique does not require all the cells to be of equal size, which leads to geometric flexibility (Alcrudo, 2002, Darby and Van de Wiel, 2003) which is of importance in channel-floodplain interactions especially in regions of complex topography. The use of finite element methods for solving the flow equations has been noted to demand less computational time whilst providing a high order of accuracy (Darby and Van de Wiel, 2003). The other method available uses control volumes to represent the area of interest; these are Finite Volume Methods (FVM). In FVM, space is divided into geometric shapes over which the shallow water equations are integrated to give equations in terms of fluxes through the control volume boundaries. FVM have a number of advantages in terms of conservativeness, geometric flexibility and conceptual simplicity (Alcrudo 2002). FVM can be used upon both structured and unstructured grids.

The choice of which discretization strategy to use may lead to small variations in the results of the model simulations (Bates *et al.*, 1996) but the biggest variations arise in the choice of grid resolution (Hardy *et al.*, 1999). On the one hand, there is the desire of the modeller to simulate over a grid with a resolution that would produce the maximum amount of information. However, this is not always computationally possible and so often a compromise is needed. The grid resolution does however have a significant impact on the model output (Hardy *et al.*, 1999) and although often it may seem like model output accuracy increases with increased grid resolution due to increased numerical stability there seems to be a threshold point at which increased resolution does not yield significant increases in the model output (Bates *et al.*, 1996 and Hardy *et al.*, 1999). Thus, it is paramount in any hydraulic modelling application that the sensitivity of an hydrodynamic model to grid resolution is assessed and the grid resolution chosen is one that is considered to achieve 'grid independence' with the coarsest grid to reduce computational time (Bates *et al.,*1996).

It is not just the grid resolution that contributes to the sensitivity of the hydrodynamic model, the shape and the size distribution of elements is important too. A mesh can be structured (mesh nodes have an equal number of adjacent elements) or unstructured (mesh nodes can have an unequal number of adjacent elements). Unstructured grids allow more flexibility as the density of mesh elements can be varied according to geometry and areas of varying flow diversity. This choice can enable increased accuracy and the reduction of computer run times (Nex and Samuels, 1999). Whether a grid is structured or unstructured depends largely on the type of numerical scheme used in approximating the flow, structured grids are used in finite difference schemes whereas unstructured grids are found in finite volume and finite element schemes (Nex and Samuels, 1999). For the purposes of modelling large wood accumulations where topography is likely to change rapidly and where the presence of wood as a geometric element will make mesh construction complex, the diverse flow patterns around large wood are likely to be better approximated with a higher level of grid cells. However, despite varying the density of cells within the grid it is imperative to limit abrupt changes in grid density, which may cause numerical diffusion (Bernard, 1993). A grid or mesh does not account for all topographic variations; those features that are finer than the grid resolution are not included and need to be represented by a separate roughness function.

## Bed Surface Roughness

The bed surface is a boundary condition that is often thought of as a stable boundary that does not move. Grid cells adjacent to the bed surface are assumed to be in the wall-region and that a concept known as the 'law-of-the-wall' applies (Prandtl, 1925). One consequence of this assumption is that the velocity at the interface between the bed and the flow must be zero. Thus, a velocity gradient is present between the bed and the flowing water that is referred to as the boundary layer, which extends to a height (Y) above the bed. Attempting to model this layer using the Navier-Stokes equations would prove futile, as the gradient is usually relatively steep requiring a large number of grid cells within the boundary layer, which would lead to a dramatic increase in computational time. Following this, boundary roughness is commonly modelled using the empirical wall function that relates wall conditions to those just outside the boundary layer. The so-called universal law of the wall is one such model:-

$$\frac{u}{u_*} = \frac{1}{k}\ln\left(y^+ E\right) \qquad \textbf{(3.2)}$$

where $u$ is the velocity parallel to the wall, $k$ is the Von Kárman constant, $y^+$ is a dimensionless measure of the distance of the measurement of $u$ from the wall based on the equation $Y^+=U_\tau Y/\mu$ where Y is the normal distance to the wall and μ is the dynamic flow viscosity ($10^{-6}m^2s^{-1}$) for water, $u_*$ is the shear velocity and $E$ is a roughness parameter. This logarithmic function has been widely used within fluvial geomorphology to assess shear stresses and in CFD applications to evaluate the hydraulics in the boundary-adjacent cells (Nicholas, 2001). However CFD applications have shown that this wall function does not provide adequate representation of flow where the velocity profile deviates from the logarithmic function for example, in the following cases; flow across riffles (Hodskinson, 1996), around braid bars (Nicholas and Sambrook-Smith, 1999) or in the presence of vegetation (Nicholas, 2003), which all portray regions of high relative roughness (Bathurst, 1978). Another problem may arise regarding the areas of stagnation and separation that may exist adjacent to large wood accumulations as the dimensionless roughness height ($y^+$) should be between 30 and 100 to achieve accurate simulation, but such a value may not exist in these areas of flow stagnation or separation (Rodi, 1980). However, this issue is related to grid design and it may be necessary to re-mesh the grid in order to achieve a roughness height within the desired range. There is no general consensus on any alternative methods for quantifying the topographic roughness in these areas of separation and stagnation, Rodi (1980) commented that they are usually small and exert little influence and Lane *et al.* (1999) claimed that three-dimensional models went some way to overcome this problem because as long as the grid cell dimensions were specified properly then the application of the law-of-the-wall assumption is limited to those cells in the wall region, which can be hoped to exert a minimal influence on the main body of the flow. However, it is likely that large wood and its accumulations will have a significant influence on the main body of flow so care should be taken in CFD studies of river channels and floodplains influenced by large wood.

## Inflow and Outflow Characteristics

Once the model has been set up, the equations representing the processes chosen and the area of interest represented by a mesh, it is still necessary to specify the flow at the inflow boundary. The inflow data is quite specific and is needed at a high resolution. At the upstream boundary, the input discharge, the velocities in as many dimensions as the model uses and turbulence parameters are needed for each grid cell (Lane *et al.*, 1999). At the downstream limit of the region of interest, a water surface elevation or some other free-surface limit is required. In three-dimensional models, there is a need for increased amounts of input data, especially compared to simpler two-dimensional, depth-averaged models. There is a need for improved model input, calibration and validation data to improve process representation as the number of dimensions is increased (Bates *et al.*, 1998; Nicholas and Walling, 1998; Lane *et al.*, 1999,). Nicholas (2003) and Wright *et al.* (2000) used the outputs of a two-dimensional model to input into a three-dimensional model to reduce the requirement for detailed field data. The implications of this approach have yet to be fully evaluated. Wright *et al.* (2000) used the same approach to assess river rehabilitation schemes where the water surface elevation specification could not be determined prior to restoration.

## Turbulence Closure

Turbulence is important as it is a fundamental motion in non-laminar flows and affects the velocity and momentum transfer within the flow contributing to the complexity of fluid motion (Nelson *et al.*, 2003). In order to close the Navier-Stokes equations precisely, it would be necessary to solve the equations on a grid of resolution finer than the smallest turbulent motion (Younis, 1996; Lane, 1998), while the computational time step would also have to be smaller than the time associated with the shortest-lived turbulent eddies (Hervouet and Van Haren, 1996, Younis, 1996; Lane, 1998). To reduce the necessary computing power and time required to a more manageable level some kind of turbulence theory is required to parameterise the effects of turbulent motion on the flow, with the most common formulation for natural flows being the Reynolds equation (Lane, 1998; and Nelson *et al.*, 2003). This equation, shown below, assumes that the velocity vector ($V_i$) can be divided into a time-mean value (V) and a time-varying 'random' part (V*'*).

$$V_i = \overline{V} + V' \tag{3.3}$$

Introducing these terms has no implications for the mass conservation equation but does introduce some new terms into the momentum equations. Specifically, four new unknown variables, known as Reynolds stresses, are introduced, due to the addition of the momentum fluxes associated with the turbulence and these can only be defined from knowledge of the turbulent structure, which is presently indeterminate (Lane, 1998). This is because no equations or physical laws have yet been developed which allow the closure of the Reynolds-averaged Navier-Stokes (RANS) equations and this is the well-known problem of 'turbulence closure' (Lane, 1998; and Nelson *et al.*, 2003). Many attempts have been made to try to solve this problem and obtain the Reynolds stresses and perhaps the most successful method is to use available flow parameters to model the stress tensors (Lane, 1998; Nelson *et al.*, 2003).

Most models used to predict turbulence in order to close the RANS equations are based on the Boussinesq assumption that the Reynolds stress tensors are linearly proportional to the local average rate of strain with an eddy viscosity coefficient which itself has to be determined (Younis, 1996). The simplest applications of Boussinesq's assumption have used approaches where the eddy viscosity is assumed to be constant or estimates of the eddy viscosity are acquired using a mixing length hypothesis (Lane, 1998). The former is of little practical use, as the eddy viscosity value itself cannot be measured easily in the field (Lane, 1998).

The mixing length hypothesis is based upon work by Prandtl (1925) where the eddy viscosity is estimated through consideration of average velocity and a mixing length which is specified by using empirical data (Lane, 1998). However problems arise in the zero-equation methods for estimating turbulence due to the fact that the method assumes that turbulence is dissipated at its source and does not propagate through the system. In reality, this assumption is weak as flow convection and fluctuation propagate turbulence away from the source (Younis, 1996).

Other, more complicated, methods for assessing the value of the eddy viscosity coefficient use a number of differential equations and attempt to overcome the limitation of the zero-equation approaches by using transport equations, which account for the propagation of turbulence through space (Lane, 1998). Some examples of these 'one and two equation models' are the k-ϵ model and its modification the Renormalization Group Theory (RNG) type k-ϵ model. The k-ϵ model attempts to overcome the limitations of the 'zero-equation' turbulence models by solving additional transport equations for the production, transport and dissipation of turbulence (Lane *et al.*, 1999). This is perhaps the most commonly used turbulence model used in 3-dimensional models as it is sufficiently general to be used in a range of flow applications without being overly complex (Hervouet and Van Haren, 1996). However, the standard κ-ϵ model is known to have difficulty modelling flows with considerable mean strain such as those in separation zones (Hervouet and Van Haren, 1996). These separation zones are likely to occur in the presence of large wood accumulations, which block and divert flow around and through permeable sections of the accumulation. Smith and Foster (2002) simulated flow past a pipeline in a coastal environment and found that the k-ε turbulence closure scheme may have been responsible for the under prediction of downstream flow velocities. Recently there has been an increase in the use of the RNG-type k-ϵ model, which simulates increased dissipation in flow separation scenarios (Bradbrook *et al.*, 1998; Hodskinson and Ferguson, 1998; Nicholas and Sambrook-Smith, 1999). The RNG k-ε approach gives a greater dissipation of turbulence in areas of strong strain, which leads to a reduction in eddy viscosity and subsequently improves velocity predictions. The key to its improved representation of highly strained flow is the assumption of spectral equilibrium, in which the generation at large turbulent scales is immediately dissipated at smaller turbulent scales (Bradbrook *et al.*, 1998). Where strain rates are high, such as at separation and convergence points there is a significant difference between the scales at which turbulence is generated and subsequently dissipated.

However, Younis (1996) argued that the Boussinesq assumption is not necessarily the most useful basis for predictive modelling of open-channel flow due to its assumption of a linear stress-strain relationship, which may produce incorrect estimates of turbulence anisotropy; the absence of a free surface representation; and the insensitivity of the assumption to longitudinal streamline curvature. However whilst it is known that the k-ϵ model may be questioned in this respect the modified RNG-type k-ϵ models may address some of the problems of the basic k-ϵ model (Lane *et al.*, 1999) and other eddy-coefficient models based on Boussinesq's assumption.

There is a wealth of eddy viscosity concepts and equations that are extremely complex in nature, some of which are non-linear, and others that seek to overcome the limitations mentioned by Younis (1996). However, they are much more sophisticated than those used within currently available hydrodynamic models of the type that are applied to river channel and floodplain problems. Discussion of all the available turbulence closure models is beyond the scope of this review, and for a detailed description of different methods, the work of Rodi (1993) and Younis (1996) should be referred to. However, what is important is that the method of turbulence closure is the area where most hydrodynamic models vary and that when using a certain model with a particular approach to turbulence closure one must be aware of the potential errors in the closure mechanism (Nelson *et al.*, 2003). Of equal importance is to bear in mind the representation of physical processes by particular closure equations and to understand which processes are represented to a high level of accuracy and those that are not (Nelson *et al.*, 2003). By understanding the processes accurately portrayed by certain turbulence closure equations an improved understanding of the system modelled will be acquired and this is of importance when attempting to understand the impact of large wood on flow hydraulics. For this reason it is essential that a robust turbulence closure model is applied which can handle the separation of flows and the levels of turbulence that arise adjacent to large wood accumulations.

### 3.5. Application of hydrodynamic models to floodplain flows

Given the interest in the floodplain as a geomorphological and hydrological unit there has been a desire to simulate floodplain flows to gather an insight into flow and sediment storage upon the floodplain (Gee *et al.*, 1990). Due to the complex topography of floodplains, diverse flow patterns and the presence of vegetation and the conditions encountered within the field, floodplain flows are more difficult to model than those predominantly within the channel. However, it is still possible to estimate flow properties for overbank, floodplain flow. Gee *et al.* (1990) were one of the first groups to attempt to model floodplain inundation extents and floodplain flow vectors and found that the model was able to accurately predict flood hydrographs and create inundation patterns similar to those observed in the field. Other authors have used these inundation patterns and velocity vectors to predict spatial sedimentation patterns on grass covered floodplains (Nicholas and Walling, 1997; Nicholas, 2003; Sweet *et al.*, 2003). Such spatial patterns were found to be dependent on small-scale topographic features, which influenced floodplain inundation sequences and velocity vectors. This may not be the case in riverine woodlands where vegetation and large wood can have an influence upon flow patterns (Brown *et al.*, 1997).

When studying floodplain environments there are a number of criteria that a hydrodynamic model should adhere to in order to give accurate process representation and these were summarised by Bates *et al.* (1996) as:-

- A two-dimensional or higher representation of the flow to capture process dynamics.
- Efficient numerical solution algorithms to enable high space/time resolution to improve accuracy of process representation.

- The capability to represent complex topography with a minimal number of computational nodes.
- The ability to represent the drying and wetting processes that occur in a dynamically moving flow such as a flood flow (although not the case for steady state simulations).
- To represent a turbulence field that is relevant to the scale of application.

Table 3.5.1 shows some applications of different hydrodynamic models. The method of roughness specification is included in the table as are the data used to validate the model.  It is also useful to assess which type of water surface elevation method and turbulence closure methods were used in each application.

| **Authors** | **Application** | **Model used** | **Model Dimensions** | **Floodplain Present?** | **Roughness** | **Validation data** | **Turbulence** | **Lid** |
|---|---|---|---|---|---|---|---|---|
| Gee *et al.* (1990) | Large scale floodplain modelling | RMA-2 | 2 | Yes | Field estimates using Chow (1959) | Stage | Eddy viscosity coefficient | Not Specified |
| Bates *et al.* (1992) | Modelling Floodplain flows | RMA-2 | 2 | Yes | Field estimates using Chow (1959) | Hydrographs | Eddy viscosity coefficient | Not Specified |
| Nicholas and Walling, (1997) | Modelling flood hydraulics and overbank deposition on river floodplains | St Vernant equations | 2 | Yes | Channel and floodplain roughness calibrated from Water Surface Elevations | Ground photographs for inundation extents<br>Sedimentation rates from $^{137}$Cs analysis | Not Specified | Fixed lid |
| Bradbrook *et al.* (1998) | Secondary circulation in a simple confluence geometry | PHOENICS | 3 | No | Law of the wall | Velocity measurements | RNG k-Є model | Free surface approximation |
| Hodskinson and Ferguson (1998) | Separated flow in river bends | Fluent | 3 | No | Law of the wall | Velocity measurements<br>Stage | RNG k-Є model | Fixed Lid |
| Lane and Richards (1998) | Modelling of flow processes in a multi-thread channel | STREMR | 2 | No | Manning’s n from Strickler (1923) equation | Velocity measurements | Length scale equation | Fixed lid |
| Nicholas and Walling (1998) | Modelling of floodplain hydraulics and suspended sediment transport and deposition | RMA-2 | 2 | Yes | Calibrated using water surface elevations | Floodplain inundation extents<br>Flow depths<br>Velocity measurements<br>Patterns of suspended sediment dispersion and deposition | None | Fixed Lid |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nicholas and McLelland (1999) | Hydrodynamics of a floodplain recirculation zone | Fluent | 3 | Yes | Estimated from $D_{50}$ of channel sediment | Velocity measurements | RNG k-ε model | Fixed Lid |
| Nicholas and Sambrook-Smith (1999) | Simulation of three-dimensional flow in a braided river | Fluent | 3 | No | From bed sediment | Velocity measurements | RNG k-Є model | Fixed lid |
| Siggers *et al.* (1999) | Modelled overbank hydraulics | TELEMAC-2D | 2 | Yes | Manning's n from Chow (1959) | Medium term sedimentation rates from radionuclide analysis | Eddy viscosity Coefficient | Not Specified |
| Stewart *et al.* (1999) | Modelling floods in hydrologically complex lowland river reaches | TELEMAC-2D | 2 | Yes | Manning's n | Discharge hydrographs Flood Inundation extents | Eddy viscosity coefficient | Not specified |
| Lane *et al.* (2000) | Secondary circulation cells in river channel confluences | PHOENICS | 3 | No | Roughness height estimated from sedimentological data | | Large Eddy simulation | Free surface approximation |
| Booker *et al.* (2001) | Flow structures in natural pool-riffle sequences | SSIMM | 3 | No | Used $D_{84}$ Calibrated | Velocity measurements | k-Є model | Not Specified |
| Connell *et al.* (2001) | Two-dimensional floodplain flow | Hydro2De MIKE11 | 2 and 1 | Yes | -Calibrated from flood extents or in case of 'uncalibrated run' estimated from published information | Flood inundation extents from survey and photographs | Not Specified | Hydrostatic Assumption |
| Fischer-Antze *et al.* (2001) | Modelling open - channel flow with submerged vegetation | SSIIM | 3 | No | Vegetation drag estimated from vegetation density and stem width | Velocity profiles | k-Є model | Fixed Lid |
| Nicholas | Boundary | Fluent | 2 | No | Wall function and a | Velocity measurements | RNG k-Є | Fixed lid |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (2001) | roughness in gravel bed rivers | | | | random elevation model that simulates the effects of supra scale roughness elements | | model | |
| Ali and Karim (2002) | Simulation of flow around piers | FLUENT | 3 | No | Law of the wall | Verified the relationship for maximum depth of scour hole with laboratory and field data from other authors | k-Є model and a RNG k-Є model | Fixed lid |
| Horritt and Bates (2002) | Evaluation of 1d and 2d models for predicting river flood inundation | HEC-RAS LISFLOOD-FP TELEMAC-2D | 1, and 2 | Yes | Calibrated Manning's n | Inundation extent provided by remotely sensed imagery | Not specified | Not Specified |
| Lane et al. (2002) | Modelling of 3D flow over complex river bed topography | PHOENICS | 3 | No | Roughness height for skin friction only<br>Form drag represented by a porosity-based approach | Velocity measurements | RNG k-Є model | Numerical porosity scheme |
| Smith and Foster (2002) | Modelling of flow and scour around a pipeline | FLOW-3D | 3 | No | Specified relative roughness | Compared amount of scour with that from other authors | k-ε model | VOF method |
| Bates *et al.* (2003) | Use of high-resolution topographic data in flood inundation models | TELEMAC-2D | 2 | Yes | | Discharge hydrographs | Zero-equation model | Dynamic flooding so used a wetting and drying algorithm |
| Nicholas (2003) | Modelling flow and suspended sediment transport in lowland river floodplain environments | Hydro2de | 2 | Yes | Calibrated | Velocity measurements<br>Suspended sediment concentration | k-ε model | Fixed lid from 2d model output |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nicholas and Mitchell (2003) | Simulation of overbank processes in topographically complex floodplain environments | Hydro2de | 2 | Yes | Initial estimates from velocity profiles and then calibrated using stage-discharge curves | | None- Assumed negligible | Hydrostatic Assumption |
| Sweet *et al.* (2003) | Estimating rates of overbank sedimentation on British lowland floodplains | Hydro2De | 2 | Yes | Calibrated from observed and modelled stage discharge relationships | -Sediment deposition rates were compared to those from $^{137}$ Cs analysis | Not Specified | Hydrostatic Assumption |
| Wilson *et al.* (2003) | Modelling of compound channel flows | SSIIM and TELEMAC2D | 3 and 2 | Yes | Specified value | Velocity measurements Water Surface Elevations | k-ε model | Not-specified |
| Pasternack *et al.* (2004) | Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment of the Mokelumne River, California | FESWMS-2DH | 2 | No | Roughness tables | | Eddy-Viscosity coefficient | Fixed Lid |

**Table 3.5.1: Applications of hydrodynamic models**

## Representing Floodplain Vegetation within Hydrodynamic Models

Vegetation imparts an important resistance upon flow within vegetated channels and floodplains (Chow, 1959). It is particularly important in the case of floodplain flow dynamics as, for inundation less than 1 metre in depth, vegetation dominates the boundary friction term (Cobby *et al.*, 2003). However, within hydrodynamic models vegetation is often ignored or used as a calibration parameter, which can reduce a model's predictive ability (Cunge, 1998; and Cobby *et al.*, 2003). With the recent interest in floodplain processes (Anderson *et al.*, 1996), there is a requirement to account for the effect of vegetation (Vionnet *et al.*, 2004). In the majority of modelling studies, the floodplain vegetation is short grasses and is usually represented as a boundary roughness function. There are a number of methods that can be used to estimate the value of the vegetative roughness parameter at each grid node.

One method is to choose a value of roughness from tables such as those produced by Chow (1959) and Arcement and Schneider (1987) or from empirical equations relating vegetal properties to roughness such as those developed for short vegetation by Kouwen and Unny (1973) and Kouwen and Li (1980) and those for tall and intermediate vegetation developed by Fathi-Moghadam and Kouwen, (1997) and Kouwen and Fathi-Moghadam (2000). This may mean the channel and floodplain resistance is represented by a single value (eg. Nicholas and Mitchell, 2003; and Pasternack *et al.*, 2004) or spatially distributed roughness values (eg. Mason *et al.*, 2003; and Cobby *et al.*, 2003). Where a single value is chosen, it is often calibrated in order to allow a 'best fit' between modelled and observed flood events (eg. Bates *et al.*, 1998; and Nicholas and Mitchell, 2003). However, it has been argued that such *ad hoc* adjustments destroy a model's predictive capability and severely hamper the development of physically-based and generic models (Cunge, 1998; Cobby *et al.*, 2003; Pasternack *et al.*, 2004). A spatially distributed friction model has an advantage in that it is physically based (Cobby *et al.*, 2003). However due to the wide range of floodplain vegetation it is often difficult to specify accurate roughness coefficients (Darby, 1999; Vionnet *et al.*, 2004). There is also no currently accepted practice for the representation of large wood and its accumulation within hydrodynamic models. Pasternack *et al.*, (2004) suggested that large wood could be represented through the variation of local flow parameters in order to allow the model simulations to achieve parity with the observed conditions and this approach could be applicable for the simulation of the effect of large wood accumulations

Vegetation can also be represented within a hydrodynamic model as vertical cylinders. Fischer-Antze *et al.*, (2003) used vertical cylinders to model aquatic vegetation with a drag force included as a sink term in the Navier-stokes equations. The drag force approach simply requires a plant density to be specified. They found that the method compared well with results from flume studies. The method was found to be advantageous as the effects of the vegetation were accounted for throughout the water depth rather than just affecting the flow near the bed (Fischer-Antze *et al.*, 2003). Olson (2001) reports that this approach gives good results although there are problems given that the vegetation often contains leaves and that the vegetation may be flexible which require further research.

In riverine woodland environments, short vegetation like that present in other lowland environments is relatively rare and the main floodplain vegetation is stands of trees, which contribute to roughness and cause variations in flow patterns (Li and Shen, 1973; Harwood and Brown, 1993). However where individual trees can be discriminated it is possible to represent the vegetation as topographic elements within the mesh over which the RANS equations are solved. This approach is similar to those studies that look at flow patterns around bridge piers and underwater pipelines (eg. Richardson and Panchang, 1998; Brørs, 1999; Tseng *et al.*, 2000; Smith and Foster, 2002). In the case of a relatively small floodplain reach, it could be possible to allow the representation of individual trees within the generated mesh.

However, with large wood it is often the case that whereas the general geometry of the wood accumulation can be specified, the porous nature of the accumulation means that it cannot be represented as a solid obstruction. Cobby *et al.* (2003) meshed hedgerows within a river floodplain system by specifying the location, and then specifying a roughness parameter depending on the hedgerow height, as derived from airborne scanning laser altimetry. This method may be useful in the simulation of large wood accumulations but would require a robust method that relates resistance to the specific nature of the large wood. This would allow the model to be used as a predictive tool to evaluate large wood restoration.

Lane (2005) argued that in some cases the idea of roughness is misleading. He argues that the "*…real meaning of roughness… is as a component of topography that has to be parameterised rather than a component that has any meaning in itself.*" (Lane, 2005 p251). This is because roughness is scale-dependent. As the resolution is increased, the description of roughness changes to encompass topographic effects not explicitly covered by classic fluvial dynamics description of roughness (i.e. where topographical surfaces protrude through the viscous sub-layer). By increasing the resolution of the spatial scale, it is necessary to change the amount of topography that must be parameterized as roughness. A roughness parameters assumes that the effect of roughness is only upon the amount of momentum loss. However, in reality sub-grid scale topography and vegetation may also effect the routing of the flow through the result of blockage. When a flow route is blocked, the required roughness value tends to infinity and therefore is likely to be outside of the range for which roughness coefficients were developed (Lane, 2005). An alternative would be to use a porosity-based method which uses a regular block structured mesh and represents bed topography and vegetation through a porosity parameter where the cell porosities are 1 for cells that are all water and 0 for cells that are all blocked and cells that are partially blocked are given a value between 0 and 1 (Olson and Stokseth, 1995; Lane *et al.*, 2002). A drag term is also included to account for the drag contributed by a blockage (Lane *et al.*, 2002).This approach was found to give a better estimation of flood inundation extent than those obtained with conventional roughness parameterization (Yu and Lane, 2006). However, this approach is not entirely theoretically based and no guidelines are available on how to specify the porosity of those cells with a partial blockage. Furthermore, although the method has potential to be used in representing vegetative roughness (Lane and Hardy, 2002) at present it is yet to be applied to examples where vegetative roughness is likely to cause a significant flow blockage, as it may in the case of large wood.

## 3.6. Summary of Hydraulic Modelling

Although hydraulic modelling is an important tool for investigating fluvial forms and processes at spatial and temporal scales that cannot be monitored and in environments where direct measurement is difficult, caution must be used when using the approach. It is all too easy to use hydraulic modelling as a black box approach with no understanding of the physical basis for such models. It is also important to accurately input the system characteristics of the area to be modelled as this could be where many of the differences between observed and simulated outputs may arise. In terms of modelling river-floodplain systems with large wood there is a need for accurate representation of the hydraulic processes that occur (see Knight and Shiono, 1996) and therefore a two-dimensional or three-dimensional code is required. There is also a need for a relatively advanced scheme to take into account the highly variable free surface that may occur at large wood accumulations where the backwatering effect is important (Gippel *et al.*, 1992). For this reason, a two-dimensional code has been chosen for use within this study justification for which is outlined in section 5.6.

# 4. Field Sites

## *4.1. Introduction*

Large Wood in rivers is a phenomenon that is most commonly associated with relatively undisturbed woodland streams, of which there are very few locations in western Europe (Brown, 1997). Most rivers in lowland Britain have been significantly altered through various engineering works designed to straighten watercourses in order to hasten the passage of water to the sea. Although not entirely natural, one location where such woodland streams exist is the New Forest, which is the largest area of ‘unsown’ vegetation within Lowland Britain (Tubbs, 2001) and the largest area in Western Europe where heathland, grassland, mire and pasture woodland survive together. The New Forest is situated in southern England located between the Solent and the south coast (see location map in Figure 4.1.1). It was recently designated a National Park covering just over 57,000ha where over half (56%) is an area of national or international importance for nature conservation.

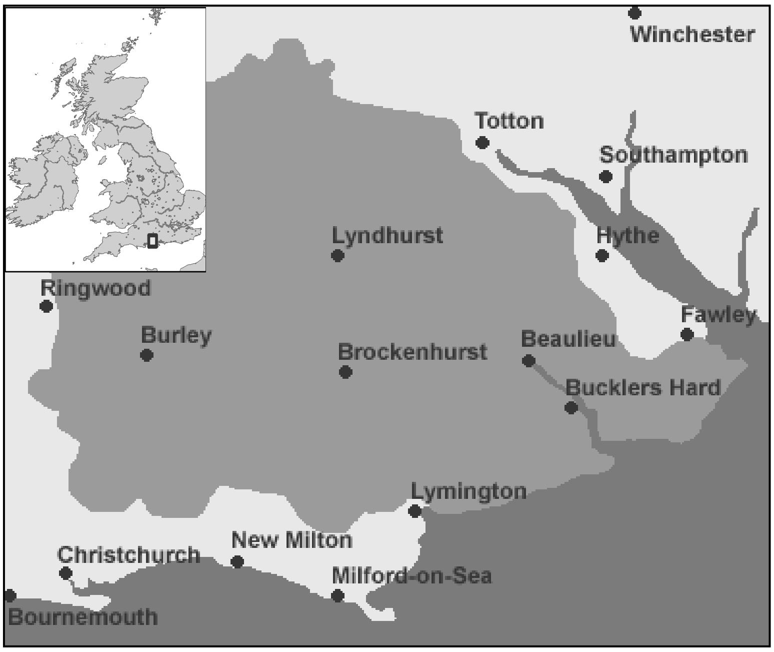



**Figure 4.1.1: The New Forest and its location.**

## *4.2. Geology*

The New Forest is in the centre of a chalk basin known as the Hampshire Basin. The rocks are of Eocene and Oligocene age and are covered by sands (Barton Sands with local loam) and clays (Barton Clays of marine origin) laid down in a series of sedimentary episodes during the Tertiary era (see Figure 4.2.1). The current floodplains are composed of mostly fluvially deposited clays, silts, sands and gravels. There is some evidence of rivers terraces which suggest that sea level change led to a period of downcutting beginning 3-6000 years ago leaving relict floodplains in some areas (Tubbs, 1986). The complex geology means that dry heaths, bogs acidic soils and alkaline soil environments all co-exist within the New Forest.

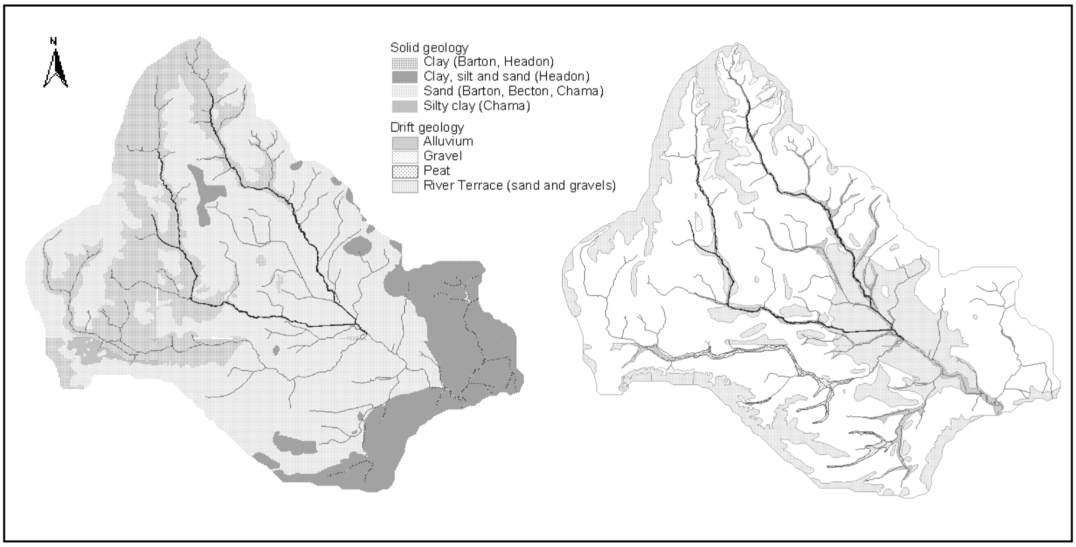



**Figure 4.2.1:-Solid and drift geology for the Lymington River catchment (from Geodata, 2003).**

The soils of the New Forest are essentially mesotrophic, which have a low fertility, and this precludes agriculture within the catchment. Floodplain soils are poorly drained clay soils leading to bog woodland and mires, which are important habitats within the New Forest.

The mostly impermeable soils and rocks result in a high level of surface runoff and create a ‘flashy’ regime to the hydrology as shown in the flow hydrograph from the Highland Water 2 gauging station at Brockenhurst in Figure 4.2.2 (location of gauging station shown in Figure 4.4.2). The current drainage patterns reflects reworking of the solid and drift geologies during the Pleistocene period (Tubbs, 1968).

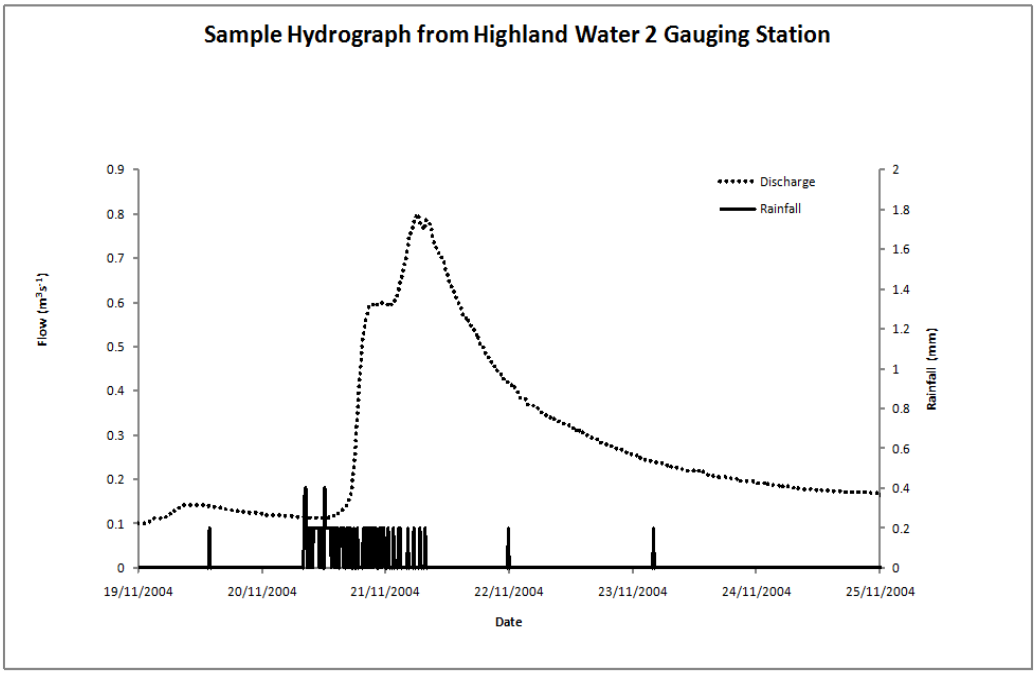



**Figure 4.2.2: Flow Hydrograph from Highland Water 2 gauging station downstream of the Highland Water Research Catchment.**

## *4.3. Land Cover and Management*

The New Forest mainly comprises of two main land cover types; heathland and woodland. The heathland is mostly dry heathland dominated by the dwarf shrub species *Calluna Vulgaris*. However, there are wetter patches of heath and bog areas that include such varieties as *Erica tetralix*, *Myrica gale*, *Juncus app* and *Sphagnum app*.

Within the woodlands are stands of semi-natural deciduous woodland and Forestry Commission managed coniferous forest. This reflects the main land use;

forestry which is managed by the Forestry Commission. Forestry has had an impact upon the nature of the drainage system through the cutting of drainage ditches to encourage draining of valley sides to allow the growth of conifer plantations.

The other major land use is commoning, which is an important feature within the New Forest. Large herbivore livestock such as pigs, cattle, New Forest ponies and wild deer are free to roam in areas of the open forest (as opposed to plantations and other enclosures). The resulting heavy grazing influences the understorey vegetation cover, which is almost non-existent, and reduces the density of the vegetation such that it is much lower than that of the natural, climatic climax assembly (Jefferies *et al.*, 2003). Commoning rights pre-date any statutory legislation although they were officially ratified in the New Forest Act of 1698, which entitled the Commoners to the open forest.

The whole of the New Forest has Sites of Special Scientific Interest (SSSI), Special Protection Area (SPA) and Special Area of Conservation status (cSAR). Furthermore, the SSSI is also a RAMSAR site due to the plant and invertebrate species associated with some of the wetland areas.

The New Forest is one of the few areas within the UK where woodland river channels remain relatively unmanaged. The New Forest is therefore ideal for the study of the role of large wood in influencing fluvial systems. Some have even suggested that the Highland Water could be used as an analogue for natural river systems although large wood densities are still only a small proportion of what may have been present in historical times (Gregory, 1992).

## *4.4. The Highland Water*

The Lymington River drains most of the New Forest flowing south into the Solent and draining a catchment area of 98.9km$^2$. There are three main tributaries; the Highland Water, Blackwater and Oberwater (see Figure 4.4.1).

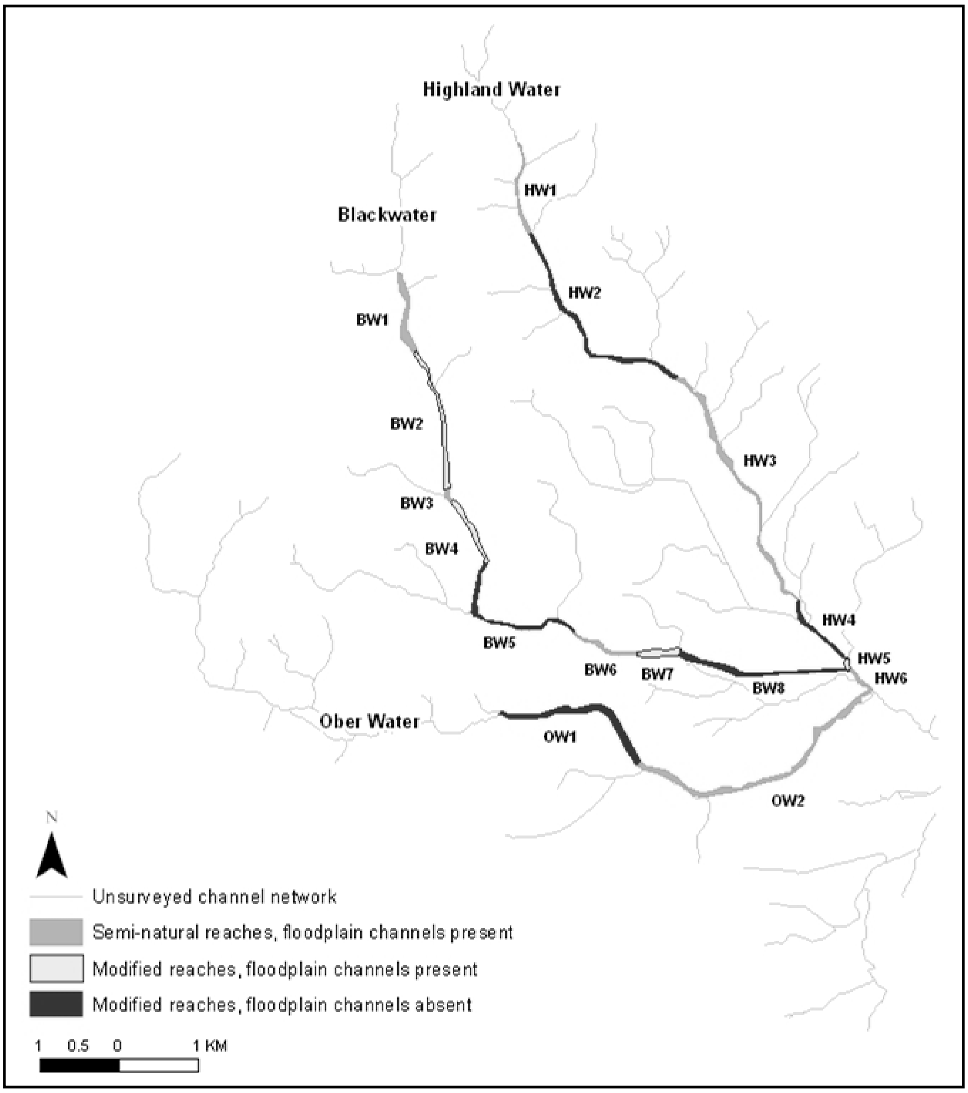



**Figure 4.4.1: Drainage network of Highland Water, Blackwater and Oberwater basins (from Sear *et al.*, 2010).**

The Highland Water is a headwater sub-catchment of the Lymington River with a catchment area of 25km$^2$ and a main stream length of 10.6km. The channel is a third-order, meandering stream with a drainage density of 1.76, which is positively correlated with sediment yield (Gregory and Walling, 1976). The Highland Water rises in an incised valley before opening out at its confluence with the River Blackwater. The drift geology overlaying the Highland Water catchment is mainly alluvial silts, however for a short distance it does flow across sand and gravel, which are former river terrace deposits. The channel is of a low slope typically of the order of 0.0075m/m and the typical width is 3m mainly comprising of gravel beds with cohesive silty clay banks. The main geomorphological features within the river are pool and riffle sequences, which are ubiquitous throughout the Highland Water, and gravel bars (Gregory *et al.*, 1994).

What is uncommon about the Highland Water is that it is forested for much of its length and this leads to substantial quantities of large wood both within the channel and on the floodplain (Gurnell and Sweet, 1998). The floodplain vegetation cover is predominantly semi-natural deciduous woodland with species such as sessile oak (*Quercus robur)*, (ash) *Fraxinus excelsior*, holly (*Ilex aquifolium*), alder (*Alnus glutinosa*), and beech (*Betula pubescens*). Again, due to grazing by large herbivores, ground vegetation is sparse but includes bracken (*Pteridium aquilinium*), bramble (*Rubus spp.*), and blackthorn (*Rubus fruticosus*) with some dense bryophyte patches (Peterken *et al.*, 1996). There are some reaches of the Highland Water where the channel flows through coniferous plantations with the main species being Common Spruce (*Picea abies*) and Douglas Fir (*Pseudotsuga menziesii)*. The presence of large wood is important to New Forest rivers as its presence is valuable in improving river habitat, modifying sediment budgets and flood hydrographs.

The Highland Water, with the shade given by the woodlands that flank it and with the prevalence of large wood within the channel, is a good habitat for species such as Brown Trout (*Salmo trutta*), eel (*Anguilla Anguilla*), Brook Lamprey (*Lampeta planeri*), Minnow (*Phoxinus Phoxinus*) and the Bullhead (*Cottus Gobin*) as well as a range of macrophytes and invertebrates.

The hydrology of the Highland Water is essentially natural with no artificial abstractions or discharges. However, there is a long history of drainage associated with the forestry within the catchment. The high hydraulic conductivity of the gravels and impermeable clays in the valleys give rise to rapid surface runoff which result in relatively steep hydrographs with high peaks and little base flow.

It is not uncommon for the channels to dry out during the summer months leaving a series of stagnant pools, which become linked when the system responds rapidly to any significant summer rainfall.

The Highland Water has been used as a research catchment since the 1970s and a large number of instruments recording a variety of environmental parameters have been installed. Rainfall gauges and weather stations provide meteorological data for a number of locations throughout the catchment. The main river also has a number of flow gauging stations that record discharge at a number of key locations on the Highland Water. Figure 4.4.2 shows the locations of the main gauging stations on the Highland Water as well as those present on the adjacent Blackwater. There are also sediment-monitoring stations in the catchment that measure bedload and suspended sediment concentrations.

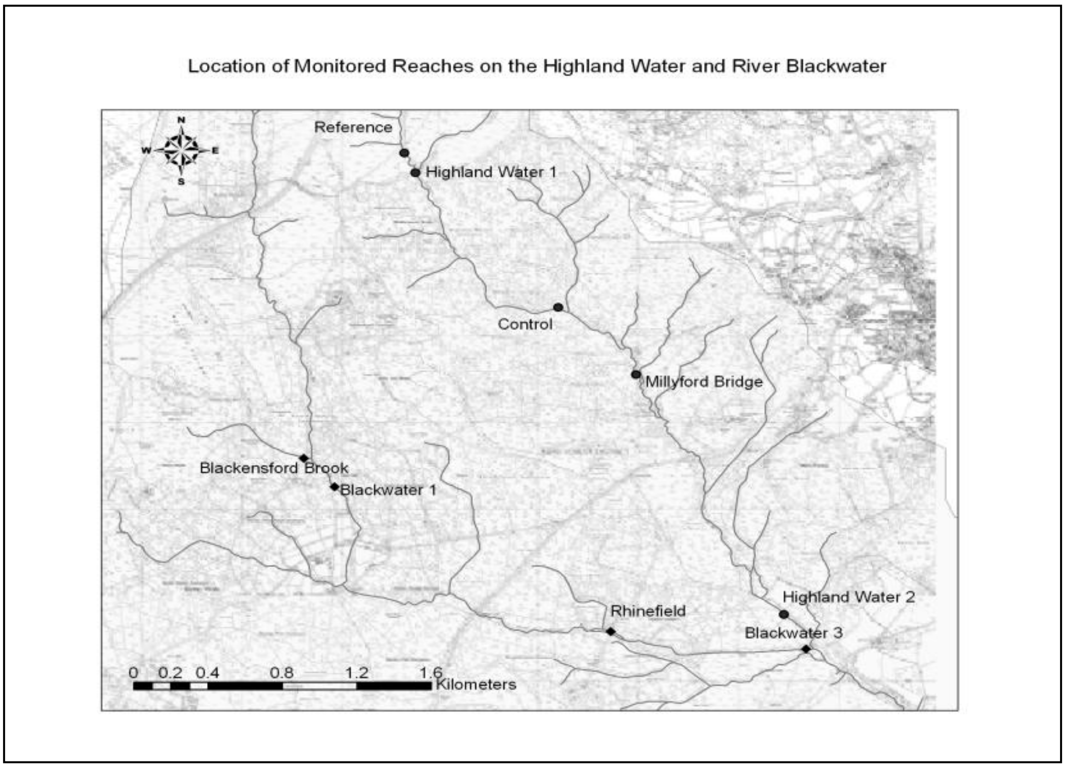



**Figure 4.4.2: Location of the gauging Stations on the Highland Water and Blackwater, New Forest.**

The climate of the Highland Water is similar to that of much of southern England with a maritime climate characterised by mild wet winters and warm wet summers. Annual Rainfall is of the order of 750mm and the typical temperature range is 2°C to 25°C. Uniquely in the English lowlands, the New Forest streams are largely free of sources of significant pollution (Tubbs, 1986).

## Historical Change

The New Forest and the Highland Water have undergone some historical landuse change as a result of a series of statutory acts (summarised in table 4.4.1) which apply to communing and can influence the numbers of large herbivores and the areas of forestry enclosures within the catchment. However perhaps of most significance to this project is the historical management of the river channels and floodplains. Management has taken two forms; channelisation and re-grading of the river channels for drainage, and; the management of the large wood within the channel to increase conveyance.

| Period | Landuse |
|---|---|
| Bronze age | Partly cleared for arable cultivation and pastoral agriculture - poor soil was never very fertile |
| Ca. 1100 | Forest law imposed by the Crown: commoners no longer had total rights to graze their stock |
| 1698 | New Forest Act - enclosed 6,000 acres of land for inclosures |
| 1851 | The Deer Removal Act (deer were no longer hunted because woodland became more economically viable than hunting) included another 10000 acres of woodland inclosures |
| 1851 to 1871 | Inclosure between these dates amounted to 5,037 acres under the 1851 Act, and 4,228 acres under the 1698 Act of the total 67,000 acres of Open Forest |
| 1877 | New Forest Act - allowed the verderer's court to exercise the power of common rights, thus eroding the interests of the crown. Also reduced the power of inclosure for forestry, which meant that a maximum of 16,000 acres was to be enclosed at any one time of the 67,000 total forest acres (total forest acreage is 90,000 acres). |
| 1949 | This Act allowed a further 5,000 acres to be inclosed for forestry, although only 2,000 acres were actually affected; these 'verderer's inclosures' require the verderers agreement and are only allowed to exist for an agreed term of years before reverting to open forest. |

**Table 4.4.1: Statutory changes affecting landuse in the New Forest (from New Forest Life Partnership, 2006).**

In terms of channelisation, periodic works have been undertaken since the 1840s, which channelised and re-graded large sections of the New Forest rivers. The period of the most intense work was the 1950s and early 1960s when large sections of the Highland Water were subject to engineering works. The valley sides and floodplain mires were drained and the channel channelised in order to reduce localised flooding and improve the soil for forestry. Many maps show the extent of some of the channel straightening and in some locations, incision associated with the channelisation has led to the disconnection of the channel from its floodplain. This has meant that, with little sedimentation or geomorphological work upon the floodplain, the relic meanders and wandering channels that were previously occupied by the river are still present in the terrain.

The history of large wood management is less well documented due to the lack of information being kept. The New Forest Act of 1949 gave the Forestry Commission the duty to secure proper drainage of the New Forest. One of the greatest pressures was from the commoners who wanted land drained for pasture improvement. Therefore, it was general practice to remove large wood accumulations for drainage purposes. It is also likely that historically, large wood would be removed from floodplains for fuel and firewood. Gurnell and Gregory (1995) noted that between 1982 and 1984 there was a short period of no significant management of large wood accumulations, which they took as an example of an undisturbed channel system. Prior to this, they found that that formal removal of large wood had taken place. In January 1990, there was a specific act of debris clearing however, the effect of this was short lived as a large storm on the 24th January 1990 resulted in considerable treefall, which increased large wood loadings within the channel and floodplain (Gurnell and Gregory, 1995). Since the 1990s, the management of large wood has been more relaxed with no formal clearance, indeed the current general advice is that large wood accumulations should be left in place due to their benefits to ecology, hydrology and geomorphology. It is within this context of relaxed management that the EU LIFE 3 restoration projects have occurred.

## 4.5. EU LIFE 3 PROJECT

Due to the potential for high ecological value within the New Forest there have been a number of restoration projects carried out in order to rehabilitate sections of the New Forest ecosystem. Between 1997 and 2001, an EU LIFE 2 project restored 4000ha of wet heath, valley mire and broad leaf woodland habitats as part of an ecological restoration project. This was followed by an EU LIFE 3 project, which was commissioned in July 2002, and funded by the European Commission and other project partners (www.newforestlife.org.uk). The aim of the EU LIFE 3 project was to develop sustainable wetland restoration in the New Forest to achieve a better understanding of the hydrological processes that occur in this semi-natural location. The key objectives were to restore 604 hectares of priority interest features of the Special Areas of Conservation within the New Forest. This involved 10km of river restoration together with the creation of 261 hectares of riverine woodland as well as recreation of conditions favourable for the development of significant areas of other priority habitat (New Forest Life Partnership, 2006). These objectives fit within both the Water Framework Directive (EU, 2000) and the EU Habitats Directive (EU, 1992). The EU Life 3 project was one of the biggest river restoration projects to be conducted within the UK and had as its objectives:-

- Recreate hydrological conditions that are favourable for the development of riverine woodland analogous to other sites within the catchment
- Demonstrate that the restoration led to no net increase in downstream flooding.
- Demonstrate the use of large wood as a method of allowing natural recovery of river channels and in improving the channel-floodplain connectivity

Reconnection of the channel to its floodplain could recreate a flood pulse to the floodplain, which is critical to the development of diverse environments (Gurnell, 1997; Petts, 1998, Tockner *et al.*, 1998; Tockner *et al.*, 2000; Tockner and Stanford, 2002). The use of large wood was a novel approach especially within a

UK context and thus the EU LIFE 3 project provided an excellent opportunity to improve understanding of the hydraulic and hydrological role of large wood and its structures.

The two main locations subject to restoration within the New Forest were the River Blackwater and the Highland Water. Being part of the University of Southampton's Research Catchment, the Highland Water had undergone 30 years of study in the fields of hydrology and fluvial geomorphology. The length and nature of this research record and associated databases (see for example, Gregory *et al.*, 1985, Gurnell and Sweet, 1998; Jefferies *et al.*, 2003) together with the restoration opportunity provided an excellent opportunity to study the influence of large wood on the hydrological and hydraulic nature of the catchment. It was as part of this restoration project that this research was funded.

The Highland Water had undergone widespread channelisation prior to the 20th century. This was deemed desirable at the time for reasons of improved forestry drainage. As a result of channel straightening and widening, widespread incision occurred. The management and clearance of large wood increased channel conveyance as average velocities almost doubled compared to those that existed before the clearance (Gregory, 1992). Channel incision led to a knick point passing upstream through the catchment as the base level changed (*as per* Schumm *et al.*, 1984). Passage of the knick point reduced the thalweg elevation, which led to an increase in bank height (see Figure 4.5.1). The subsequent increase in channel cross-section area increased channel conveyance, which subsequently led to the disconnection of the channel from its floodplain. The objective of the EU Life 3 restoration project was to re-create those conditions favourable for the regeneration of riverine woodland, part of which was a need to restore the link between the channel and its floodplain. In order to achieve this, a two-stage approach was taken which looked at the hydro-geomorphological and ecological components. This comprised of river restoration together with the removal of non-native vegetative species from the floodplain. The removal of non-native species included plantation species such as Turkey Oaks (*Quercus Cerris*) and rhododendrons (*Rhododendron ponticum).*

**Figure 4.5.1: Bank Height of the Channelised Reaches of the Highland Water.**

## EU Life 3 Approach to River Channel and Floodplain Restoration

Restoration of river channels and their floodplains can be approached in many ways depending on the objectives of the restoration. Kern (1992) highlighted the need for a '*leitbild*' or an end goal of which to work to, to fulfil the objectives of the project. As stated earlier, the main objective of the EU Life 3 New Forest restoration project was to re-establish the link between the river channel and its floodplain in order to recreate the conditions favourable for the development of riverine woodland, which is priority habitat under the EU habitats directive (EU, 1992). Reconnection of the channel-floodplain link can give rise to a diverse ecological habitat such as riverine woodland (Tockner *et al.*, 1998; Tockner *et al.*, 2000). It is this natural level of habitat heterogeneity that any restoration should seek to address at a number of spatial scales to ensure that there are improvements at both the reach and catchment scale (Clarke *et al*., 2003).

The theory for the restoration of channel-floodplain connectivity is well known (Brookes, 1996; Holmes, 1998) but what is rarer is practical opportunities to put into practice some of the theory of floodplain restoration, especially given a general lack of government funding for restoration projects (Bruce-Burgess, 2004). The New Forest EU Life 3 restoration project represented one such opportunity. The objectives of the restoration enabled implementation of one of Brookes *et al.* (1996) general approaches to floodplain restoration: less intensive restoration of larger floodplain areas. The approach taken was to restore the flood pulse by reconnecting the channel to its floodplain so that in times of high flow levels, water would spill onto the floodplain. Although less intensive, the approach taken is a sustainable one through which the natural processes are restored to create conditions that will be favourable for the development of the riverine woodland form.

Two approaches were invoked to restore connectivity between the channel and the floodplain at the locations shown in figure 4.5.3. The first was a more intensive planform restoration approach that sought to re-occupy former channels that were abandoned when the river was channelised. These abandoned channels had much lower banks than the channelised reaches and thus the connection between the channel and floodplain could be re-established during high flows. The abandoned channels were also much more sinuous than the currently occupied, channelised reach. Figure 4.5.2 shows a map that illustrates the difference in sinuosity between the channel prior to restoration and those meander loops of the former channel abandoned which were present on the floodplain. In this particular example, the channelised reach had a sinuosity of 1.07 and the abandoned channel had a sinuosity of 1.54. The location of the former abandoned channels was relatively well defined upon the floodplain by the presence of topographic low points.

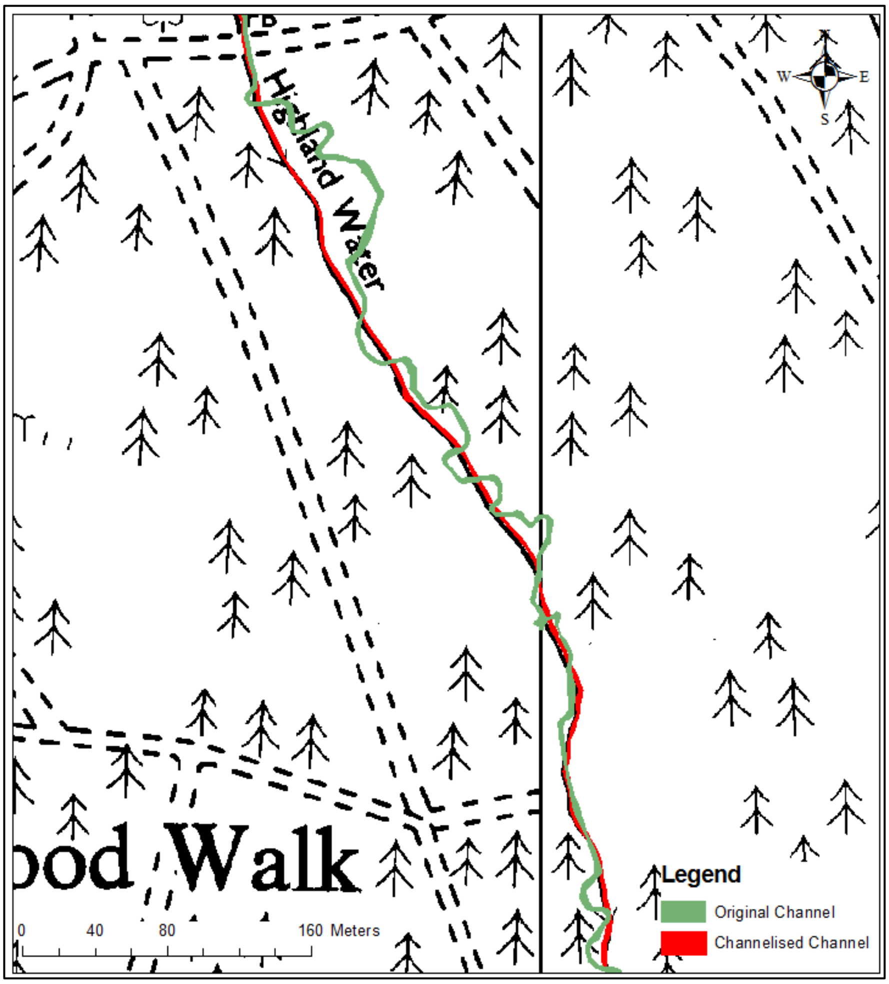



**Figure 4.5.2: Difference in Sinuosity between the Original (green) and Channelised Reaches (red).**

The reason for this was two-fold, the abandoned channel was not infilled and the floodplain had been subject to little development with the planting of coniferous forest being the main pressure on the floodplain. Restoration involved in-filling the straightened channel reach using a combination of clay bunds, material from spoil heaps located on the bank tops of the channelised reach (a remnant from the past channelisation works), large wood and locally sourced gravel. This intensive planform restoration required the use of heavy plant machinery and large quantities of material for infilling the channel. Although the restoration was essentially reach-based (albeit a long reach), the connectivity of the river meant that this reach-scale restoration could also have impact throughout the catchment (Clarke *et al.*, 2003).

In other parts of the catchment, the channel had begun to recover a more natural form autogenically through erosional and depositional processes. The natural form of the channels of New Forest rivers is small and sinuous with variable widths and depths but the channelised reach was conversely relatively uniform, wide and straight. The presence of large wood can significantly influence channel morphology (Zimmerman *et al.*, 1967) and can influence channel sediment storage (Nakamura and Swanson, 1993; Keller *et al.*, 1995) and within a few locations in the New Forest, reductions in channel cross-sectional area and increases in channel sinuosity had begun to occur where large wood supply was high. Bank erosion can also be initiated through the deflection of flow by large wood (Shields *et al.*, 2001) which can result in a reduction in bank height and widening of the channel (see for example the conceptual model of Simon and Hupp (1986) and Simon (1989)).

At some sites within the Highland Water, channel sinuosity had begun to increase and bank heights were significantly lower than those areas where planform restoration was required. Natural recovery had begun to occur although natural recovery is known to take many decades (Brookes, 1995) and could be impossible in less dynamic systems such as lowland streams.

Therefore, as natural recovery had already begun it was decided that an approach to accelerate recovery would be preferable. One approach to accelerate the natural recovery is through the use of large wood. Large wood is a significant component of most forested rivers including the Highland Water (Gregory, 1992) and in recent times has been used in other locations for the purposes of natural channel rehabilitation (Collins and Montgomery, 2002; Shields *et al.*, 2004; Lehane *et al.*, 2002; Brookes *et al.*, 2004). Therefore, it was decided to use large wood to accelerate natural recovery of the Highland Water river channels to improve the channel-floodplain connectivity. The approach taken was a sustainable one, which required little management or intervention. Key large wood pieces were added at jam points within the river system and were allowed to form large wood accumulation structures (Geodata, 2003). Management practice was also altered to limit the removal of large wood from both the channel and the floodplain. There are a number of sources of large wood in forested river systems such as the Highland Water, which can provide large amounts of large wood. However, active management can often limit the amount of large wood that spends significant time in the channel and consequently forms large wood accumulations. It was hoped that the presence of these large wood accumulations would significantly retard flow through increased roughness, which in turn lead to backwatering affects that could result in floodplain inundation. It is the role of the large wood within a restoration context which is the focus of chapter 6 and leads on to the rest of this thesis.

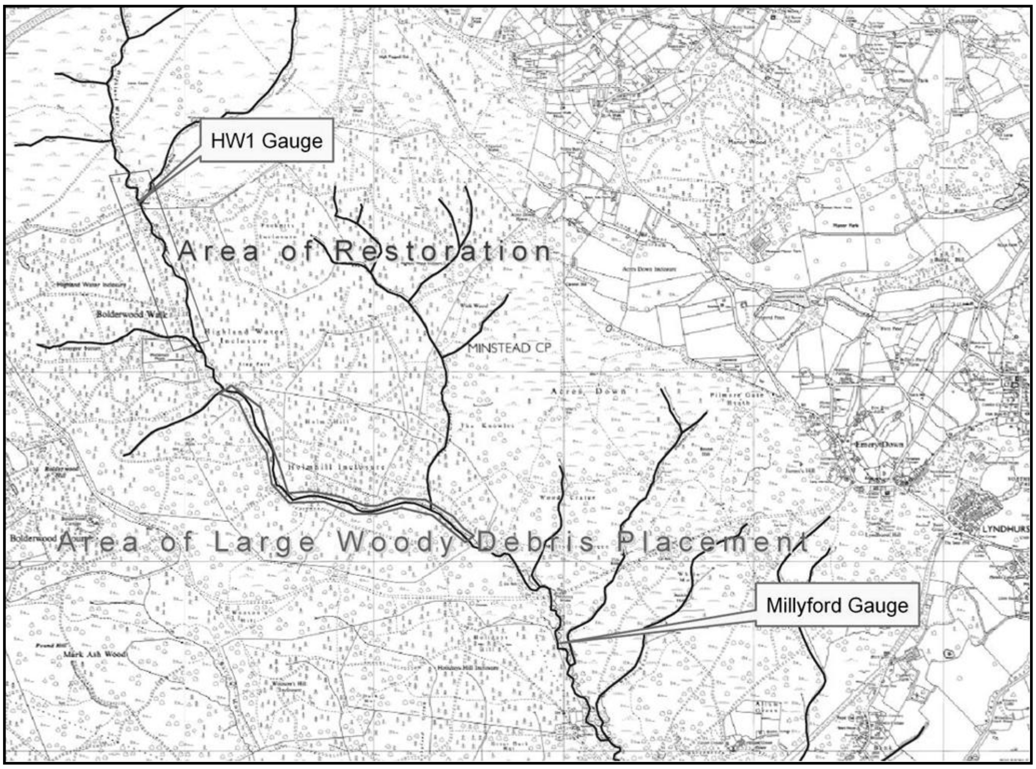



**Figure 4.5.3: The two reaches subject to two types of restoration; planform restoration and restoration through the input of large wood.**

## Previous Research

Due to the Highland Waters standing as a research catchment, a large amount of research has been conducted within the catchment (summarised in table 4.5.1) and as such, the catchment is well monitored and has various datasets stretching back to the 1960s. The high density of hydrological and sediment gauging stations together with the unique presence of heathland and woodland provided the ideal location for studying the interactions of semi-natural vegetation and hydro-geomorphological processes.

Early research studied drainage densities and ephemeral drainage networks of different types of heathland vegetation (Gurnell, 1978 and 1981) and the interaction between heath vegetation and hydrology (Gurnell *et al.*, 1985; 1993; Gurnell and Gregory, 1987).

Research conducted on large wood within the Highland Water include work on its spatial distribution (Gregory *et al.*, 1993), its character and persistence (Gregory, 1992), its role in influencing geomorphological form and process (Gregory and Davis, 1992; Gurnell and Sweet, 1998; Piégay and Gurnell, 1997), its role in influencing flood hydrology and the attenuation of flood peak magnitudes and travel times (Gregory *et al.*, 1985; Gregory, 1992) and the role large wood plays in influencing sediment dynamics upon a forested floodplain (Jefferies *et al.*, 2003).

In terms of hydrodynamic modelling studies, Booker *et al.* (2001) used a high-resolution three-dimensional code to simulate flow structures in pool-riffle sequences however, this was limited to in-channel flow with a fixed water level. At present, there has been no work that has attempted to model the floodplain inundation dynamics on the Highland Water.

| Authors | When | Where | Field | Notes |
|---|---|---|---|---|
| Gurnell | 1978 | Withybed Stream | Hydrological Processes | Study into the dynamics of a drainage network within the Highland Water. |
| Gurnell | 1981 | Withybed Stream | Hydrological Processes | Study into the effect of vegetation cover upon drainage networks. |
| Gurnell *et al.* | 1985 | Withybed Stream | Hydrological Processes | Study into prediction of the effect of vegetation cover upon drainage networks. |
| Gurnell *et al.* | 1993 | Withybed Stream | Hydrological Processes | A GIS study into the effect of vegetative management upon hydrology. |
| Gurnell and Gregory | 1987 | Withybed Stream | Hydrological Processes | Study into the use of hydrological characteristics of heathland to develop the approach to estimate discharge in ungauged heathland catchments. |
| Gregory *et al.* | 1993 | Highland Water Research Catchment | Large Wood | A study into the spatial distribution of large wood including evaluation of input mechanisms. |
| Gregory *et al.* | 1994 | Highland Water Research Catchment | Geomorphology | Study into the spatial distribution of pool-riffle sequences in a wooded catchment. |
| Gregory | 1992 | Highland Water Research Catchment | Vegetation Processes | Review of the effect of the effect of vegetation on river channel processes. |
| Gregory and Davis | 1992 | Highland Water Research Catchment | Large Wood | Study into the management of river channels in woodland areas including the management of large wood. |
| Gurnell and Sweet | 1998 | Highland Water Research Catchment | Large Wood | Study into the dynamics of large wood with respect to management and the subsequent effect upon channel morphology. |
| Piégay and Gurnell | 1997 | Highland Water Research Catchment | Large Wood | Study into the dynamics of large wood and its role in influencing river geomorphology in different environments including the Highland Water. |
| Jefferies *et al.* | 2003 | Millyford Large Wood Accumulation site | Floodplain Dynamics | Study into the floodplain sediment dynamics and the role of large wood and vegetation. |
| Booker *et al.* | 2001 | near Millyford Bridge Gauging Stations | Pool-riffle hydraulics | CFD study into the hydraulics of pool-riffle sequences. |
| Millington and Sear | 2007 | various sites in Highland Water Research Catchment | Large Wood | Study into the impact of river restoration upon large wood dynamics. |
| Sear *et al.* | 2010 | various sites in Highland Water Research Catchment | Large Wood | Study into the role of large wood accumulations on the channel-floodplain interaction and effect on the floodplain geomorphology |

**Table 4.5.1: Summary of the previous research conducted on the Highland Water Research Catchment.**

## 4.6. Monitoring Sites

Three monitoring sites were selected within the Highland Water catchment to assess the impact of restoration upon the reach-scale floodplain hydrology. Two restored sites were subject to two different types of restoration and these are indicative in the names of the two sites: Restored-Planform and Restored-Large Wood. The other site was upstream of the restored reach. The upstream site was not subject to restoration and served as both a reference site, and as a semi-natural control site and it was subsequently named the Semi-Natural Control reach.

Figure 4.6.1 shows the location of the three sites on the Highland Water which are characterised in table 4.6.1.

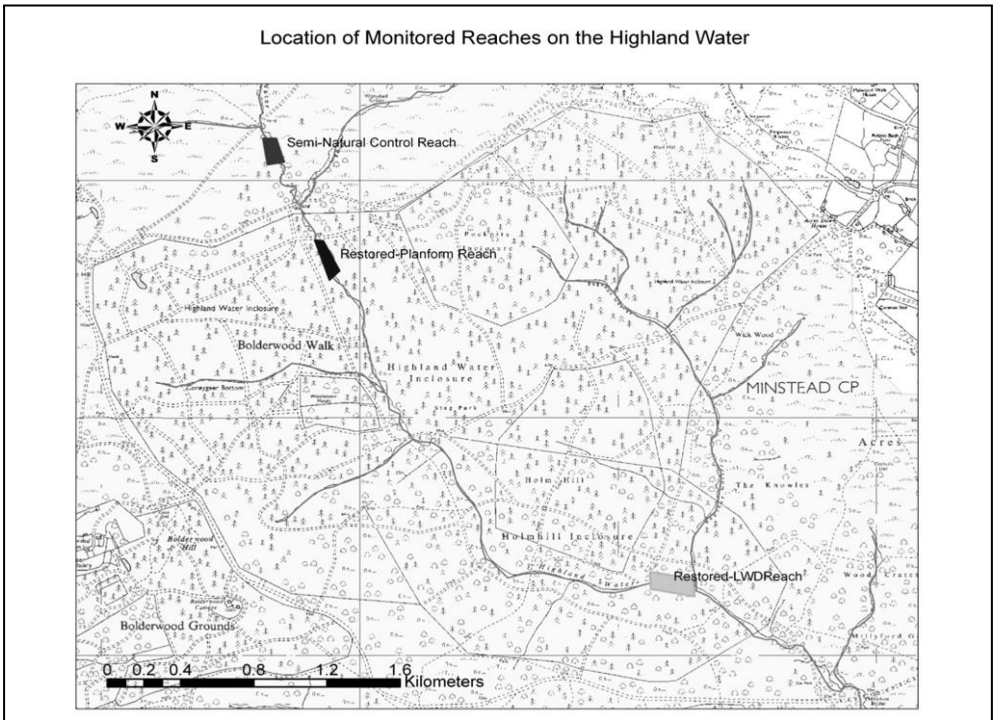



**Figure 4.6.1: Location of the 3 monitoring reaches.**

As can be seen there are similarities between all sites in respect to sediment grain size and the channel slope. As expected, under the principles of downstream hydraulic geometry, there is a significant variation in the bankfull width and channel area. However, these variations are proportional to discharge and are unlikely to affect any comparisons made between any of the sites. What follows is a detailed description of each monitoring site in order to set the scene together with a description as to what restoration works were carried out at each site.

| **Reach** | **Catchment Area ($km^2$)** | **Channel Slope (m/m)** | **Bankfull Width (m)** | **Median Grain Size (mm)** | **Channel Area ($m^2$)** |
|---|---|---|---|---|---|
| **Restored-Planform Pre-Restoration** | 7 | 0.008 | 5.91 | 44 | 9.29 |
| **Restored Planform Post-Restoration** | 7 | 0.005 | 4 | 23 | 4.3 |
| **Restored-Large Wood** | 11 | 0.0057 | 3.73 | 37 | 5.49 |
| **Semi-Natural Control** | 5 | 0.0078 | 1.88 | 38 | 3.6 |

**Table 4.6.1:- Characteristics of the three monitoring reaches**

## Restored-Planform Reach

The Restored Planform Reach (SU 2478, 0993) was situated 200m downstream of the inflow of the Withybed Brook into the Highland Water. The reach is situated in the Forestry Commission Highland Water enclosure and the predominant landcover was coniferous woodland planted for forestry. The Restored-Planform reach flowed through the woodland (average sinuosity of 1.07) with minor drainage channels entering at its downstream limit. Figure 4.6.2 shows the Restored-Planform reach before and after restoration.

Prior to restoration, the Restored-Planform site was a 100m long, highly incised reach. The reach had been channelised in 1966 and subsequent incision had led to clay being exposed in places on the channel bed. Where the clay was not exposed, the bed consisted of coarse gravel ($D_{50}$=44mm).

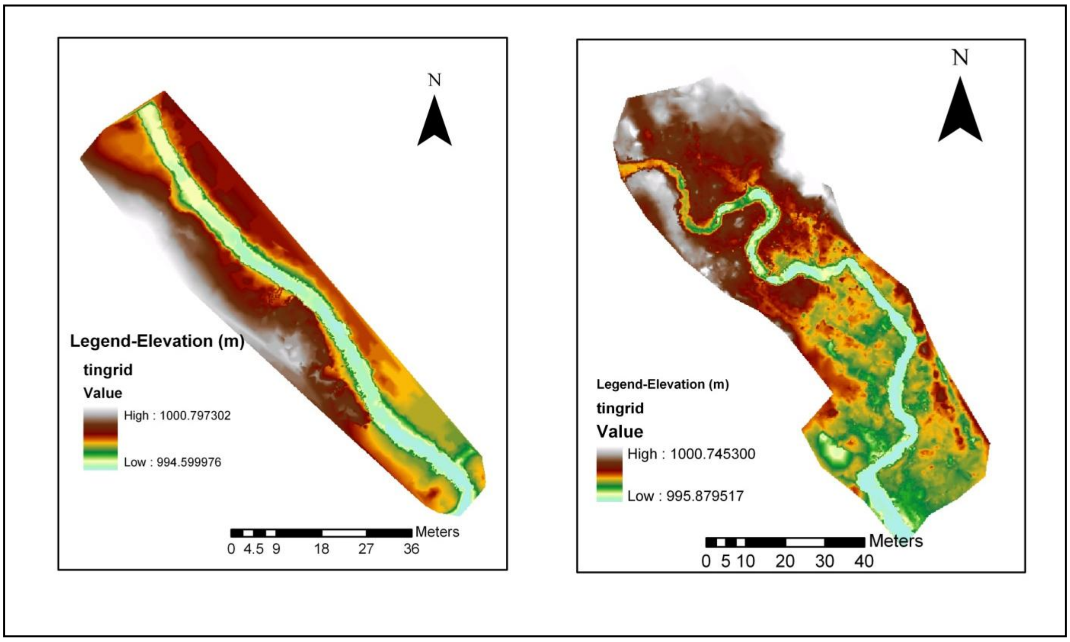



**Figure 4.6.2:- The Pre- and Post- Restoration DEMs for the Restored-Planform Reach.**

Bank height reached over 2.5 metres in places with an average bank height of 2.35m, which resulted in a disconnected floodplain that was subsequently poorly drained. This was partly due to the presence of spoil heaps on the top of the left banks where material removed from the channel straightening measures was deposited. The geomorphology was limited in the channel to two riffles with a run between them. A tree that had grown across the channel was the only evidence of any large wood within the channel and only influenced flow in high flow events. The valley gradient was 0.0062m/m and channel gradient was 0.008m/m. Figure 4.6.3 shows a long profile of the reach prior to restoration together with some representative cross-sections throughout the reach.

Due to the location of the channel in the valley floor, the right bank was essentially connected to the valley side with the disconnected floodplain positioned on the left of the channel (see Figure 4.6.4). Vegetation on the floodplain was a mixture of coniferous spruce, Douglas fir with some stands of Alder Carr, which were remnants of the riparian vegetation on the previously abandoned channel. The remnant channel was visible in the floodplain and ponded water during the winter months. The remnant channel was therefore used as a template for the restoration of the channel planform.

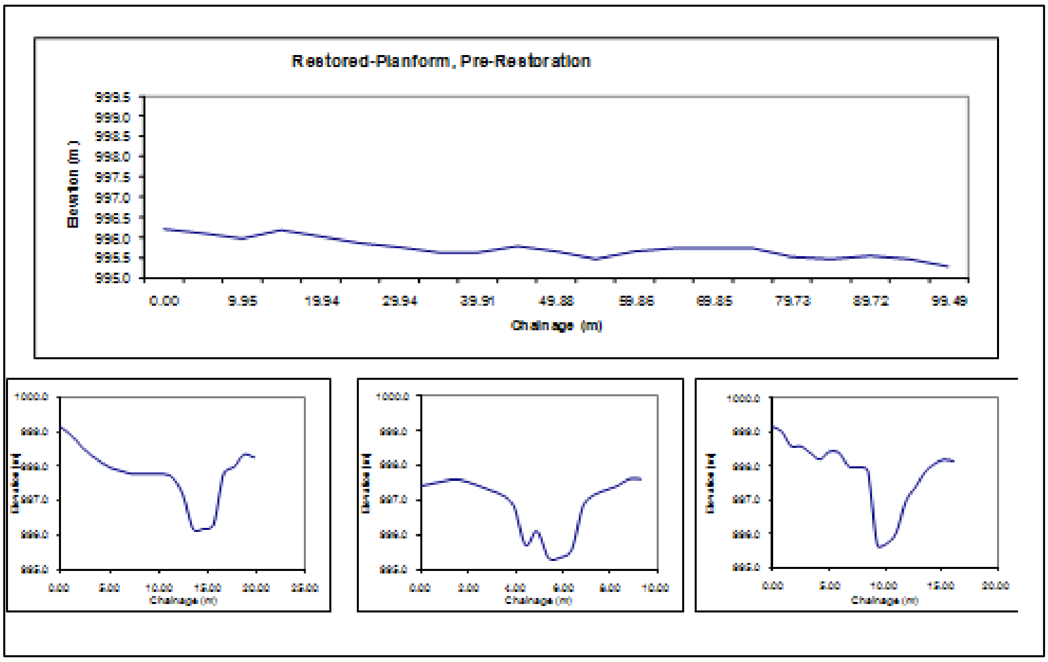



**Figure 4.6.3: Long Profile of the Restored-Planform Reach Prior to Restoration**

In order to restore the channel to its previous form clays plugs were put in place at the upstream and downstream ends of the incised channel. The top soil was then scraped out of the remnant meandering channel until the original bed material was found. Within a few weeks, the channel had reformed some of the bed features that would have been present before the channel was abandoned. In order to stop flow reclaiming the channelised channel, the channel was filled in using the spoil material at the top of the bank as well as locally sourced gravels. The non-native tree species were removed from the floodplain although the stumps were left in place and all native species were left on the floodplain. The work was conducted using heavy plant machinery and although the work was carried out during the summer months, this had the effect of churning up soil along the line of the channelised reach.

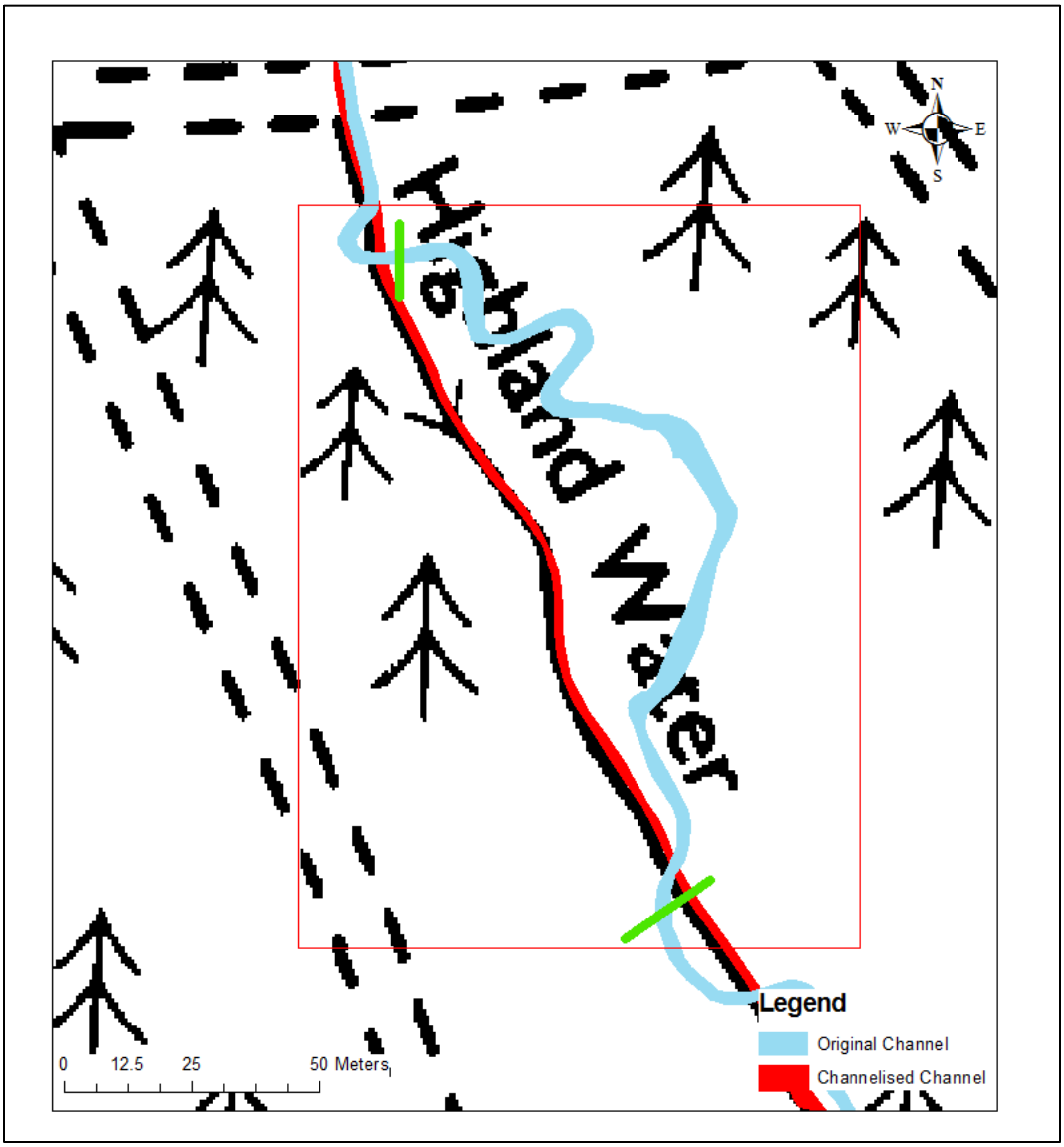



**Figure 4.6.4: Plan of the Restored-Planform Reach showing the channel path prior to restoration. The red box represents the study reach and the green lines represent the limits of the reach represented in the hydrodynamic model.**

Post-Restoration, channel length had increased to 160m and channel sinuosity was increased 58% to 1.54. Channel slope had been reduced to 0.005m/m and the average cross-sectional area of the new channel was 4.3m$^2$. The channel meandered across the floodplain and the bank heights were a lot lower with an average of 0.83m and a maximum of 1.4m. As a result, the channel was more connected with its floodplain and flow paths were visible on the floodplain. Figure 4.6.5 shows a long profile for the reach after restoration together with an indication of the cross-section form throughout the reach. At the lower end of the reach, the channel widened and flow depth was relatively shallow. As non-native species had been removed as part of the restoration measures, the predominant vegetation was alder. During the restoration, the inclosures were opened to large herbivores, which meant that there was little ground vegetation.

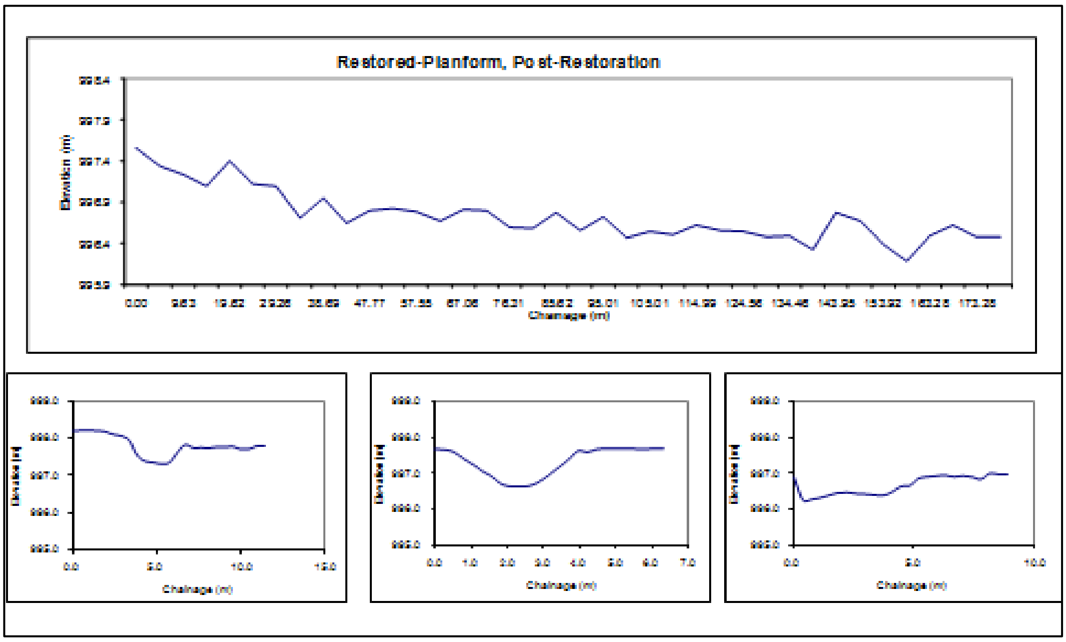



**Figure 4.6.5: Long Profile of the Restored-Planform Reach after Restoration**

Geomorphologically, there were two sets of pool-riffle sequences as well as a 0.6m step in bed elevation that was associated with a large wood accumulation. This overflow accumulation had a scour pool downstream of it, created a large head of water during flood events and forced flow onto the floodplain on its upstream side. There were other accumulations of large wood on the floodplain and some within the channel although these were mobilised within the first two large flow events.

Channel planform restoration occurred for another 400m upstream and for approximately 1500m downstream. Large wood was also added to the river channel although these were not deliberately placed within artificial large wood accumulations but left to form natural accumulations by natural transport processes.

## Restored-Large Wood

The Restored-Large Wood reach (SU 2616, 0836) is 2.2km downstream of the Restored-Planform reach and just upstream of the confluence with a small tributary known as the Bagshot Gutter. The 85m reach is situated within Holmhill Inclosure, which means that the channel flows through an area of coniferous woodland with deciduous trees species such as Turkey Oak (*Quercus Cerris*). The channel was one that was channelised, cleared of debris and dredged in around 1917. Figure 4.6.6 shows a DEM of the Restored-Large Wood site.

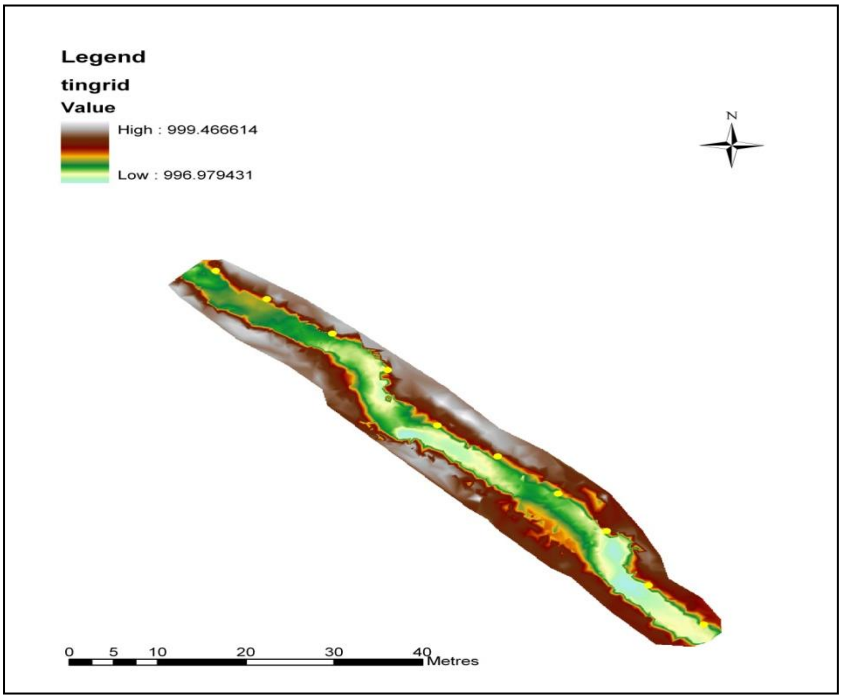



**Figure 4.6.6: DEM of the Restored-Large Wood Reach**

As can be seen, although the channel is essentially straight, it has shown signs of recovering the natural sinuosity and there are some geomorphological features along the channel including pools, riffles and side bars. There were no large wood accumulations present, as due to the straightness of the channel there were no jam points at which large wood could accumulate. Due to the relatively high channel banks (average bank height=1.2m with a maximum of 1.5m) there was little floodplain inundation.

Coarse gravel covered the channel bed and there was evidence of bed armouring. The banks were formed of silty sands held together with tree roots, with a gravel toe of up to 50% of bank height. Figure 4.6.7 shows the long profile and it can be seen that there is a pool-riffle sequence within the reach.

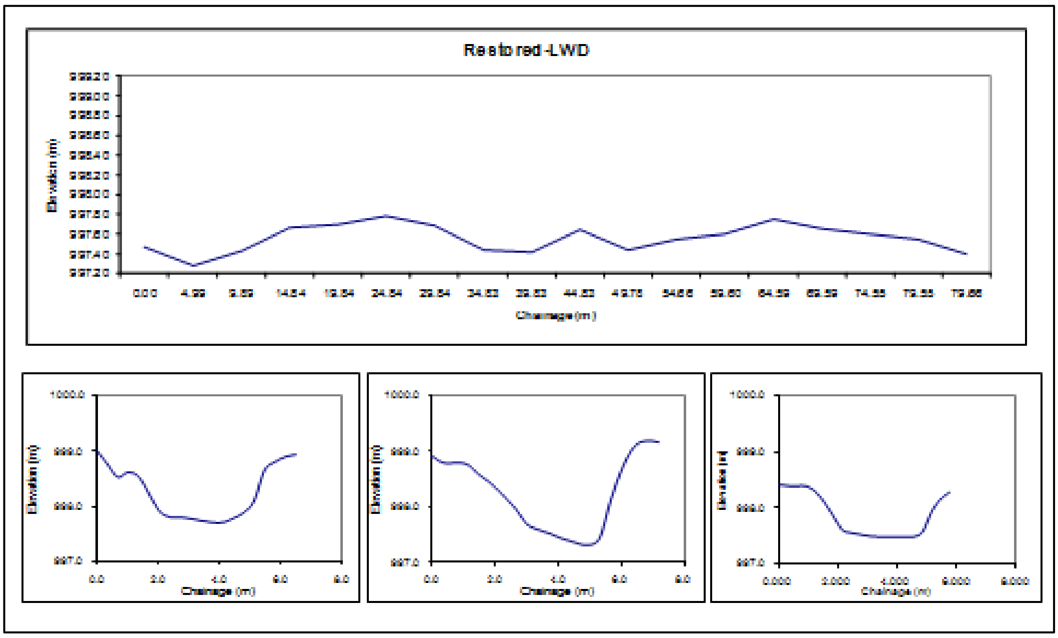



**Figure 4.6.7: Long Profile of the Restored-Large Wood reach.**

As the reach was in an inclosure, large herbivores did not influence the under-storey vegetation and therefore the floodplain surface was short grass and bracken. This meant floodplain geomorphology was hidden although walking through the area it was possible to identify the relic meander bends that were abandoned during the period of channelisation (see Figure 4.6.8). However, due to the self-recovery of the channel it was decided that planform restoration was not necessary and the reach was therefore subject to large wood restoration only in the hope that it would accelerate any natural recovery.

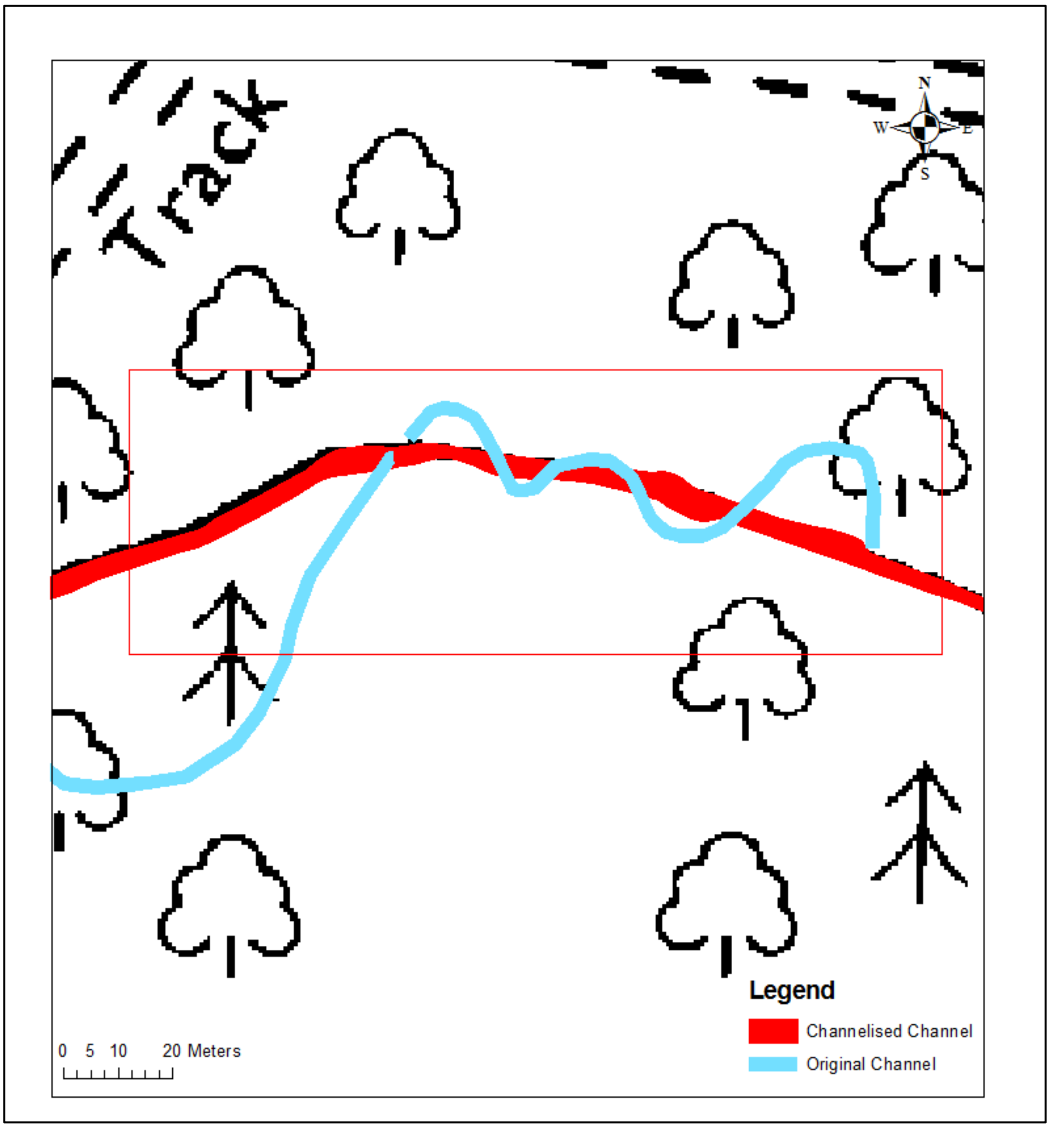



**Figure 4.6.8:-Plan of the Restored-Large Wood reach showing the previous channel planform. The Study reach is shown within the red box.**

## Semi-Natural Control

The semi-natural control reach (SU 2469, 1011) was located the furthest upstream and is situated 300m upstream of the confluence with the Withybed Brook. It is situated in open woodland, which is considered semi-natural due to the limited management that occurs. Only the influence of large herbivores precludes it from classification as completely natural. Species present within the reach are Oak, Alder with some Holly and Bracken patches. The presence of large herbivores meant that the floodplain surface was essentially bare soil with little grass and a few locations of leaf litter. The channel itself is a meandering channel (see Figure 4.6.9) with a sinuosity of 1.41 with a relatively steep channel (0.0078) and floodplain gradient (0.011) (see Figure 4.6.10).

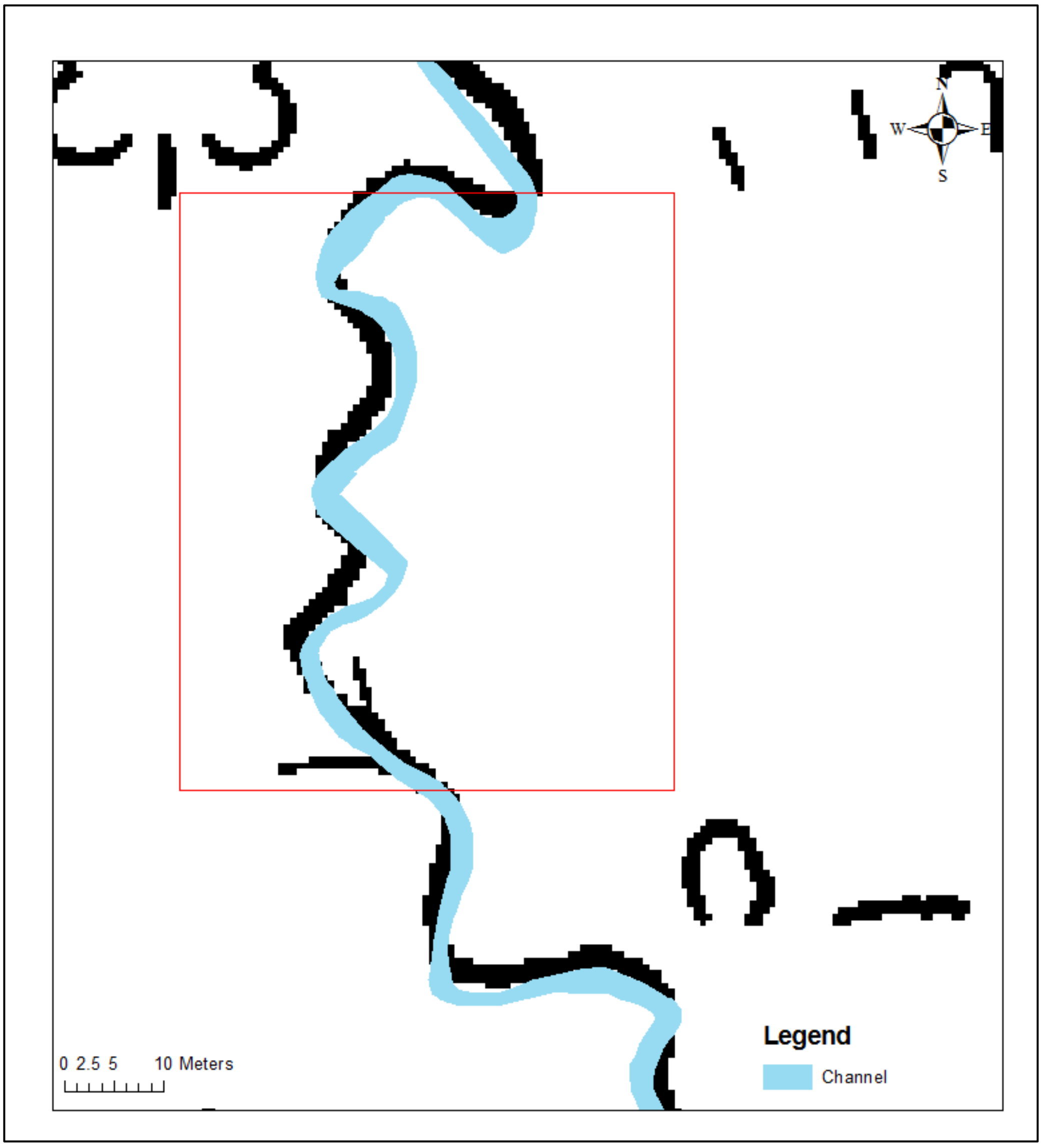



**Figure 4.6.9: Plan of the Semi-Natural Control Reach. The red box shows the study reach.**

With the channel being in open woodland and in the headwaters it has been largely unaffected by any channelisation or any channel management. However, about 100m downstream of the site there is a large knickpoint which had travelled upstream as a direct result of the channelisation work downstream. In one event in December 2004, the knickpoint had cut upstream by over 1.5m. As part of the restoration, this knickpoint was re-graded. The one case of channel management was the clearance of large wood accumulations in 1989.

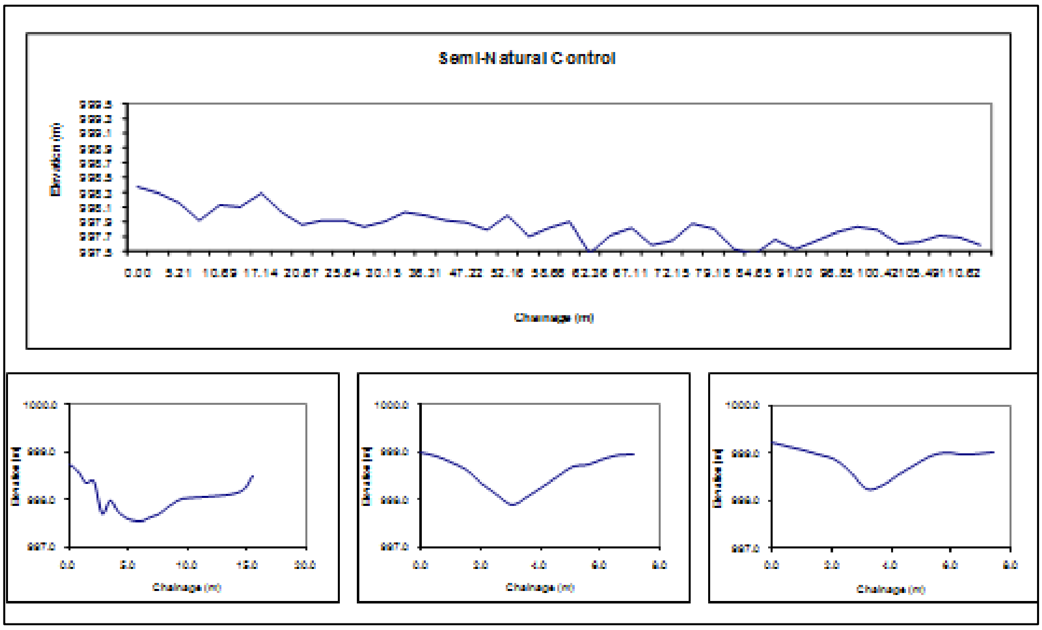



**Figure 4.6.10: Long Profile of the Semi-Natural Control Reach**

The channel is dominated by pools and riffles throughout the reach. The meandering nature of the channel means that there are some side bars and pools on the outer bank of the meanders. Large wood is present throughout the reach, which influence flow in both low flow and high flow events. There was a hydraulically active accumulation half way through the reach that blocked the channel and acted like a small overflow dam. The bed is mainly gravel and the banks are formed from gravels and silty sands that were held together by tree roots. The banks are generally low with an average height of 0.63m.

Due to the tree density, a full floodplain topographic survey was not carried out at this site, as line-of-sight was limited. However, cross-sections and a long profile were surveyed. Although used as a hydrological control site from which it was possible to assess hydrological changes at the other monitored reaches as a result of restoration, the Semi-Natural Control site also portrayed some of the characteristics of a reference site towards which the restoration aimed to move the two impact sites. Small areas of low-lying riverine woodland were present especially on the left bank of the reach although monitoring suggested that inundation of the floodplain was perhaps not as frequent as had been expected based on other research projects within the Highland Water catchment (Jefferies *et al.*, 2003).

## *4.7. Summary*

With its long history of hydrological monitoring and datasets on the spatial distribution of large wood, the Highland Water is an excellent location for research into the use and effect of large wood within a restoration context. The EU Life 3 catchment restoration project gave an excellent opportunity to continue and enhance this monitoring and allow this research to take place.

Three particular monitoring reaches were chosen to assess the effect of the role of large wood in restoration and in influencing the hydraulic and hydrologic processes that can be favourable for the development of riverine woodland. These reaches were chosen to fulfil the BACI (Before-After Control Impact) approach taken for the initial part of this research. The reaches comprised of two restored sites that were subject to planform and large wood restoration respectively and a semi-natural control site, which was used to act as a baseline to which any impact could be compared (Smith, 2002). The effect of the restoration and in particular the role of large wood in these reaches is described in the next chapter.

# 5. Methodological Approach

## 5.1. Introduction

In recent times there has been an increase in the use of large wood in restoration due to its low cost (Shields *et al.*, 2001) and its ability to reduce bank erosion, improve geomorphological diversity (Shields *et al.*, 2004), improve hydrological connectivity between the river channel and its floodplain (Gurnell, 1997; Jefferies *et al.*, 2003) and provide aquatic habitats (Lehane *et al.*, 2002). As has been identified in the previous chapter, at present there has been no attempt to quantify the effect of different types of large wood accumulations on floodplain inundation extents, patterns, frequency or duration. Furthermore, each of these factors is likely to have a subsequent impact on the catchment flood hydrology and in particular flooding downstream. It is the aim of this thesis to assess the applicability and performance of large wood as a restoration tool in promoting conditions favourable for the development of riverine woodland through the restoration of the channel-floodplain link. This will be done by assessing the impact of large wood accumulations on in-channel hydraulics, floodplain flow hydrology and catchment flood hydrology. In order to do this it is necessary to look at a range of scales using a variety of approaches. This requires a nested approach as is highlighted in the following section.

## 5.2. Nested Approach

To assess the role of large wood in influencing local channel hydraulics, reach-scale hydraulics, floodplain hydrology and catchment scale hydrology a nested approach was taken which aimed to look at three different spatial scales and the linkages between those scales. The three scales were the large wood accumulation scale, the reach scale and the catchment scale. Put simply, the different scales represent the interaction of different numbers of large wood accumulations and different parts of the system. At the individual large wood accumulation scale, in terms of hydraulics and hydrology, it is the hydraulics which are most affected. At the catchment scale, with a high number of large wood accumulations of different types, it is the hydrology that is predominantly influenced by the large wood. This continuum is true for the reach scale, which has a number of large wood accumulations that can influence both the hydraulics and hydrology. Figure 5.2.1 suggests the mechanisms that are likely to be influenced by large wood within a forested river system at three different scales.

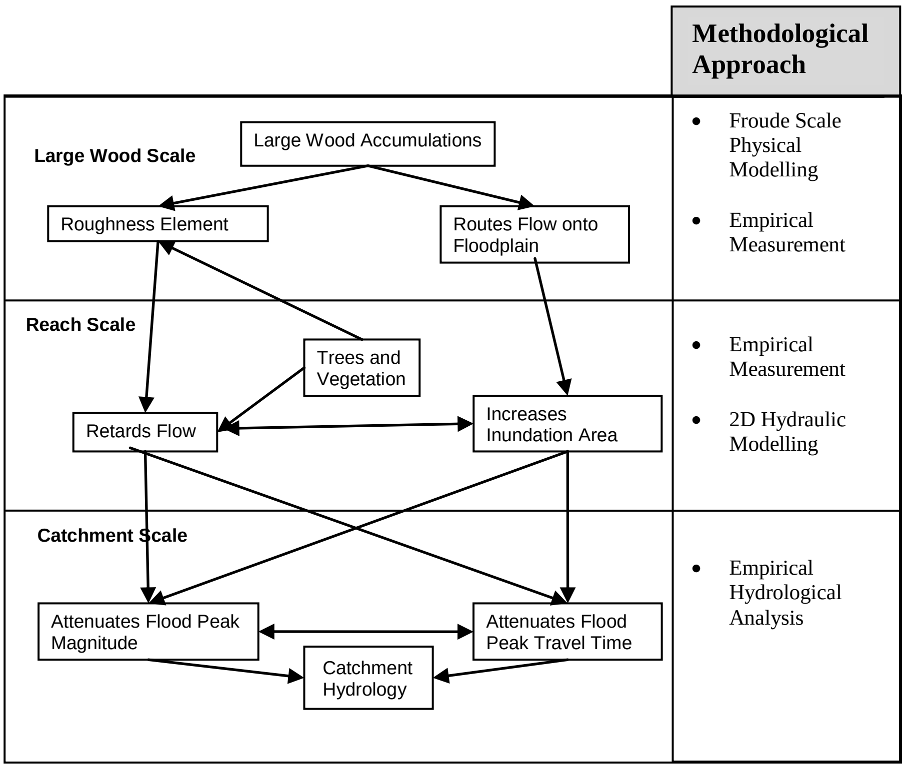



**Figure 5.2.1: Conceptual Model of the Link between Large Wood and Catchment Hydrology.**

At the reach scale, the presence of large wood accumulations is likely to create a significant roughness element, which reduces channel conveyance and routes flow onto the floodplain. The storage of flow on the floodplain will influence catchment flood hydrology through the attenuation of the flood peak magnitude and lengthening flood peak travel time. To investigate the links between the scales and a number of approaches involving field measurement, hydrodynamic modelling and hydrological analysis were undertaken to gain an insight into the role that large wood plays within a forested river channel and, in particular, its effects on floodplain hydraulics and flood hydrology. The framework and driver for this research has come from a restoration scheme designed to use large wood to restore conditions favourable for the development of riverine woodland.

## 5.3. Monitoring Restoration

Although river restoration has occurred for over 15-20 years in the UK (Sear, 1995; Brookes 1996), it has been largely based on an *ad-hoc* basis with a focus on mimicry of form rather than the understanding of any of the processes occurring (Kondolf, 1998). In recent years, there has been a different approach to restoration with restoration designs tailored to the specific physical characteristics and process history of a particular system (Sear, 1995; Sear *et al.*, 1998). Effective river and floodplain restoration requires that a number of phases are undertaken. From Brookes and Shields (1996) these commonly are:-

- A planning and feasibility study,
- Design,
- Implementation,
- A maintenance plan, and
- Post-project monitoring and appraisal.

The first four of these phases are conducted relatively successfully through the design process but what is often missing is a rigorous project-monitoring programme. A monitoring programme is needed to develop an understanding of the impacts of restoration upon rivers and floodplains and to inform others of the successes and failures of a particular project (Kondolf, 1998; Holmes, 1998; Kondolf and Micheli, 1995). Monitoring is the process of obtaining information in order to detect changes in performance parameters (Burt, 2003). Often, due to time and funding constraints, it is the project monitoring which is neglected. Currently little is known about the success of different restoration approaches and this is due a lack of monitoring of restoration performance either before or after project implementation primarily due to a lack of funding (Wohl *et al.*, 2005). Without effective monitoring, it is impossible to assess whether a particular restoration project has achieved the goals it set out to achieve. The monitoring of restoration projects can also give feedback to project managers and an opportunity for adaptive management based on monitoring results, which will ultimately lead to the better management of the resource (Bash and Ryan, 2002). Monitoring prior to restoration can also create a baseline that can assist in the reduction of uncertainties in the restoration programme. The existence of reliable data sets increases the ability to make decisions about the way river catchments are managed (Burt, 2003). Figure 5.3.1 summarises the benefits achieved from the effective monitoring of restoration.

| **Why is there a need to Monitor River Restoration Projects?** |
|---|
| To assess the performance of restoration in meeting its objectives |
| Adaptive Management based on results |
| Improved understanding of the impacts of Restoration |
| Improved understanding of process and form |
| Provide examples of what works and what does not. |

**Figure 5.3.1: Why Monitor Restoration? (adapted Skinner *et al.*, 2008)**

A monitoring programme was built into the EU Life 3 project at an early stage in order to assess the performance of the restoration in achieving its goals. Monitoring of the effect of large wood restoration on hydrological and hydraulic processes forms the basis of this thesis. A field monitoring approach was taken to assess the affect of large wood upon hydraulic and hydrologic processes at two spatial scales, the reach scale and the catchment scale. At the catchment scale, the role of large wood upon the catchment flood hydrology was assessed through the monitoring of hydrological flows at a number of sites in order to provide information regarding the magnitude and timing of flood flow events. At the reach scale, floodplain hydrology was monitored using a number of gauges to determine the inundation frequency at a number of sites that were subject to different forms of restoration including using large wood accumulations. The intention was to understand the hydraulic and hydrological performance of large wood in a restoration context and establish a starting point from which to research the role of large wood.

To supplement the monitoring data, field data was taken at the large wood accumulation scale to determine the hydraulic effect of in-channel large wood accumulations and the processes by which they influence the reach-scaled resistance. Data obtained from the large wood accumulation field data was subsequently fed into a reach-scale hydrodynamic model to simulate the role of large wood in influencing floodplain hydraulics and hydrology, thus providing an understanding of the link between the large wood accumulation scale and the catchment scale. The methodology for the development of understanding these connections is described in the following sections.

## 5.4. Catchment Scale Hydrology

Inundation of a floodplain by a river can lead to attenuation of flood waves and suppress the growth of floods downstream (Archer, 1989). This is due to the storage of flow on the floodplain as well as the resistance offered by the rougher floodplain surface. The initiation of floodplain inundation by large wood accumulations can thus also lead to attenuation of flood peak magnitude and reduction of downstream flood probability (Gregory *et al.*, 1985; Gippel *et al.*, 1994). This can give rise to an altogether different flood hydrograph than that experienced in the absence of large wood (Gregory *et al.*, 1985). Although this can reduce the downstream flood probability for floods of a small return period, the associated risk to property, infrastructure and people in the small catchment monitored (11km$^2$ in catchment area) by Gregory *et al.*, (1985) is small. Whether such effects scale up to larger catchments for larger return period floods have yet to be demonstrated.

With the increasing use of large wood for restoration, it is imperative to understand the affects of large wood and its accumulations on the routing of the flood wave, its effect on downstream flooding and the flood hydrograph. One potential benefit of restoration, such as that of the EU LIFE 3 project, is that by reconnecting the channel with its floodplain and introducing large wood accumulations into the channel, the use of the available floodplain storage could be increased and therefore the downstream flood hydrology would be altered. Thus, less critical areas can be beneficially flooded in order to protect higher risk areas downstream. Where these less critical low risk areas are not subject to urban development, beneficial floodplain storage can also be tied in with ecological work to restore the flood pulse leading to improvement of floodplain habitat diversity and river quality which are desirable under the Habitats Directive (EU, 1992) and Water Framework Directive (EU, 2000).

The extensive network of gauges on the Highland Water (see Figure 4.4.2), provides an excellent opportunity to assess the effect of the restoration on catchment hydrology. An assessment of the hydrological dataset can give an indication of the performance of the restoration. A simple time series helped identify any general long-term trends. Before and after hydrological statistics such as the mean daily average flow, $Q_{5,}$ and $Q_{95}$ were used to build a picture of the effect of the restoration in influencing the flood peak magnitude and timing.

An event based assessment was also conducted that assessed a total of 47 events (19 pre-restoration, 28 post-restoration-summarised in table 5.4.1) between November 2003 and February 2006 at both the Highland Water 1 and Millyford Bridge gauges to assess the impact upon flood peak magnitude and timing. This was done by picking 47 distinct high flow events, defined as having a discharge of $0.15 m^3 s^{-1}$ or more, from the hydrograph and then comparing peak discharge and timing of these flood peaks at the two gauging stations. This approach is a commonly used hydrological technique and has been used in this particular catchment by Gregory (1992). Data from Gregory (1992) was used to enable comparison of different large wood loadings over 20 years in the Highland Water catchment and their effect on flood travel time.

| | **Highland Water 1** | | **Millyford Bridge** | |
|---|---|---|---|---|
| **Date** | **Time of Peak** | **Peak Discharge ($m^3s^{-1}$)** | **Time of Peak** | **Peak Discharge ($m^3s^{-1}$)** |
| | | **Pre-Restoration** | | |
| 30/10/2003 | 22:10:00 | 0.39 | 23:30:00 | 1.17 |
| 02/11/2003 | 10:55:00 | 0.38 | 12:10:00 | 1.19 |
| 03/11/2003 | 02:45:00 | 0.33 | 04:30:00 | 0.69 |
| 12/11/2003 | 07:40:00 | 0.26 | 09:20:00 | 0.33 |
| 21/11/2003 | 08:10:00 | 0.41 | 10:34:00 | 0.33 |
| 22/11/2003 | 14:40:00 | 0.67 | 16:04:00 | 0.79 |
| 11/12/2003 | 10:15:00 | 0.18 | 11:44:00 | 1.03 |
| 29/12/2003 | 11:50:00 | 0.19 | 13:22:00 | 1.41 |
| 01/01/2004 | 06:55:00 | 0.25 | 08:12:22 | 1.66 |
| 08/01/2004 | 08:45:00 | 0.49 | 10:42:00 | 2.44 |
| 11/01/2004 | 05:50:00 | 0.26 | 07:20:00 | 1.69 |
| 12/01/2004 | 10:15:00 | 0.66 | 12:10:00 | 2.72 |
| 14/01/2004 | 07:50:00 | 0.15 | 09:20:00 | 0.99 |
| 15/01/2004 | 19:20:00 | 0.16 | 20:40:00 | 1.05 |
| 31/01/2004 | 10:35:00 | 0.31 | 11:43:00 | 2.00 |
| 01/02/2004 | 18:25:00 | 0.61 | 20:13:00 | 2.46 |
| 18/04/2004 | 12:55:00 | 0.45 | 14:10:48 | 2.29 |
| 21/04/2004 | 14:45:00 | 0.28 | 16:30:00 | 1.75 |
| 04/05/2004 | 09:50:00 | 0.17 | 11:05:00 | 0.98 |
| | | **Post-Restoration** | | |
| 19/12/2004 | 05:15:00 | 1.05 | 06:43:00 | 2.74 |
| 28/12/2004 | 03:15:00 | 0.54 | 05:08:00 | 1.13 |
| 08/01/2005 | 06:40:00 | 0.21 | 09:48:00 | 0.37 |
| 09/01/2005 | 19:10:00 | 0.22 | 21:58:00 | 0.43 |
| 10/01/2005 | 14:15:00 | 0.52 | 16:33:00 | 1.28 |
| 22/01/2005 | 23:15:00 | 0.43 | 01:36:00 | 0.85 |
| 12/02/2005 | 08:20:00 | 0.18 | 10:51:00 | 0.35 |
| 13/02/2005 | 14:50:00 | 0.16 | 17:41:00 | 0.21 |
| 22/03/2005 | 06:55:00 | 0.41 | 09:14:00 | 0.75 |
| 24/03/2005 | 02:40:00 | 0.30 | 04:55:00 | 0.60 |
| 29/03/2005 | 22:00:00 | 0.49 | 23:20:00 | 1.29 |
| 18/04/2005 | 05:00:00 | 0.48 | 06:55:00 | 1.01 |
| 24/04/2005 | 18:55:00 | 0.40 | 20:57:00 | 0.82 |
| 21/05/2005 | 12:10:00 | 0.58 | 13:42:00 | 1.48 |
| 24/10/2005 | 03:50:00 | 0.44 | 05:33:00 | 1.22 |
| 24/10/2005 | 20:20:00 | 0.92 | 22:18:00 | 2.67 |
| 30/10/2005 | 14:05:00 | 0.31 | 16:23:00 | 1.02 |
| 02/11/2005 | 01:05:00 | 1.08 | 03:18:00 | 2.82 |
| 02/11/2005 | 16:55:00 | 0.74 | 18:38:00 | 2.28 |
| 03/11/2005 | 07:15:00 | 1.04 | 09:08:00 | 2.39 |
| 03/11/2005 | 14:30:00 | 0.77 | 16:23:00 | 1.77 |
| 06/11/2005 | 12:30:00 | 0.74 | 14:23:00 | 1.95 |
| 02/12/2005 | 06:30:00 | 0.68 | 08:23:00 | 2.10 |
| 02/12/2005 | 20:15:00 | 0.93 | 22:03:00 | 2.67 |
| 07/12/2005 | 22:05:00 | 0.96 | 23:52:00 | 2.53 |
| 30/12/2005 | 12:50:00 | 0.42 | 15:32:00 | 1.25 |
| 01/01/2006 | 01:50:00 | 0.31 | 04:27:00 | 0.48 |
| 11/01/2006 | 09:25:00 | 0.28 | 11:32:00 | 0.48 |

**Table 5.4.1: Summary of the Events over the $0.15m^3s^{-1}$ threshold that were analysed.**

In order to monitor the effect of large wood on reach-scale floodplain hydraulics, a series of monitoring sites were used to assess the role of large wood accumulations in encouraging overbank flow and increasing its frequency and magnitude. To fulfil the requirement of the Before-After-Control-Impact (BACI) monitoring approach three sites were chosen, as described in chapter 4, which were monitored before and after restoration. The BACI approach attempts to determine whether the environment, in this case the hydrological and hydraulic functioning of the floodplain, has undergone any changes due to a stress, the restoration works (Smith, 2002). The control site was chosen as a hydrological control site and enables a causal inference to be made and thus reduces the uncertainty involved in a ‘before’ and ‘after’ study, which is limited in its observations (Smith, 2002). Two sites were selected which were subject to restoration and one which was unaffected to act as a hydrological control site. One important feature of a hydrological control site is that it is unaffected by the restoration works that are carried out. Within fluvial studies, especially at a catchment study this is difficult due to the continuous nature of the river system (Vannote *et al.*, 1980). Due to the nature of the river system and the works conducted, it was necessary to have a hydrological control site that was upstream of the restoration. This meant that the effects of restoration would only be identified should any backwater effects occur. Three separate sites on the Highland Water, the Restored-Planform, Restored-Large Wood and Semi-Natural Control (shown in Figure 4.5.1), were investigated to assess the impact of different restoration options upon floodplain hydrology. Crest gauges were installed throughout these three reaches to provide high-resolution information on peak water levels so that the frequency and duration of floodplain inundation could be assessed throughout each reach including in the vicinity of large wood accumulations.

To assess the extent of any large wood restoration, the distribution of large wood was determined. A walkthrough survey of large wood was carried out on the Highland Water between the A31 to the North and the A35 to the south shown in

Figure 6.2.1, whereby the large wood accumulations were accurately mapped and classified according to Wallerstein *et al.* (1997). The Wallerstein *et al.* scheme was preferred as it gave an indication of the hydraulic influence exerted by the large wood. This gave a spatial dataset of large wood to provide large wood densities and the spatial distribution of particular types of large wood accumulations. Large wood density, the number of large wood accumulations per 100 metres, is a commonly obtained statistic in large wood studies and this allows this project and study site to be placed in context with other studies into large wood.
The large wood survey was also compared to previous large wood surveys conducted on the Highland Water by other authors (Gregory *et al.*, 1985; Gregory *et al.*, 1993; Piégay and Gurnell, 1997; Geodata, 2003) to provide a temporal pattern of the large wood dynamics and place the large wood restoration into context.

## 5.5. Large Wood Accumulation Scale

Large wood accumulations are considerable roughness elements that can route flow onto the floodplain thus initiating floodplain flow (Gippel *et al.*, 1996). This is the initial stage within any model of large wood restoration as it is the initial building block to recreate conditions favourable for the development of riverine woodland. The quantification of channel roughness contributed by large wood accumulation has been conducted in a number of previous studies. The roughness is a useful parameter as it gives an indication of the hydraulic influence of the large wood accumulation.

Although it is well known that large wood does have a large control on flow resistance it is extremely difficult to quantify and is often impractical due to the complexity of the large wood accumulations. The approach used for this research is the approach suggested by Gippel *et al.* (1996) which uses a drag coefficient approach as summarised in Chapter 2. Field data on the contribution of large wood accumulation to local reach scale roughness is required as, at present, there is a little information on large wood resistance currently limited to river environments in the USA and Australia. The roughness contributed by the large wood accumulations was measured in the Highland Water to gain an understanding of hydraulic impact of different types of large wood accumulations. The roughness values were also compared to those in other studies of large wood resistance in order to gain insights regarding the role of large wood accumulations in influencing hydraulic resistance in a number of different fluvial environments. A flume investigation was also used to attain additional data and control some of the factors that may strongly influence the hydraulic resistance. Such parameters are discharge, large wood type, and number of key pieces. The flume environment can be used to give an insight to the roughness coefficient associated with large wood accumulations with different volumes of wood and different blockage ratios. In most applications, the flume is usually smaller in size than that of the prototype channel. To allow comparison between the flume simulations and those conditions encountered in natural channels the flume dimensions are scaled to achieve geometric, kinematic and dynamic similarity which means that there is form, motion and force correspondence between the model and prototype (Yalin, 1971; Peakall *et al.*, 1996).

What is unique about this study into the resistance offered by large wood and its accumulations compared with other work (see Shields and Gippel, 1995; Curran and Wohl, 2003) is that large wood accumulations were classified according to the scheme developed by Wallerstein *et al.* (1997). This scheme gives some insight of the hydraulic processes that occur in the presence of large wood accumulations of a particular architecture and allows some understanding of the averaged resistance values obtained within the field. This will lend itself to providing large wood accumulation roughness values for different large wood accumulations that could be easily used by river practitioners. This can allow easy parameterisation of the roughness provided by a particular type of large wood accumulation. From this, it is possible for the design of restoration projects

and also to predict the effect on channel conveyance and/or downstream flood risk.
The roughness values for each classification were also used as an input into a reach-scale hydrodynamic model to assess how different types of accumulations could affect the floodplain inundation frequency, extent and patterns. The use of a roughness value to represent vegetation is a commonly used method in hydraulic modelling (Wu *et al.*, 1999). It is this modelling approach that will enable the link between large wood accumulations and catchment flood hydrology discussed in the following section.

## 5.6. Reach Scale

To fully understand the link between the large wood scale and the catchment scale it is necessary to look at the reach scale and, in particular, the mechanisms by which large wood transfers flow onto the floodplain and the subsequent mechanisms that occur on the floodplain.

Initially a field monitoring approach was undertaken to identify the processes occurring on the floodplain in areas with and without large wood. However, it quickly became apparent that capturing enough appropriate field data, especially in terms of flood event inundation data, and the limited number of study sites would become impractical due to the short duration of flood events in the catchment and logistical limitations. Therefore, it was recognised that a hydrodynamic modelling approach would be the more beneficial approach to understanding the role of large wood in influencing reach-scale hydraulics and floodplain inundation processes by providing synoptic information on flow depths and flow velocity within a reach. Modelling in its broadest sense has now developed into an important philosophical approach to understanding processes and landforms (Rhoads and Thorne, 1996). Essentially models can be viewed as simplified representations of real world processes that provide an insight into the functioning of the natural environment and, ultimately, predicting those processes (Kirkby, 1996; Darby and Van de Wiel, 2003). Modelling represents a methodology to assess a particular understanding of a process and as such can be used to explain outcomes or verify the understanding of those operating processes (Kirkby, 1996). Previous hydraulic modelling studies have looked at meander bends (Hodkinson and Ferguson, 1998), confluences (Parsons *et al.*, 2004), and floodplains (Nicholas, 2003). Hydraulic Models have also been used to assess the effect of channel restoration (Sear and Newson, 2004) but the use of hydraulic modelling as a tool to inform the understanding of large wood processes is novel.

A hydrodynamic model was used to simulate a reach to which it was possible to add hypothetical large wood accumulations to assess their performance as restoration measures to initiate floodplain inundation. Although it was originally desired that a three-dimensional CFD model would be used to represent the three-dimensional hydraulics which would be present both around the large wood accumulation and the channel-floodplain interface, it became apparent whilst trying to create the mesh geometry that the complexities involved in modelling a riverine woodland reach would prove too difficult and that accurate representation of the large wood accumulation would be impractical. Although three-dimensional models are desired for the modelling of flow structures at the channel-floodplain interface which may display strong three-dimensional patterns, they are not currently setup to efficiently model flows with time-varying free surfaces on a floodplain surface. This is because they are computationally expensive and the specification of the complex geometry can be problematic for software and codes primarily designed for simple geometries and lines, which are easily represented with Computer Aided Design (CAD) programs. Currently there is a requirement for the free surface to be specified *a priori (*Nicholas, 2005*)*, which for the purposes of this study cannot be set as it is the inundation extent that is of interest in this study. There are methods to model the free surface such as the volume-of-fluid method although currently this is only practical for cases of simple geometries and can add significant time to that required for a three-dimensional CFD model to converge. As the floodplain inundation extents and frequencies were of prime interest in this study, a two-dimensional hydrodynamic model was considered the most appropriate (Nicholas and Walling, 1996; Nicholas and Walling, 1998; Connell *et al.*, 2001; Nicholas, 2003; Nicholas and Mitchell, 2003; Sweet *et al.*, 2003). Therefore, a review of the available two-dimensional hydrodynamic codes was undertaken to assess which would be most suitable for use in a complex floodplain environment.

## Two-Dimensional Model

The modelling of flows on a riverine woodland floodplain in this study is made difficult due to the specification of the complex and non-uniform surface topography. The majority of large –scale floodplain modelling studies use a code, which requires the creation of mesh geometry, typically generated using a Delaunay triangulation approach, to represent the surface topography (Bates *et al.*, 1998; Bates *et al.*, 2003). The Delaunay triangle type algorithms are typically designed to give detail around the channel regions by calculating the distance of a particular node from the channel before assigning the size of the elements surrounding this particular node (Horritt, 2000; Cobby *et al.*, 2003). Subsequently these algorithms can limit the amount of detail represented in the floodplain surface especially in the presence of vegetation where the specification of an elevation is difficult. One simple approach to this issue is to use a hydrodynamic code that accepts a Digital Elevation Model raster as input geometry. The structured grid of a raster allows a uniform representation of the surface topography representing both channel and floodplain at the same resolution. The use of rasters can also be beneficial as they can be readily produced from topographic survey data in a Geographical Information System (GIS) such as ArcGIS of MapInfo and furthermore can be readily edited which is useful in eliminating spurious data and in representing different model scenarios such as the presence of rigid standing vegetation. One such code that allows the input of geometry in raster format is Hydro2de. Hydro2de has been used in a number of floodplain flow studies including those with complex floodplain topographies (Connell *et al.*, 2001; Nicholas, 2003; Nicholas and Mitchell, 2003; Sweet *et al.*, 2003) and is considered relatively efficient in solution compared to other two-dimensional models (eg. Telemac2D, McLelland personal communication). Hydro2de can also handle dry and wet cells so can simulate the gradual inundation of the floodplain whilst also representing turbulence using the Boussinesq approximation, which is considered applicable to the simulation of turbulence in areas of flow separation (Nicholas, 2003) and for these reasons, was chosen for use in this research.

### Hydro2de

Hydro2de is a grid-based two-dimensional floodplain flow model (Beffa and Connell, 2001). It uses a finite volume scheme to model flows over a uniform grid. Hydro2de is based on the depth averaged shallow water equations and uses a finite volume method to solve equations using an explicit integration method to calculate the flow depth and two horizontal unit discharge components. Further details are given in chapter 8. As noted before it has been used in numerous floodplain studies and is considered suitable for use in complex floodplain environments (Connell *et al.*, 2001).

A Hydro2de model was produced for the Restored-Planform reach for the post-restoration scenario. The model was calibrated and validated against field data to ensure it gave an accurate process representation and could be used as an experimental tool.

## *5.7. Modelling Methodological Framework*

Patterns of inundation are of most interest in riverine woodland as they are not unidirectional as is often assumed of floodplain flow on non-vegetated floodplains (see Knight and Shiono, 1996). Topographic variability and the presence of biotic matter upon the floodplain surface create a complex multi-directional flow field that has been observed in the field (Brown *et al.*, 1995). This leads to complex inundation patterns where topographic high points protrude from the water surface like islands. The complex pattern of floodplain inundation also leads to a range of flow habitat types as the pattern of flow depths and flow velocities give rise to ponded areas, recirculation zones and areas of high velocity. These flow types are a feature of floodplains with complex topography (Nicholas and Walling, 1998; Nicholas and McLelland, 1999) as well as vegetation (Brown *et al.*, 1995) and are important in providing habitat diversity (Newson and Newson, 2000).

Once a calibrated hydrodynamic model of the post-restoration channel had been developed then it was possible to 'add' different types of large wood accumulations to the model to assess how they influenced flood inundation extents and flow patterns. The modelling work had a number of outputs:-

- An understanding of riverine woodland hydraulic processes,
- An assessment of whether restoration has moved the floodplain hydraulic processes in the direction of those observed in natural wooded river systems,
- A methodology for modelling the effect of large wood accumulations,
- An assessment of the effects of different types, location and types of large wood accumulation in routing flow from the channel onto the floodplain to gain insight into which large wood structures are best suited for this purpose,
- An understanding of the role large wood plays in the creation of heterogeneous flow habitats.

It was decided to run a number of models of various discharges ($0.16m^3s^{-1}$, $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$) where the roughness value was systematically varied to simulate the effect of different large wood accumulations upon the inundation extent. These models were run and then inundation extents were used to assess the performance of each type of large wood accumulation as a restoration tool in order to initiate floodplain inundation.

The outputs were assessed in terms of inundation extents, flow depth patterns and velocity vectors. A feature of hydrodynamic studies conducted within the literature to date is the qualitative nature of analysis with often the results showing that simulated extents show a good match with observed data (Connell *et al.*, 2001; Horritt and Bates, 2002). This is more common for large scale floodplain studies, and although some progress has begun to be made with regards to quantifying patterns within river channels (see for example the work of Emery *et al.*, 2003) this work seeks to go further using techniques commonly used in landscape ecology. A spatial pattern analysis program, Fragstats, (McGarigal *et al.*, 2002) was used to assess the spatial patterns that are present within each simulation setup. Originally used for habitat analysis and land cover change the software was used to calculate landscape metrics which can be used to characterise and, perhaps more importantly, quantify spatial patterns of flow depth and velocity to assess the diversity of complex flow patterns that arise in these environments.

Landscape metrics are indices that quantify patterns of patches, classes or entire landscape patterns within a categorical map (McGarigal *et al.*, 2002). Patches are the fundamental units of the landscape mosaic and are specific to an individual's area of interest. Within deforestation studies, they normally refer to a stand of forest (McGarigal *et al.*, 2002) although in this study the patches will be different classes of flow depth or flow velocity. Patch classes are the family that a particular type of patch belongs to, class metrics will therefore refer to the aggregate properties of patches within a specific class type. Landscape metrics are then easily defined as the next level up from class and refer to the properties portrayed by the class types within the landscape mosaic (McGarigal *et al.*, 2002). The composition of the landscape refers to characteristics associated with the variety and abundance of different units within the landscape without considering the spatial pattern of the patches within the landscape mosaic (Gustafson, 1998). Composition indices include diversity and the relative abundance of each patch type. This will allow a methodology for comparing the different roles of various components of a forested floodplain system. For example, it can be used to see whether the addition of large wood affects the diversity of floodplain flows.

The role of topography and geomorphological features in exerting control over floodplain inundation has been further observed and modelled (Simm, 1993; Nicholas and Walling, 1997). Previous two-dimensional modelling studies have found that topography plays a key role in influencing floodplain inundation (Mitchell and Nicholas, 1998) although these have been in low-energy lowland areas where the main land cover was pasture. In a forested floodplain environment, where the vegetation is much more rigid and multi-directional flow has been observed (Brown *et al.*, 1995; Jeffries *et al.*, 2003), vegetation and large wood is likely to play a key role in creating diverse multi-directional flow patterns. It is this hydraulic diversity that can create the conditions favourable for the sustainability of forested floodplains (Fetherston *et al.*, 1995).

## 5.8. Summary

Through the use of a nested approach, which looks at a continuum of spatial scales it is possible to improve the understanding of large wood. In particular, the role that large wood plays in influencing local reach scale hydraulics, floodplain inundation and catchment hydrology is investigated. The EU Life 3 restoration project provides an excellent opportunity to study the links between these scales and processes. However, time constraints have also restricted the approach taken. The time constraints meant that limited detailed reach-scale data was collected prior to restoration, although the use of the Highland Water as a research catchment by the University of Southampton means that some baseline hydrology data prior to the restoration is available. The inconsistencies of the UK weather meant that observations of flood events, from which to observe and monitor floodplain inundation patterns, were limited and thus a hybrid approach is taken. This resulted in a three-stage approach being taken which looked at field monitoring, flume modelling and hydrodynamic modelling. This enables the hydraulic and hydrologic effect of large wood to be evaluated, which can assist restoration practitioners in the future. The nature of the Highland Water makes this an excellent location for such work, as it is one of the few areas in Western

Europe where forested floodplains occur and where large wood is known to be an important feature (Jeffries *et al.*, 2003).

# 6. The role of Large Wood upon Floodplain Hydrology and Catchment Flood Hydrology

## *6.1. Introduction*

The use of floodplain storage as a means of reducing flood probability, the chance of a flood event, and subsequently flood risk, the potential impact of a flood event, is something that has been widely carried out. Schropp and Jans (2000) report on a flood alleviation scheme in the lower Rhine where river embankments were removed to restore potential floodplain storage in order to reduce flood risk downstream. The presence of embankments was thought to be partially responsible for large scale flooding in 1994. The problem with embankments is further illustrated by the work of Acreman *et al.* (2003) who found that the presence of embankments on the River Cherwell in south-east England was responsible for an increase in peak flow of 50-150%. The channelisation of river channels appears to have systematically increased the flood peak in catchments (Wilcock and Wilcock, 1995) and Sear *et al.* (2000) claim that the loss of floodplain wetlands and associated storage functions, largely due to channel modifications, channelisation and embankments, has profoundly affected the hydrology of UK rivers. The restoration of the channel-floodplain connection through the use of large wood accumulations is likely to subsequently impact on the catchment hydrology of river catchments. As flow is stored upon the floodplain the floodwave is attenuated thus reducing and delaying the peak discharge (Burt, 1997) which can have potential benefits for the catchment flood hydrology. Large wood is a critical component of many river systems with its influence on hydraulics, geomorphology, ecology and hydrology within both the channel and the floodplain. The use of large wood as a restoration tool is a relatively recent application within the river restoration sphere (Collins and Montgomery, 2002; Brookes *et al.*, 2004; Shields *et al.*, 2004).

Although it is known that large wood acting as a roughness element would lead to some improvement of the channel-floodplain link thus encouraging floodplain inundation (Gippel *et al.*, 1995; Jefferies *et al.*, 2003), the mechanisms by which it provides this link are poorly understood. Jefferies *et al.* (2003) have identified that large wood can play a significant part in encouraging overbank inundation through the connection of the river channel with its floodplain. They found that large wood accumulations can increase the floodplain inundation frequency by up to 41%. This inundation of the floodplain can result in the storage of water, which can subsequently slow the passage of a flood wave (see Gregory *et al.*, 1985; Gregory, 1992). The role of large wood in influencing the catchment hydrology is currently limited with many claims regarding its influence upon flow routing lacking supportive data (Gippel *et al.*, 1992).

The EU LIFE 3 restoration project has provided an excellent opportunity within a monitored catchment to provide an insight into the role of large wood accumulations within a restoration context, in particular looking at its influence on both reach-scale and catchment-scale hydrology. This provides an important understanding of the hydrological dynamics of large wood accumulations, which may allow the use of further large wood restoration in other restoration projects and locations.

Large wood is both dynamic and versatile and thus complex in nature. It often forms accumulations that can affect channel hydraulics in a number of ways depending on their architecture and locations (Abbe and Montgomery, 1996; Wallerstein *et al.*, 1997). Thus, the following chapter will begin with a review of the spatial distribution of large wood within the study catchment before looking at its hydrological role at the reach-scale and the catchment-scale. At the reach-scale, large wood plays an important role in encouraging overbank inundation and this will be assessed using observed data from the Highland Water showing the effects of the restoration as well as providing the basis for the further research presented within this thesis. At the catchment-scale, large wood accumulations are known to influence the timing and magnitude of flood peaks (Gregory *et al.*, 1985; Gregory, 1992).

## 6.2. The Distribution of Large Wood in the Highland Water

The Highland Water is unique in the context of the UK as there is a long history of research into the spatial distribution of large wood through the research of authors such as Gregory and Gurnell. A number of walk-through surveys have been conducted which have sought to map and categorise the locations of large wood accumulations create a picture of the large wood dynamics. Surveys have been conducted in 1983, 1990, 1996 and reported in the work of Gregory *et al.* (1985), Gregory *et al.* (1993), and Piégay and Gurnell (1997). These have been supplemented by three other surveys in 2002, 2004 and 2006 conducted for EU LIFE 3 monitoring purposes. The work presented here only relates to the Highland Water from the A31 to the North and the A35 to the south, as shown in Figure 6.2.1 and therefore only represents a subsection of the surveys from 1985 to 2006.

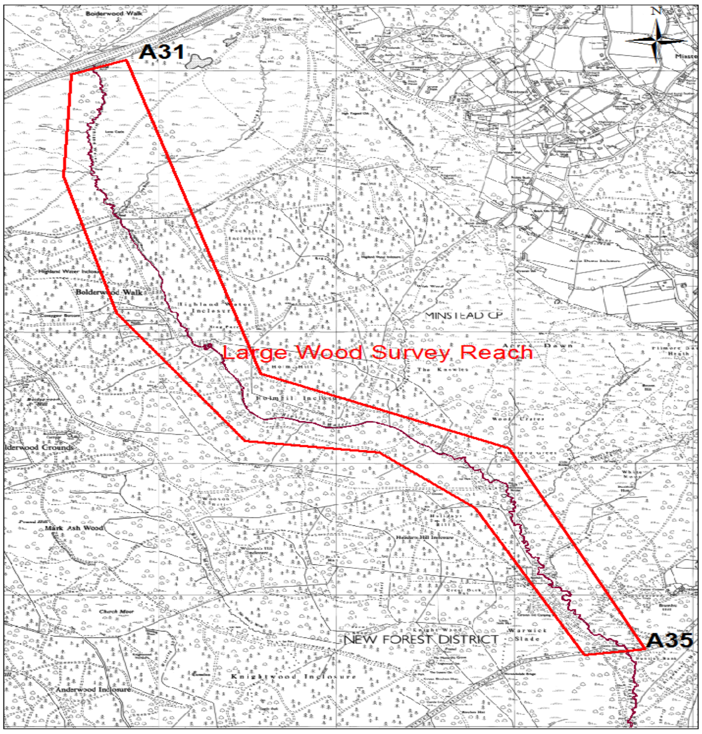



**Figure 6.2.1: The Location of the Large Wood Survey Reach on the Highland Water, New Forest.**

The early large wood surveys distinguished the types of large wood accumulations using a simple classification scheme (Gregory *et al.*, 1985). The two recent surveys of 2004 and 2006 further elaborated the classification by using the classification scheme developed by Wallerstein *et al.* (1997). The scheme used by Wallerstein *et al.*, (1997) is considered to provide a more theoretical understanding of the hydraulic role provided by the large wood accumulation and is therefore deemed more relevant to this work.

The classification scheme used by Gregory *et al.* (1985) can be easily re-assigned to a classification from the Wallerstein *et al.* (1997) scheme based on the channel hydraulics and is shown in table 6.2.1. Although not directly comparable, the active large wood accumulations classified in the Gregory *et al.* (1985) scheme can be reclassified as overflow accumulations as they both lead to a hydraulic head between the water level upstream and downstream of the large wood accumulation. The partial accumulation of Gregory *et al*. (1985) can be considered equivalent to the deflector accumulation of Wallerstein *et al.* (1997) as both do not completely span the channel and divert the river flow to a particular part of the river cross-section. The high water accumulation of Gregory *et al.* (1985) can be equivalent within the Wallerstein *et al.* (1997) scheme to the underflow accumulation. This is due to the fact that neither impact upon the flow regime until higher flows. The complete accumulation of Gregory *et al.* (1985) has no direct comparison in the scheme of Wallerstein *et al.* (1997) but observations have found that these complete accumulations can allow flow through the accumulation under the water surface and thus these accumulations portray similar hydraulic characteristics to underflow accumulations. The Parallel/Bar Head jam found by Wallerstein *et al.*, (1997) is not found in the study catchment due to the high key piece length to channel width ratio which reduces the potential of the large wood anchoring to a bar head.

| Type | Description | Wallerstein *et al.*, 1997 Classification |
|---|---|---|
| Complete | Spans the channel width but does not cause a step in the water surface profile. | Not directly classed in the scheme of Wallerstein *et al.*, 1997 but flow is often transferred through the large wood accumulation often under the water surface between large wood pieces and therefore complete accumulations were re-classified as underflow accumulations |
| Active | Spans the channel width and causes a step in the water surface profile | Overflow accumulations |
| Partial | A large wood accumulation which partially spans the channel width | Deflector accumulation |
| High Water | Spans the channel but does not influence the flow until high water flows | Underflow accumulation |

**Table 6.2.1: Large wood accumulation classification from Gregory *et al.*, (1985) compared to that of Wallerstein *et al.* (1997).**

The long record of walk-through surveys together with the classifications and mapping of large wood accumulations has enabled the development of a time series showing the temporal distribution of large wood accumulations from 1983 to 2006. Figure 6.2.2 shows the temporal distribution of large wood in this period. The distribution of large wood per 100m is also shown in table 6.2.2 for the various survey dates. This provides a more accurate picture as it also represents the increase in sinuosity and thus channel length since the channel planform restoration. It also provides a methodology to compare with large wood distributions in other river channels throughout the world.

During the period of large wood monitoring, there have been significant events that have affected the number of large wood accumulations. Between 1983 and 1990 there was a period relatively free from channel management, which also included a major storm in October 1987 of some note within a UK context. This high magnitude storm resulted in 15 million trees being blown over throughout southern England as windspeeds hit a maximum of 90 knots (Met Office, 2009). Within the Highland Water catchment, this led to significant input of large wood into the river system through wind blowdown (Gregory, 1992). This period of high inputs of large wood and minimal management resulted in large wood accumulation densities per 100m as high as 1.77. A value between one and six is similar to those found in other areas of the New Forest but are lower than other streams in the USA and Australia, where large wood accumulations can frequently occur between 10-15 times per 100m (Gurnell *et al.*, 1995).

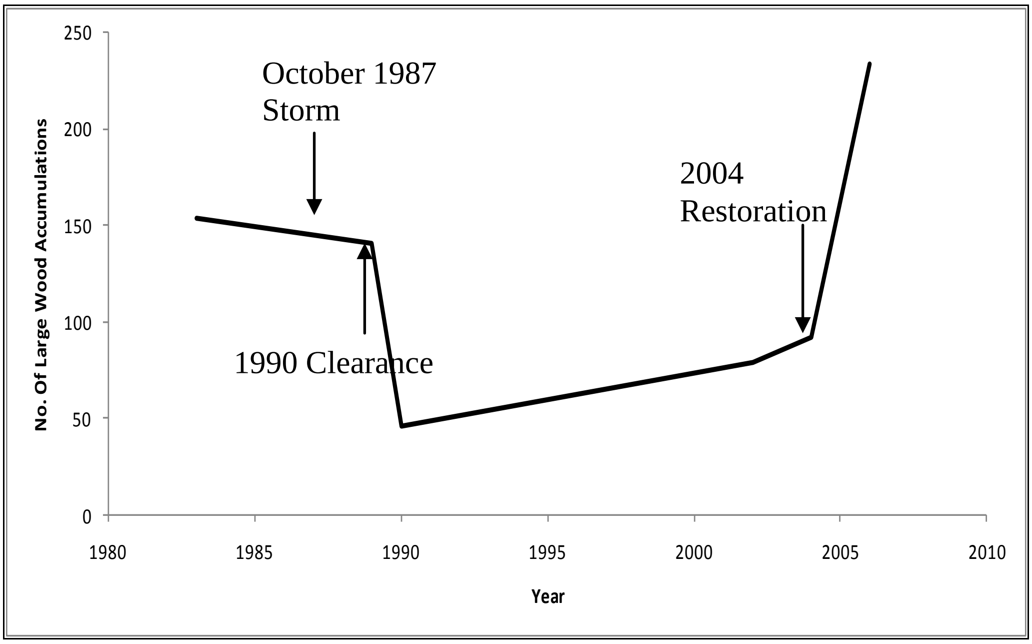



**Figure 6.2.2: Temporal Pattern of Large Wood Accumulations within the Highland Water Research Catchment.**

Following the 1987 storm, there was increased management of the channel incorporating clearance of large wood from the channel in 1990, which led to the widespread removal of large wood accumulations (Gregory and Davis, 1992). This is shown as a low level of total accumulations with large wood accumulation density dropping to 0.53 per 100m in 1990. By Highland Water standards, this is extremely low and gives an indication of the effect of the management of large wood within the river system.

| Year | No of Large Wood Accumulations | Channel Length (km) | Large Wood Accumulations per 100m |
|---|---|---|---|
| 1983 | 154 | 8.7 | 1.77 |
| 1989 | 141 | 8.7 | 1.62 |
| 1990 | 46 | 8.7 | 0.53 |
| 2002 | 79 | 8.7 | 0.90 |
| 2004 | 92 | 8.7 | 1.06 |
| 2006 | 234 | 9.1 | 2.57 |

**Table 6.2.2: Large Wood Distribution in the Highland Water Research Catchment. Highlighted data is post-restoration.**

Since 1990, there has been a steady increase in the number of large wood accumulations up to 2004 where large wood accumulation density rose to 1.06 per 100m. This was largely a function of more relaxed management policies.

As part of the current restoration, there has been an increase in the number of large wood accumulations up to 234 accumulations. This is higher in both total numbers and in densities per 100m (2.57 accumulations per 100m) than the long period of relative low management in the early 1980s. This shows that the restoration measures have led to a significant post-restoration increase in the frequency of large wood accumulations within the Highland Water. This ties in with some of the higher densities of large wood accumulations found in other parts of the Highland Water catchment by Gregory *et al.* (1993) (Bagshot Gutter had a density of 11.84 accumulations per 500m, equivalent to 2.37 accumulations per 100m). Gregory *et al.* (1993) found large wood density within the Highland Water to be 4.99 accumulations per 500m (equivalent to 1 per 100m) and suggested that this may only account for 7% of the total net load that could have been present with limited management and removal. Therefore, the large wood accumulation density achieved by the restoration scheme is approximately equal to those densities found in other parts of the catchment whilst also providing scope for further development of large wood accumulation frequency through management practices.

The increase in total number of large wood accumulations within the research catchment is a function of both the input of new pieces of large wood, the discovery of relic large wood accumulations within the restored, previously abandoned channel together with the increased retention of wood pieces within the channel due to increased planform sinuosity, the increased number of in-channel trapping sites for large wood accumulations and channel bars (Millington and Sear, 2007). Prior to restoration, the straight and highly incised channels meant that channel velocities were relatively high, there was little connectivity between the channel and the floodplain and, consequently, large wood pieces travelled significant distances (up to 900m over a 44 month monitoring period). The creation of large wood accumulations provided a trapping point for further large wood, which meant that over time, the accumulations began to develop, becoming increasingly hydraulically active and more stable. Restoration of the sinuous, meandering channel recreated the processes that occur in natural wooded streams (Brown *et al.*, 1995). The sinuous channel meant that deep pools and side bars were present which acted to trap large wood. Millington and Sear (2007) showed that although the presence of large wood accumulations was most important in the retention of wood pieces; pools, side bars and bank vegetation were also significant. In addition, the re-connection of the channel with its floodplain meant that large wood on the floodplain surface could be mobilised during an inundation event and transported into the channel.

The temporal pattern of large wood density provides an indication of the dynamic nature of large wood with many large wood accumulations changing position or type. Gregory *et al.* (1985) found, that over a 12 month period, 36% of large wood accumulations changed position. This is further supported by data from Sear *et al.* (2010) who observed that 86% of large wood accumulations changed location over a 23 year period. Of those accumulations that remained in the same position, 69% changed type (Sear *et al.*, 2010). The dynamic nature of large wood accumulations can cause problems for management as they can be trapped at hydraulic structures and bridges thus creating a flood risk. However, there are some large wood accumulations that remain stable over longer periods; for example, the Millyford Bridge accumulation, which was first identified in 1993 and is still present in its original location within the Highland Water (shown in figure 6.2.3).

**Figure 6.2.3: Millyford Bridge Overflow Large Wood Accumulation**

Other authors have observed even higher residence times of up to 40-90 years (Hogan *et al.*, 1995).

## *6.3. Large Wood Accumulation Classifications*

The number of different classifications of large wood accumulations can also be assessed through time in a similar approach to above. Table 6.3.1 shows the temporal distribution of each large wood accumulation type and shows that although overall there has been an increase in the number of large wood accumulations that is not represented within all classifications. For example, restoration led to an increase in deflector and underflow accumulations although the number of overflow accumulations was reduced. Part of this difference may be due to differences in classifications between different surveys but management policies and the dynamic nature of large wood accumulations are likely to be the predominant factors.

| Year | Overflow | Deflector | Underflow | Total |
|---|---|---|---|---|
| 1983 | 33 | 89 | 32 | 154 |
| 1989 | 10 | 87 | 44 | 141 |
| 1990 | 15 | 26 | 5 | 46 |
| 2002 | 30 | 20 | 29 | 79 |
| 2004 | 22 | 30 | 40 | 92 |
| 2006 | 6 | 123 | 105 | 234 |

**Table 6.3.1: Temporal Pattern of Different Large Wood Accumulations.**

Between 1983 and 1989 there was a reduction in the number of overflow accumulations as these were cleared as part of river management practices in 1989 (Gregory and Davis, 1992). However, the numbers of deflector and underflow accumulations stayed fairly stable. Between 1989 and 1990, large-scale large wood clearance reduced the amount of large wood present within the river channel, which meant that there was a reduction in the number of deflector and underflow accumulations.

The restoration produced an increase in the numbers of deflector and underflow accumulations whilst also leading to a reduction in the number of overflow accumulations. The placement of large wood as part of the restoration measures was carried out using heavy plant machinery. In some locations, trees close to the bank were removed by chainsaw or by uprooting the tree straight into the channel. A variety of large wood accumulations were placed within the channel, with type and number of key pieces varied to mimic natural processes. In both circumstances the large wood pieces were anchored either by inserting one end into the bank or by its rootwad. Despite this stability, observations showed that the first high flows that were experienced subsequent to installation led to scouring under the key piece of the accumulation resulting in the formation of an underflow accumulation. The large wood accumulation deformed the flow field, which locally accelerates the near bed flow resulting in scour of the bed. This led to large wood accumulations appearing as naturally occurring bridges across the channel (Hickin, 1984). Large wood accumulations are known to deflect flows and result in both bed and bank scour (Wallerstein *et al.*, 1997; Davis and Gregory, 1994, Gurnell *et al.*, 2002). The scour increases the channel cross-sectional area, reducing the relative blockage area of the large wood accumulation and creating either an underflow accumulation or a deflector accumulation. It is suggested that the creation of deflector and underflow accumulations is easier than that of an overflow accumulation. This is shown in the increase in the number of deflector and underflow accumulations between 1990 and 2004 (see table 6.3.1). It is argued that overflow accumulations take a lot longer to develop but that once they have developed they are more stable, as shown by the relatively stable numbers of overflow accumulations between 1989 and 2004 together with the semi-permanent nature of the Millyford Bridge accumulation. Observations showed that through time there was a reduction in scour near to the large wood accumulation and the entrapment of further wood pieces led to further development of accumulations. This resulted in large wood accumulations with higher blockage ratios and therefore an increased hydraulic resistance.

As part of the restoration project, there was a requirement to monitor the performance of the restoration measures to ensure that they fulfilled the criteria and objectives that had been set prior to the restoration. Two objectives concerned the effect of the large wood restoration on catchment flood hydrology and localised floodplain inundation. These were both assessed via a monitoring approach, which also gave an insight into the role of large wood accumulations in promoting overbank inundation.

## 6.4. Hydrological Monitoring Approach

Monitoring programmes, if well designed and properly maintained, can provide important evidence of restoration impact and a stimulus to experimental research (Kondolf, 1998). The existence of long, reliable data sets considerably increases our ability to make informed decisions about the way we manage our river catchments. Good baseline data is essential for the success of any monitoring programme so that it is possible to measure change in the variable of interest and assess a 'restoration-effect'. This can prove difficult due to the length of the feasibility and design phase of the restoration that often means a monitoring system is not set up far enough in advance to record baseline data.

As a research catchment, the Highland Water has a long record of hydrological data at a catchment scale, a good baseline exists and thus catchment scale effects could be assessed. Figure 4.4.2 shows the location of the hydrological gauges on the Highland Water. On the Highland Water, there are five stage recorders for which hydrological data was available. The gauges were a range of pressure transducers summarised in table 6.4.1. Each gauge automatically recorded stage and were supplemented with spot-gauging, which enabled the creation of stage-discharge relationships for each gauge.

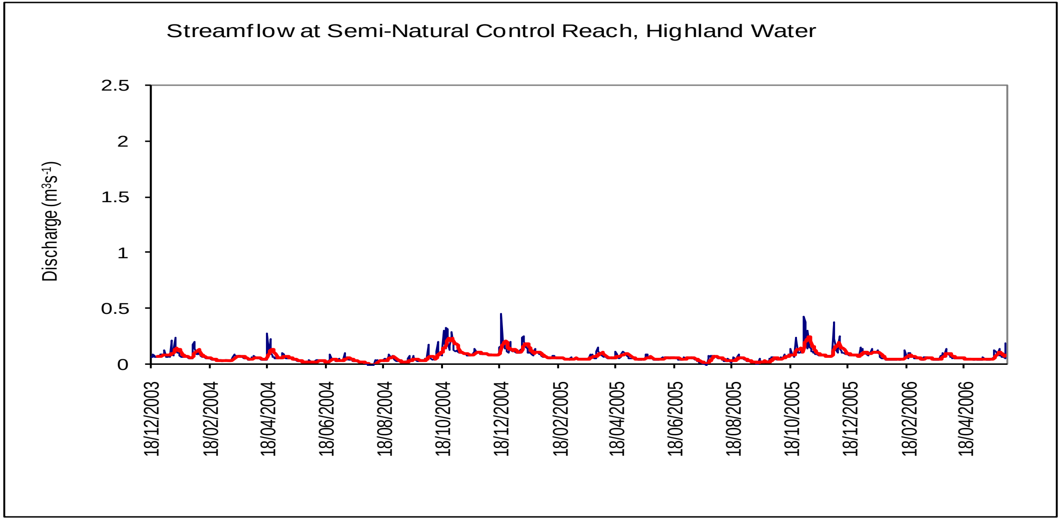
The Semi-Natural-Control and Restored-Large Wood Reach gauges were installed in December 2003 to provide at-a-site measurements at particular reaches within the Highland Water. The Highland Water 1 gauge is an Environment Agency run gauge that was installed in January 2003. It was installed in a location close to a former University of Southampton research gauge. This, together with the Millyford Bridge gauging station, enabled direct comparison with the data of Gregory *et al.* (1985) and Gregory (1992) as well as providing data at both upstream and downstream limits of the restoration reach.

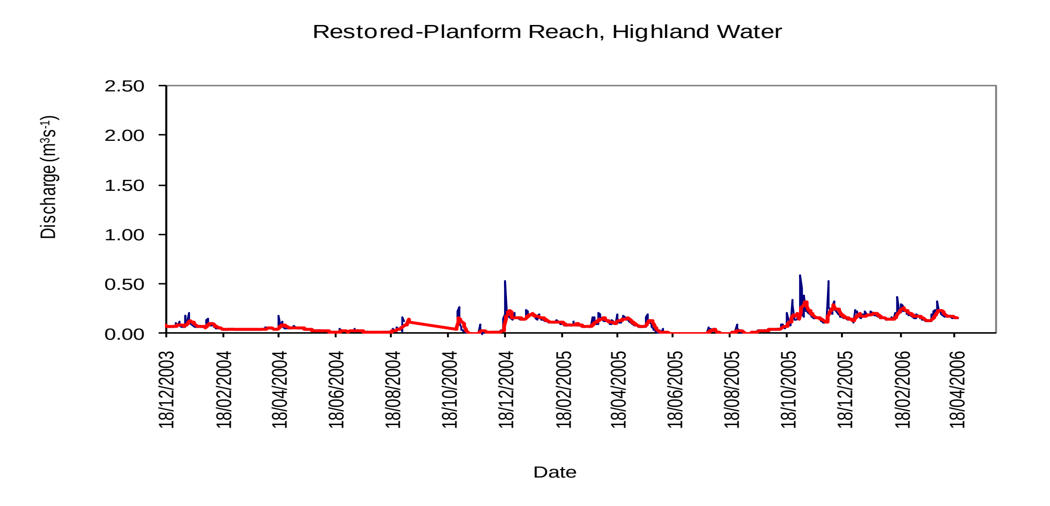
| Location | Gauge Name | Grid Reference | Specification | Start of Data Record | End of Data Record | Sample Frequency |
|---|---|---|---|---|---|---|
| Highland Water 1 | Highland Water 1 | SU 2477, 0988 | Unknown Pressure Transducer | 01/01/2003 | 20/04/2006 | 15 minutes pre-10/03 5 minutes post-10/03 |
| Highland Water 2 | Highland Water 2 | SU 2839, 0475 | Thalimedes Shaft Encoder | 01/04/2004 | 17/02/2006 | 5 minutes |
| Semi-Natural Control Reach | Reference | SU 2464, 1014 | Druck PDCR1830 PT | 18/12/2003 | 01/06/2006 | 5 minutes |
| Restored-Large Wood Reach | Control | SU 2620, 0832 | Druck PDCR1830 PT | 15/12/2003 | 01/06/2006 | 5 minutes |
| Millyford Bridge | Millyford Bridge | SU 2698, 0758 | Trans-America PT | 11/03/1998 | 31/05/2006 | 10 minutes pre-03/04 5 minutes post-03/04. |

**Table 6.4.1: Hydrological Monitoring Sites used in this Study**

The data from Highland Water 2 is not used within this study but has been used to assess the impact of the timing of the Highland Water especially in conjunction with the timing of the River Blackwater as part of the EU Life 3 official monitoring report.

Figure 6.4.1 shows the flow hydrographs for the three study reaches (Restored-Planform, Restored-Large Wood and Semi-natural Control Reaches) over the monitoring period.



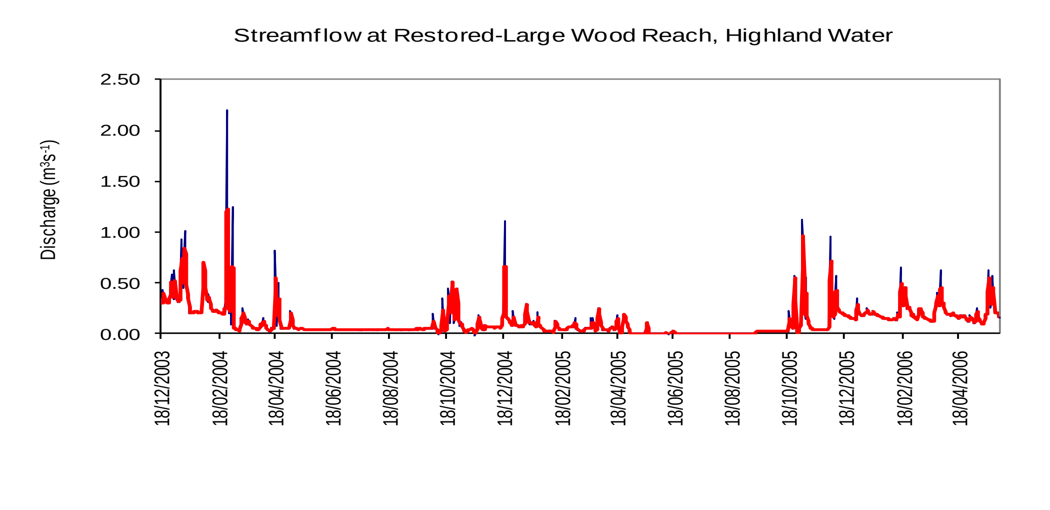




**Figure 6.4.1: The Flow Hydrographs for the three monitored reaches on the Highland Water.**

## Monitoring Period

The hydrological monitoring for the EU Life 3 restoration officially began in January 2003 with the Environment Agency gauges at Highland Water 1 and Highland Water 2 monitoring stage supplemented by monthly spot gauging. At this point, the Millyford Bridge gauging station was already operational but the gauges at the Semi-Natural Control and Restored-Large Wood sites were not installed until December 2003 with the advent of this study. Monitoring for the EU Life 3 project appraisal took place until June 2006.

Within the period of monitoring, central southern England suffered some of the driest years on record. Between November 2004 and January 2006, 13 of the 15 months experienced below average monthly rainfall totals and for the whole monitoring period, 23 out of the 34 months had rainfall totals below the average. Table 6.4.2 shows the monthly breakdown of the hydrological data for the monitoring period from the Meteorological Office together with the totals for the various years (the yearly value is based on flood seasons, which in this study refer to the period 1$^{st}$ October-30$^{th}$ September).

The restoration took place in August-October 2004 so therefore, the wettest year was the one prior to the restoration (813mm rainfall in 03/04) and the two preceding years were relatively dry. This highlights the need for further long term monitoring of the EU Life 3 restoration as well as identifying the difficulties in designing a monitoring programme which will fit into the relatively short time scales of a PhD research project. The dry nature of the monitoring period had a knock on effect for both the monitoring and the research conducted within this thesis. The limited high flow dataset during the monitoring period meant that the methodological approach had to be modified and for this reason, a modelling approach was developed to assess the role of large wood as described in chapter 8. However, there is some useful hydrological data that can give an indication of the broad scale impact of the role of large wood in restoring riverine woodland hydrological processes.

| | Year | | | |
|---|---|---|---|---|
| **Month** | **2003** | **2004** | **2005** | **2006** |
| **January** | | 103.9 | 39.3 | 23.4 |
| **February** | | 32.5 | 24.8 | 57.5 |
| **March** | | 43.6 | 51.3 | 58.6 |
| **April** | | 76.9 | 50.1 | 38.9 |
| **May** | | 51.7 | 33 | 95.9 |
| **June** | | 33.3 | 34.5 | 20.9 |
| **July** | | 53.1 | 61.5 | 39.5 |
| **August** | | 102.5 | 55.1 | |
| **September** | | 35.1 | 40.4 | |
| **October** | 51 | 129.6 | 98 | |
| **November** | 144.1 | 34.8 | 54.4 | |
| **December** | 85.3 | 59.3 | 69.2 | |
| | | **2003/2004** | **2004/2005** | **2005/2006** |
| | **Total** | 813 | 613.7 | 689.1 |

**Table 6.4.2: Monthly Rainfall Totals in mm for central southern England as taken from the Met. Office (Highlighted represents drier than long-term average).**

## 6.5. Hydrological Impact of the Restoration

The catchment hydrology is sensitive to changes in a number of factors that can either occur within the catchment boundaries or be external to the catchment limits. Those factors that occur outside of the catchment are referred to as systemic whereas those changes that can occur at the local scale and have a net effect upon catchment hydrology are known as cumulative change (Arnell, 2002). Table 6.5.1 shows a number of cumulative and systemic factors that may impact upon the catchment dynamics.

| **Cumulative** | **Systemic** |
|---|---|
| Land Cover Change (eg. Deforestation)<br>Water Use (eg. abstractions)<br>Physical Infrastructure (eg. Dam Creation)<br>Channel Management (eg. River Restoration, Dredging, Large Wood removal) | Climate Change<br>Global Environmental Change |

**Table 6.5.1: Factors affecting Catchment Hydrology.**

Any of the changes shown in Table 6.5.1 can influence the hydrology in different ways with the three main responses being a change in volume of flow and storage, a change in the timing of a flow or a change in the water quality (Arnell, 2002). The objective of the EU LIFE 3 restoration scheme was to increase localised inundation and show no net increase in downstream flood probability. The inundation of a floodplain is a function of the volume of flow and the timing of the flood peak, which it can subsequently affect through floodplain storage (Wolman and Leopold, 1957). As the volume of water in the system increases, the storage in the channel increases until such point as it spills onto its floodplain. The floodplain acts as a storage reservoir and, like all storage reservoirs, this leads to an amelioration of flood peak both in terms of magnitude and timing (Brown, 1997; Leopold, 1997). By increasing the frequency of the use of the floodplain, it is possible to reduce the flow volume and/or change the timing of the flow. The change in timing can often be beneficial to flood risk but it can also be detrimental with the delay in the travel of the flood peak potentially resulting in peak flows being synchronised with those from other tributaries. For the purposes of the EU LIFE 3 restoration, a catchment flood modelling exercise was undertaken to determine the effect of the restoration upon the synchronisation of flood peaks for design flood events on the Highland Water and the neighbouring River Blackwater (Norton, 2003) with no adverse effects upon downstream flood risk discovered for a range of design flood events.

The hydrological behaviour of a river catchment varies temporally due to climatic factors, which are external to the system and make it difficult to detect any changes in the time series. Therefore, it is difficult to isolate the effect of large wood upon flood hydrology using historical flow records (Gippel 1995). It is, however, possible to ascertain significant changes by assessing a temporal pattern before and after an impact, in this case restoration, whilst also using a control to show that the impact of the restoration is a significant change rather than a function of climactic variations. One drawback of this approach is that hydrological time-series are notoriously ‘noisy’ and any induced change in the hydrological behaviour may be masked by the background noise. Hydrological time series were assessed at a number of locations within the catchment for before and after the restoration works. The continuous nature of a river channel meant that the control data would have to be either from a similar nearby catchment (see paired catchments studies such as Plynlimon (Kirby *et al.*, 1990; Kirby *et al.*, 1997) or a site within the same catchment.

The neighbouring catchments to the Highland Water, the River Blackwater and Cadnam Brook, were significantly different in terms of drainage density, geology and land cover and for these reasons an upstream control site was chosen. This is not ideal as a restoration effect can impact upon downstream and, in some cases, upstream hydrological behaviour. The three monitoring sites together with the Millyford Bridge gauging station gave a total of four hydrological datasets at various points in the Highland Water catchment. At the upstream end was a control dataset set in semi-natural woodland that was not subject to restoration. The Highland Water 1 gauging station was situated 200m upstream of a large 1km reach that had undergone planform restoration. The Restored-Large wood gauge was situated in a 2km reach where the restoration approach consisted of the input of large wood without any modification of the channel planform. The Millyford Bridge gauging station was outside of the area of restoration and thus can give an indication of the effect of the complete restoration works on the catchment hydrology.

## 6.6. At-a-Site Hydrological Effect

Hydrological conditions were monitored at three sites, the Restored-Planform, Restored-Large Wood and Semi-Natural Control, to ascertain the hydrologic connectivity between the channel and its floodplain and provide a grasp of the relative importance of the planform restoration and the presence of large wood accumulations. A series of crest gauges were deployed to monitor the peak water levels throughout the three reaches. The crest gauges were a low cost approach that consisted of a drain pipe with an inner rod that was located on the bank of the channel (see Figure 6.6.1). The drain pipe had a number of holes drilled into it to allow the entrance of water. Within the drain pipe, polystyrene balls were placed which when water entered the drain pipe, were able to float on the rising surface and stick on the inner rod at a crest stage. After an event, it was possible to carefully remove the rod from the drainpipe in order to measure the level of any polystyrene balls on the inner rod and subsequently obtain the peak water level. The crest gauges were surveyed relative to a datum using an electronic total station (a Geodimeter 620) so that the water level could be set to an arbitrary water elevation. This also meant that water elevations could be directly compared before and after restoration. Crest gauges were often placed at an angle on the bank and thus the angle was measured to allow the correction of the elevation. The measurement error associated with the crest gauge is estimated to be in the order of 5-10cm. Measurement of a number of crest gauges throughout the reach enabled the identification of significantly spurious data that were removed and therefore assisted in the accuracy of the technique.

**Figure 6.6.1: Two Photos of Crest Gauges used in the field to monitor peak water levels.**

Channel cross sections were also surveyed at each crest gauge so it was possible to relate the stage to the channel cross section and ascertain whether the flow was confined within the bankfull channel or was sufficient to spill onto the floodplain. The crest gauges were checked on as close to an event by event basis as practically possible and at least on a tri-weekly basis over the three monitored flood seasons starting on October 16th 2003. Water levels were monitored before and after the restoration with monitoring for this project ending in June 2006.

The crest gauges allowed the identification of peak water elevation throughout the reach but when coupled with an inlet discharge taken from the available gauging stations it was possible to determine stage discharge relationships for each crest gauge. Consequently, it was possible to calculate the associated stage for each measured discharge value and thus water level can be effectively estimated for each crest gauge at 5 minute intervals providing a high-resolution record of floodplain inundation onset, frequency and duration. This would help assess the performance of the restoration and improve the understanding of the role of large wood accumulations in influencing the floodplain hydrology within the monitored reaches. What follows is the description of the monitoring results from the monitored sites which are then drawn together to produce conclusions regarding the performance of large wood in initiating floodplain inundation.

## Semi-Natural Control Hydrology

The Semi-Natural Control reach was chosen for monitoring as it portrayed characteristics that were desired for the restored reach. The low bank level, sinuous planform, geomorphologically active floodplain and native vegetation are all features of riverine woodland and thus the semi-natural control site fulfilled the requirement for a reference site. The use of a reference site allows any restoration to be judged on how well those processes at the reference site are recreated.

The daily average streamflow for the monitoring period is shown in Figure 6.4.2. The average daily discharge for the pre restoration monitoring period (18/12/2003-30/09/2004) is $0.02 m^3 s^{-1}$ (standard deviation=0.05) compared to a value of $0.04 m^3 s^{-1}$(Sd=0.01) for the post-restoration monitoring period (01/10/2004-01/06/2006).

The significance of the daily average discharge results was determined using a t-test statistical analysis. The t-test is a commonly used statistical test to determine whether two groups of data are statistically different from one another. The t-value is expressed as a ratio of signal to noise and is calculated using the following formula.

$$T - Value = \frac{\overline{x_T} - \overline{x_c}}{SE(\overline{x_T} - \overline{x_c})} \tag{6.1}$$

Where $\overline{x_T}$ and $\overline{x_C}$ are arithmetic means of two different data groups $_T$ and $_c$. The SE is the Standard Error of the Difference calculated using the equation below:-

$$SE = \sqrt{\left(\frac{Var_T}{n_T} + \frac{Var_c}{n_c}\right)} \tag{6.2}$$

Where Var is the variance and n is the number of data values in each data group (T and C).

Although the change in average daily discharge between the pre-restoration and post-restoration period is small ($0.02m^3s^{-1}$), it is significant to the 5% level using a two-sample t-test. This suggests that the semi-natural control site was subject to increased daily average flows. This is despite the drier conditions experienced in the post-restoration monitoring period.

Table 6.6.1 shows the hydrological statistics for the reference reach for the pre-restoration and post-restoration monitoring period.

| Metric | Pre-Restoration value | Post-Restoration Value |
|---|---|---|
| Average Discharge ($m^3s^{-1}$) | 0.02 | 0.04 |
| Standard Deviation | 0.05 | 0.1 |
| $Q_5$ ($m^3s^{-1}$) | 0.04 | 0.12 |
| $Q_{95}$ ($m^3s^{-1}$) | 0.01 | 0.01 |

**Table 6.6.1: Hydrological Flow Statistics for the Semi-Natural Control Reach**

The $Q_5$ and $Q_{95}$ represent the 5$^{th}$ and 95$^{th}$ percentile of the data respectively and are an indication of the discharge exceeded 5% and 95% of the time thus representing extreme high flows and low flows respectively. What is interesting about the values for the $Q_5$ and $Q_{95}$ is that they are the same at the $Q_{95}$ value but significantly different for the $Q_5$ metric. This suggests that there are an increased number of higher flows in the post-restoration case. Prior to restoration, a discharge of 0.04 $m^3s^{-1}$ is recorded 5% of the time whereas a discharge of $0.12m^3s^{-1}$ is exceeded 5% of the time after restoration.

Using the individual stage-discharge relationships from the crest gauge data it was possible to find the discharge required to reach average bankfull level (ie, the average of all the crest gauge cross-sections) as shown in table 6.6.2.

It is shown that there is almost no difference between the inundation discharge pre- and post-restoration ($1.4m^3s^{-1}$ and $1.41m^3s^{-1}$ respectively) and therefore the reach acts successfully as a control site. There is a decrease in the inundation discharge required at crest gauge 5 (from $1.01m^3s^{-1}$ to $0.8m^3s^{-1}$) which was located immediately upstream of a small overflow large wood accumulation and this can be attributed to the build up of large and fine wood upstream of the accumulation. At this particular section it was noticeable that leaf litter and silt was being stored upstream of the large wood accumulation and this led to a reduction in channel cross-sectional area. This meant that the development of a large wood accumulation was responsible for a 20.6% reduction in inundation discharge.

| | CG | Area ($m^2$) | Wp (m) | R | Average Bank Height (m) | Inundation Discharge ($m^3s^{-1}$) | |
|---|---|---|---|---|---|---|---|
| **Pre-Restoration** | 1 | 2.96 | 7.71 | 0.38 | 0.72 | 2.43(+/- 0.37) | |
| | 2 | 5.14 | 10.19 | 0.50 | 0.729 | 0.92(+/- 0.19) | |
| | 3 | 3.67 | 9.24 | 0.40 | 0.695 | 1.31(+/- 0.24) | |
| | 4 | 1.40 | 5.96 | 0.23 | 0.68 | 1.57(+/- 0.29) | |
| | 5 | 3.20 | 7.53 | 0.42 | 0.588 | 1.01(+/- 0.24) | |
| | 6 | 2.22 | 6.94 | 0.32 | 0.578 | 0.92(+/- 0.29) | |
| | 7 | 2.74 | 6.73 | 0.41 | 0.799 | 1.71(+/- 0.30) | |
| | 8 | 3.60 | 9.71 | 0.37 | 0.472 | 1.50(+/- 0.33) | |
| | 9 | 11.32 | 16.04 | 0.71 | 0.575 | 1.45(+/- 0.30) | |
| | **Average** | **4.03** | **8.89** | **0.42** | **0.65** | **1.42** (+/- 0.28) | **Percentage Difference (%)** |
| **Post-Restoration** | 1 | 2.96 | 7.71 | 0.38 | 0.70 | 2.34(+/- 0.45) | 3.8% |
| | 2 | 5.23 | 10.18 | 0.51 | 0.74 | 1.02(+/- 0.22) | 11.0% |
| | 3 | 3.67 | 9.24 | 0.40 | 0.67 | 1.45(+/- 0.31) | 10.7% |
| | 4 | 1.65 | 5.98 | 0.28 | 0.65 | 1.44(+/- 0.26) | 8.5% |
| | 5 | 2.98 | 7.53 | 0.40 | 0.53 | 0.80(+/- 0.29) | 20.6% |
| | 6 | 2.32 | 7.40 | 0.31 | 0.62 | 0.86(+/- 0.37) | 6.3% |
| | 7 | 2.95 | 8.07 | 0.37 | 0.79 | 1.78(+/- 0.37) | 3.8% |
| | 8 | 4.19 | 9.71 | 0.43 | 0.41 | 1.62(+/- 0.43) | 8.3% |
| | 9 | 12.67 | 16.06 | 0.79 | 0.63 | 1.41(+/- 0.38) | 2.9% |
| | **Average** | **4.29** | **9.10** | **0.43** | **0.64** | **1.41** (+/- 0.34) | 8.4% |

**Table 6.6.2: Summary Statistics from the Crest Gauges for the Semi-Natural Control Reach.**

## Restored-Planform Site Hydrology

The Restored-Planform reach had undergone restoration that restored planform to its original course. The site was gauged 200m upstream by the Highland Water 1 gauging station with no significant inputs in between. Figure 6.4.2 shows the streamflow for the monitoring period at Highland Water 1. Table 6.6.3 shows a number of hydrological statistics for the reach. The average daily discharge prior to restoration was $0.09m^3s^{-1}$. Since restoration, this has been marginally increased to $0.10m^3s^{-1}$.

The $Q_{95}$ value does not change significantly suggesting that there is little impact upon low flows as a result of the restoration. It is likely that the increase in $Q_5$ from $0.16m^3s^{-1}$ to $0.22m^3s^{-1}$ is a function of the longer post-restoration monitoring period and a higher number of flood events and therefore on its own few conclusions can be taken from it.

| Metric | Pre-Restoration value | Post-Restoration Value |
|---|---|---|
| Average Discharge ($m^3s^{-1}$) | 0.09 | 0.10 |
| Standard Deviation | 0.12 | 0.09 |
| $Q_5$ ($m^3s^{-1}$) | 0.16 | 0.22 |
| $Q_{95}$ ($m^3s^{-1}$) | 0.02 | 0.01 |

**Table 6.6.3: Hydrological Metrics for the Restored-Planform Reach**

A key aim of the restoration was to improve the functioning of the floodplain and increase inundation frequency and duration as without inundation there is little chance of the floodplain functioning in a way that it would under natural conditions (Hughes *et al.*, 2003). This in turn would lead to the development of floodplain geomorphology. As has previously been mentioned this was done using two techniques: restoration of planform and addition of large wood to the system. Restoring the channel to its original course with its meandering path increases the planform resistance, which slows the flow of water through a reach. The restoration of the original planform led to a 57% increase in channel sinuosity where the sinuosity is the ratio of channel length to floodplain length (Schumm, 1985). The channel sinuosity changed from 1.08 to 1.7 which is commensurate with a change from a straight channel to a highly sinuous channel (or A to C in Rosgen's (1994) classification of natural rivers). The reoccupation of the abandoned channel led to a reduction in the channel capacity such that floodplain inundation frequency increased markedly (0 events in the winter of 2003/2004 compared with 1 in the winter of 2004/2005 and 7 in 2005/2006). Given that the winter of 2003/2004 was wetter than the other monitored years of 2004/2005 and 2005/2006, and the average mean daily discharge was higher prior to restoration, this clearly shows that the restoration had been successful in promoting an increase in the inundation frequency albeit at lower discharges. This provides clear evidence of the effect of the planform restoration upon the floodplain inundation.

Using the individual stage-discharge relationships from the crest gauge data it was found that the discharge required to reach average bankfull level in the pre-restoration channel was $1.7m^3s^{-1}$ compared with $0.68m^3s^{-1}$ post-restoration. This decrease of 60% gives an indication of how floodplain inundation frequency would be increased. This compares with no observed change in inundation discharge for the upstream semi-natural control site. Table 6.6.4 shows the discharge required for a bankfull stage at all the crest gauges at the restored site before and after restoration. Prior to restoration, there were no inundation events whereas after restoration there were eight inundation events. This clearly shows that there is a reduction in the discharge required to initiate inundation. This is a function of the reduction in channel capacity represented by the cross-sectional area in table 6.6.4.

| | | **CG** | **Area ($m^2$)** | **Wp (m)** | **R** | **Average Bank Height (m)** | **Bankfull Discharge ($m^3s^{-1}$)** | |
|---|---|---|---|---|---|---|---|---|
| **Pre-Restoration** | | 1 | 5.58 | 20.98 | 0.27 | 1.75 | 1.26 (+/- 0.07) | |
| | | 2 | 8.85 | 22.94 | 0.39 | 2.46 | 2.13 (+/- 0.10) | |
| | | 3 | 11.71 | 22.98 | 0.51 | 2.72 | 1.73 (+/- 0.06) | |
| | | 4 | 8.84 | 19.93 | 0.44 | 3.43 | 2.63 (+/- 0.08) | |
| | | 5 | 8.85 | 18.27 | 0.48 | 2.39 | 1.58 (+/- 0.07) | |
| | | 6 | 6.63 | 13.49 | 0.49 | 2.59 | 2.01 (+/- 0.08) | |
| | | 7 | 8.04 | 12.78 | 0.63 | 2.19 | 1.75 (+/- 0.08) | |
| | | 8 | 7.83 | 13.25 | 0.59 | 2.19 | 1.63 (+/- 0.07) | |
| | | 9 | 7.43 | 13.55 | 0.55 | 1.74 | 1.01 (+/- 0.06) | |
| | | 10 | 5.67 | 10.89 | 0.52 | 2.03 | 1.28 (+/- 0.07) | |
| | | **Average** | **7.94** | **16.91** | **0.49** | **2.35** | **1.70 (+/- 0.074)** | **Percentage Difference (%)** |
| **Post-Restoration** | | 1 | 1.46 | 11.64 | 0.13 | 0.52 | 0.34 (+/- 0.22) | 73 |
| | | 2 | 1.30 | 8.91 | 0.15 | 0.51 | 0.57 (+/- 0.62) | 73 |
| | | 3 | 2.30 | 6.97 | 0.33 | 1.04 | 0.58 (+/- 0.34) | 67 |
| | | 4 | 2.42 | 8.96 | 0.27 | 1.05 | 0.52 (+/- 0.38) | 80 |
| | | 5 | 2.22 | 8.77 | 0.25 | 0.74 | 0.94 (+/- 0.22) | 41 |
| | | 6 | 2.20 | 8.97 | 0.25 | 0.80 | 0.56 (+/- 0.15) | 72 |
| | | 7 | 1.98 | 7.45 | 0.27 | 0.78 | 1.38 (+/- 0.22) | 21 |
| | | 8 | 2.08 | 7.50 | 0.28 | 0.74 | 0.43 (+/- 0.16) | 74 |
| | | 10 | 2.27 | 9.41 | 0.24 | 0.63 | 0.82 (+/- 0.15) | 19 |
| | | **Average** | **2.03** | **8.73** | **0.24** | **0.76** | **0.68** (+/- 0.27) | **60** |

**Table 6.6.4: Summary Statistics from the Restored Planform Crest Gauges (sections upstream of large wood accumulations are highlighted).**

There was a suggestion that the channel capacity was under designed and was initially smaller than that which would be expected for a channel carrying a similar range of flows, for example the upstream semi-natural control reach. Observations suggest that the channel is still adapting to the flows that pass through it and that the channel is yet to reach equilibrium conditions as the reach has only experienced a limited number of high channel-forming flow events. By the time of a topographic survey carried out in January 2005 the average cross-sectional area was $4.3m^2$, larger than that of the upstream semi-natural control site ($3.6m^2$).

A number of large wood accumulations were present throughout the reach both before and after restoration and the location of crest gauges immediately upstream of these are highlighted in table 6.6.4. Crest Gauge 9 in the pre-restoration scenario was located upstream of an overflow accumulation in which the key large wood piece was located 0.7m from the channel bed. The key piece was 30cm in diameter and had a significant underflow effect at high flows. The average bank height was relatively low in this area compared with the rest of the reach. Observed bank vegetation and roots were consolidating the banks although bank erosion was evident resulting in an overhang on the right bank. The discharge required for inundation of the average bank height at crest gauge 9 was $1.01m^3s^{-1}$ compared to an average of $1.78m^3s^{-1}$ for the reach. This suggests that the presence of this piece of large wood can reduce the inundation discharge by 43%.

After restoration, there were two large wood accumulations, one upstream of crest gauge 5 and one upstream of crest gauge 10. Both large wood accumulations were overflow accumulations that were relics from the previous channel occupation. The large wood accumulations occurred on tight bends that were just short of 70° and were anchored against riparian Poplar trees located on the banks. The upstream accumulation had a high blockage ratio and caused a large (up to 0.5m) step in the water surface profile acting like a weir type structure in raising upstream water levels. This led to a backwater effect upstream which resulted in inundation at discharges as low as $0.2m^3s^{-1}$. During low flows, the water depth was still high with flow depth reaching 0.6m deep highlighting the ponded nature of this part of the reach. The large wood accumulation had an effect for up to 25m upstream, which affected a number of crest gauges. Immediately upstream of the large wood accumulation a discharge of $0.52m^3s^{-1}$ was required to inundate the floodplain. Only 10m downstream of the large wood accumulation, a discharge of $0.94m^3s^{-1}$ was required for inundation.

Further downstream there was another overflow large wood accumulation that created a smaller 0.2m step in the water surface profile. Again, a backwater step was evident upstream with flow routed onto the right floodplain creating a recirculation zone on the channel-floodplain margin. The inundation discharge required upstream of this large wood accumulation was $0.43m^3s^{-1}$ compared to $0.82m^3s^{-1}$ downstream and $1.38m^3s^{-1}$ further upstream. This large wood accumulation was only present for a short period before being blown out by a large flow event indicating the dynamic nature of large wood and their accumulations (Braudrick *et al.*, 1997).

The results of the t-test analysis show that there is a significant difference in inundation discharge between the pre-restoration and post-restoration scenarios at a 0.1% level. Those sections, which were immediately upstream of large wood accumulations, had significantly different inundation discharges (at the 1% level) to the reach average. Therefore, it can be concluded that there is a more significant relationship between planform restoration and floodplain inundation than the use of large wood restoration. This is due to the significant reduction in cross-sectional area from an average of $7.94m^2$ to $2.03m^2$. However the significance of large wood in reducing inundation discharge is encouraging as in cases where full planform restoration is not feasible, large wood can be suitable as a tool for increasing localised inundation and allow natural recovery of the river system.

## Restored-Large Wood Hydrology

At a site downstream of the main reach of planform restoration, channel recovery had begun to occur naturally and large wood was added as a restoration measure to increase connectivity with the floodplain and speed up the existing recovery. Within this restored reach was the restored-large wood reach, which was monitored to assess the impact of large wood as a restoration measure. A hydrological gauge within the reach measured stage throughout the monitoring period. The daily average discharge from this gauge is shown in Figure 6.4.2 as well as some summary statistics in table 6.6.5.

| Metric | Pre-Restoration | Post-Restoration |
|---|---|---|
| Average ($m^3s^{-1}$) | 0.16 | 0.11 |
| Standard Deviation | 0.22 | 0.13 |
| $Q_5$ ($m^3s^{-1}$) | 0.5 | 0.3 |
| $Q_{95}$ ($m^3s^{-1}$) | 0.04 | 0.03 |

**Table 6.6.5: Hydrological Statistics for the Restored-Large Wood Reach.**

With an increase in flow resistance and flow residence at the upstream restored sites from pre- to post-restoration, the downstream hydrology has been affected with the average daily flow reducing by 31%. The reduction in $Q_5$, which indicates the effect on high flows, is reduced by 40% from $0.5m^3s^{-1}$ to $0.3m^3s^{-1}$, which suggests restoration measures have had some impact upon downstream flood risk. This is in direct contrast to the $Q_5$ metric at the Semi-Natural Control site, which was observed to increase between the pre- and post restoration monitoring periods. This suggests that the restoration has been successful in attenuating the flood peak. As the flow is retarded upstream, it would be expected that downstream flood magnitude would decrease. However, it is difficult to fully apportion this to restoration as it was shown earlier that the post-restoration period was drier than the pre-restoration period.

Two large wood accumulations were located within the Restored-Large Wood reach. The first accumulation was located at the beginning of the study reach and was made up of two key log pieces that were shorn of any canopy (see Figure 6.6.2). Although initially designed to act as an overflow large wood accumulation, early high flows led to local bed scour, which resulted in a reduced blockage area and the accumulation began to act as a deflector accumulation.

The second large wood accumulation was located 75m downstream and consisted of three key pieces of which branches and canopy were left in place to encourage trapping of fine wood.

**Figure 6.6.2: Large Wood Accumulation at the upstream end of the Restored-Large Wood Reach.**

Initial high flows led to local bed scour but, over time, large wood was trapped by the accumulation leading to an increased blockage area (Millington and Sear, 2007) resulting in the formation of an overflow accumulation. Monitoring at the site showed that this large wood accumulation led to a significant reduction in the travel distances of large wood tracers from 370m prior to restoration to 208m post-restoration (Millington and Sear, 2007). Stage-Discharge relationships were developed for all crest gauge sections before and after restoration. The subsequent relationships were used to calculate the discharge required to inundate the adjacent floodplain as shown in table 6.6.6.

| | CG | Area ($m^2$) | Wp (m) | R | Average Bank Height (m) | Inundation Discharge ($m^3s^{-1}$) | |
|---|---|---|---|---|---|---|---|
| **Pre-Restoration** | 1 | 2.93 | 7.14 | 0.41 | 1.06 | 2.7 (+/- 0.31) | |
| | 2 | 5.09 | 7.84 | 0.65 | 1.23 | 2.91 (+/- 0.22) | |
| | 3 | 3.51 | 8.63 | 0.41 | 1.33 | 2.88 (+/- 0.27) | |
| | 4 | 5.56 | 8.49 | 0.65 | 1.36 | 2.38 (+/- 0.22) | |
| | 5 | 4.59 | 8.3 | 0.55 | 1.64 | 2.47 (+/- 0.22) | |
| | 6 | 4.67 | 8.66 | 0.54 | 1.34 | 2.49 (+/- 0.27) | |
| | 7 | 4.87 | 8.58 | 0.57 | 0.85 | 2.88 (+/- 0.28) | |
| | 8 | 3.83 | 7.59 | 0.51 | 1.01 | 2.50 (+/- 0.29) | |
| | 9 | 4.33 | 6.83 | 0.63 | 1.25 | 2.47 (+/- 0.25) | |
| | 10 | 3.1 | 6.27 | 0.5 | 0.85 | 2.03 (+/- 0.25) | |
| | **Average** | **4.25** | **7.83** | **0.542** | | **2.57** (+/- 0.26) | **% Difference** |
| **Post-Restoration** | 1 | 2.98 | 7.11 | 0.42 | 1.06 | 2.01 (+/- 0.24) | 25.6 |
| | 2 | 4.97 | 7.83 | 0.63 | 1.23 | 2.54 (+/- 0.21) | 12.7 |
| | 3 | 3.6 | 8.61 | 0.42 | 1.33 | 2.04 (+/- 0.17) | 29.2 |
| | 4 | 5.7 | 8.58 | 0.66 | 1.36 | 1.67 (+/- 0.12) | 29.8 |
| | 5 | 4.6 | 8.37 | 0.55 | 1.64 | 1.94 (+/- 0.16) | 21.5 |
| | 6 | 4.68 | 8.84 | 0.53 | 1.34 | 1.67 (+/- 0.22) | 32.9 |
| | 7 | 4.93 | 8.6 | 0.57 | 0.85 | 1.78 (+/- 0.17) | 38.2 |
| | 8 | 3.91 | 7.78 | 0.50 | 1.01 | 1.65 (+/- 0.19) | 34 |
| | 9 | 4.37 | 6.51 | 0.67 | 1.25 | 1.8 (+/- 0.20) | 27 |
| | 10 | 3.12 | 5.97 | 0.52 | 0.85 | 1.65 (+/- 0.29) | 24 |
| | **Average** | **4.29** | **7.82** | **0.55** | | **1.84** (+/- 0.20) | **27.5** |

**Table 6.6.6: Summary Statistics from the Crest Gauges for the Restored-Large Wood Reach.**

Prior to the installation of large wood accumulations within the Restored-Large Wood reach, the average discharge required for inundation is 2.57$m^3s^{-1}$ and this is reduced by 27.5% through the introduction of large wood to 1.84$m^3s^{-1}$ (+/- 0.2$m^3s^{-1}$) As there was no planform restoration within this reach this can be solely attributed to the effect of large wood restoration. Immediately upstream of the two installed large wood accumulations, crest gauge data (gauges 1 and 8) showed the inundation discharge fell by 25.6% and 34% respectively. A t-test analysis shows that the difference between the pre- and post- restoration inundation discharge is significant at the 1% level, which is solely attributable to the presence of large wood. This shows large wood is successful in lowering the discharge required for inundation and can be used as a restoration tool for this purpose.

The difference in the effect of the two large wood accumulations give an indication into the different hydraulic impacts provided by different types of large wood accumulations as the 25.6% reduction is associated with a deflector accumulation whereas the 34% reduction is provided by the larger, overflow accumulation. This is despite the overflow accumulation having a larger cross-sectional area and thus a greater flow capacity.

The data from the three monitoring sites show some evidence of the role of large wood in influencing the floodplain hydrology and the findings from the three sites can be bought together to draw further conclusions.

## *6.7. Inundation Flood Frequency*

The crest gauge data provides an average discharge required for inundation at the three sites and it is possible to analyse this with respect to the hydrological data from the three sites. The inundation discharge was defined as the average discharge required to initiate floodplain inundation at the cross sections associated with the crest gauges. This does not mean that no inundation occurs prior to this discharge as there may be low points within the bank line over which the channel can spill and initiate floodplain inundation. By evaluating the monitored flow data, it is possible to identify those events that overtopped the bank top and thus it is possible to estimate the inundation frequency and duration of these events. The monitoring interval of 5 minutes provides a high-resolution hydrological data set, which provides duration measures accurate to 9 minutes for a single event. Table 6.7.1 shows the results of this analysis.

| | Pre-Restoration | | | | Post-Restoration | | | |
|---|---|---|---|---|---|---|---|---|
| **Site** | **Events** | **Total Duration of Events** | **Average Duration of Event** | **Longest Event** | **Events** | **Total Duration of Events** | **Average Duration of Event** | **Longest Event** |
| Semi-Natural Control | 3 | 7 hours 25 mins | 3 hours 28 mins | 3 hours 5 mins | 8 | 31 hours 40 mins | 3 hours 57 mins | 10 hours 10 mins |
| Restored - Planform | 0 | N/A | N/A | N/A | 8 | 54 hours 55 mins | 6 hours 51 mins | 14 hours 35 mins |
| | 9 | 144 hours 20 mins | 12hours 20mins | 23 hours 40mins | | | | |
| Restored - Large Wood | 3 | 20 hours 50 mins | 6 hours 56 mins | 8 hours 55 mins | 4 | 8 hours 40 mins | 2 hours 10 mins | 4 hours 35 mins |
| | 8 | 30 hours 15 mins | 3 hours 46 mins | 9 hours | | | | |

**Table 6.7.1: Inundation Frequency and Duration at the three monitoring sites. The highlighted data applies the post-restoration inundation threshold to the pre-restoration monitoring period for direct comparison of the influence of the restoration.**

The Restored-Planform site shows the starkest difference with an increase in inundation frequency from none to nine. As described before in the preceding sections, the change in inundation frequency at the Restored-Planform site is primarily a function of the restoration to the previous planform and cross-section, which has seen channel capacity reduced by almost 75%. This fulfils the requirements and objectives of the restoration by improving the connectivity between the channel and its floodplain but provides no evidence of the success of large wood in increasing the channel-floodplain connectivity. If the post-restoration site was subject to the range of flows that were monitored pre-restoration (ie, between 01/01/03 and 26/08/04) then, using the post-restoration inundation value of $0.76m^3s^{-1}$, the Restored-Planform site would have been subject to nine inundation events. These events would have a total inundation duration of 114 hours and 20 minutes, which gives an average inundation event duration of 12 hour and 42 minutes (longest duration is 23 hours and 30 minutes).

This approach eliminates any bias that may be introduced by the difference in record lengths and different preceding climate conditions, and provides clear evidence of the success of the restoration in increasing the connectivity between the channel and its floodplain.

The Restored-Large Wood site showed a slight increase in observed inundation events, which can be attributed to the presence of large wood. When the inundation frequency is averaged over the monitored flood seasons (pre-restoration, 2 events per flood season, post restoration, average of 2 events per flood season) it shows no change. Again, when the pre-restoration observed data was assessed for floods that were above the post-restoration inundation threshold ($1.84 m^3 s^{-1}$) there were eight inundation events with a total inundation duration of 30 hours 15 minutes and an average inundation duration of 3 hours 46 minutes. This is an increase in inundation frequency of 166% and an increase of 45% in total inundation duration. However, there is a decrease of 46% in the average inundation duration. This is a function of the shorter, low magnitude events that overcome the post-restoration inundation discharge but not the pre-restoration threshold value. Nonetheless, this is clear evidence of the impact that the presence of large wood can have upon inundation and frequency.

Table 6.8.1 shows a summary of the effect of restoration upon several hydrological metrics at the three monitored sites. This shows that the inundation frequency has increased at all sites including those where the frequency of large wood has increased suggesting that large wood can be used to improve the channel-floodplain connectivity.

## 6.8. Reach Scale: Planform vs Large Wood

Planform and morphological restoration is well known to impact upon floodplain inundation (Brookes *et al.*, 1996; Simons *et al.*, 2001) through the increase in both sinuosity and channel cross-sectional area and in this case is partially responsible for a 60% reduction in inundation discharge at the Restored-Planform site.

When compared to a reduction in inundation discharge of 28% at the Restored-Large Wood site it is clear that large wood restoration does not have as much of an effect upon floodplain hydrology as planform and morphological restoration. The morphological restoration which bought the bed levels to a level much closer to floodplain elevations which together with a reduction in cross-sectional area led to an improved channel-floodplain connectivity. However, within the sites, the influence of the large wood is more apparent. At the Restored-Planform site, the restoration led to a reduction in inundation discharge of 60% however, at the sections adjacent to large wood accumulations the inundation discharge was 37% lower than other sections within the reach. A similar trend is present within the Restored-Large Wood (large wood sections have a 45% lower inundation discharge) and Semi-Natural Control reach (large wood sections have a 73% lower inundation discharge) which suggests that the Semi Natural Control site was a reference site for which the restoration could be judged against. The input of large wood accumulations increases the frequency of inundation and the data described above shows that the addition of large wood to the Restored-Planform and Restored-Large Wood sites moves the frequency of floodplain inundation to that of the reference conditions portrayed at the Semi-natural Control reach. Table 6.8.1 provides the accumulated data for the three sites for before and after restoration.

| **Monitoring Site** | **Sinuosity** | **Large Wood Frequency** | **Mean Daily Discharge** | **Inundation Discharge** | **Inundation Frequency** | **Average Inundation Duration** |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Restored-Planform** | ↑ | ↑ | ↑ | ↓ | ↑ | ↑ |
| **Restored-Large Wood** | → | ↑ | ↓ | ↓ | ↑ | ↓ |
| **Semi-Natural Control** | → | → | ↑ | → | ↑ | ↑ |

**Table 6.8.1: Summary table of the direction of change for key monitoring metrics.**

The reduction in inundation discharge has related increases in inundation frequency and duration. Table 6.8.2 shows the inundation discharge for all the river sections immediately upstream of large wood accumulations together with the inundation frequency and duration assessed from hydrological flow records during the post-restoration monitoring period.

| Site | | Reach Average Inundation Discharge ($m^3s^{-1}$) with Large Wood | Reach Average Inundation Discharge ($m^3s^{-1}$) Without Large Wood | Reach Average Inundation Discharge ($m^3s^{-1}$) Large Wood Only | Difference |
|---|---|---|---|---|---|
| Restored-Planform | Pre | 1.7 | 1.778 | 1.01 | 43.2% |
| | Post | 0.68 | 0.74 | 0.47 | 36.5% |
| | | -60.0% | -58.4% | -53.5% | |
| Restored-Large Wood | Pre | 2.57 | 2.57 | 0 | |
| | Post | 1.84 | 1.89 | 1.04 | 45.0% |
| | | -28.4% | -26.5% | N/A | |
| Semi-Natural Control | Pre | 1.45 | 1.48 | 0.42 | 71.6% |
| | Post | 1.41 | 1.49 | 0.4 | 73.2% |
| | | -2.8% | 0.7% | -4.8% | |

**Table 6.8.2: Inundation Discharge for the three monitoring sites with the influence of large wood. The data is presented into columns representing all the monitored sections (those influenced by large wood and those not), those sections without large wood influence and those sections with a large wood influence.**

| Site | Crest Gauge Section No. | Inundation Discharge ($m^3s^{-1}$) | No. of Events | Total Duration of Events | % Increase in Inundation Frequency | Percentage Increase in total duration |
|---|---|---|---|---|---|---|
| Semi-Natural Control | 4 | 0.8 | 18 | 80 hrs 55 mins | 157.1 | 318.5 |
| | Reach Average | 1.5 | 5.0 | 19 hrs 20 mins | | |
| Restored-Planform | 5 | 0.52 | 15 | 73 hrs 25 mins | 36.4 | 144.7 |
| | 8 | 0.43 | 21 | 118 hrs 10 mins | 90.9 | 293.9 |
| | Reach Average | 0.74 | 8 | 30 hrs | | |
| Restored-Large Wood | 1 | 2.01 | 2 | 5 hrs 45 mins | -50.0 | -25.8 |
| | 8 | 1.65 | 11 | 22 hrs 10 mins | 175.0 | 186.0 |
| | Reach Average | 1.92 | 4 | 7 hrs 45 mins | | |
| | | | | **Average** | 81.9 | 183.5 |

**Table 6.8.3: The Inundation Discharge for the sections immediately upstream of large wood accumulations and the percentage difference between the large wood sections and the non-large wood reach average metrics.**

This table shows that although planform restoration has a significant impact upon the reach scale hydrology, large wood can also have an impact at a sub-reach scale in reducing the discharge required to initiate inundation. The local reduction in inundation discharge at those sections upstream of large wood accumulation increases the frequency of floodplain inundation (on average by 82%) and an increase in the duration of flooding (on average by 184%). The data shows some variability with the Restored-Large Wood reach showing one large wood accumulation (CG1) which appears to reduce the frequency of inundation. However, this is a function of the other large wood accumulation (CG8) within the reach, which appears to reduce the discharge required for inundation at a number of cross-sections upstream of it. This has an impact by reducing the reach-averaged inundation discharge, which in turn suggests that the large wood accumulation (CG1) at the upstream extent of the monitored reach reduces the amount of inundation. This is one limitation of the approach as it is difficult to identify those cross-sections that are influenced by downstream large wood accumulations.

However, it can be concluded that large wood does have a significant effect upon the reach-scale floodplain hydrology, which ties in with what is observed in other large wood studies. The presence of large wood is known to locally raise water level as observed by Young (1991) in the flume and in the field by Jefferies *et al.* (2003). Young (1991) found that for a 10% increase in stage it is necessary to have a large wood piece with a relative frontal area (similar to blockage area) of 0.8 (that is 80% of the channel is blocked by large wood). It has been mooted that theoretically, large wood can have a much more widespread impact for example the Murray-Darling Basin Commission calculated theoretically that the removal of 200 large wood accumulations per kilometre would lead to a theoretical reduction in water level of 0.3-0.4m, although flow records showed a reduction of only 0.2m (Gippel *et al.*, 1992). Increased stage at individual large wood accumulations in another reach was found to be as high as 0.23m by Gippel *et al.* (1992). Further data from the Lower Thomson River, in Victoria, Australia predicted affluxes of up to 1.3mm in a much larger river (Bankfull Q estimated to be 109$m^3s^{-1}$), (Gippel *et al.*, 1996). The sum of the affluxes from 95 large wood pieces throughout the 775m reach was 8.6mm, which was equivalent to 0.2% of the flow depth. This occurs in rivers where the wood size to channel ratio is low with blockage ratios less than 0.1 (a median value of 0.004).

In other systems such as the Pacific North-West in the USA, where blockage ratios are higher large wood is known to create ‘forced steps’ in the long section profile (Buffington and Montgomery, 1997). Curran and Wohl (2003) found that large wood accounted for the larger of these steps and 79% of the total water drop was accounted for by steps. Up to 14% of this total water drop was accounted for by the largest step in a particular reach. These were in step-pool river systems where the blockage was visually estimated to be 60% of the channel cross-section. Wilcox and Wohl (2006) suggested that large wood could be used in mountain streams to increase flow depth and promote step formation. Data from this study shows a similar conclusion with an increase in flow depth due to the use of large wood. This increase in flow depth and subsequently stage increases the frequency and duration of inundation can have important implications for riverine woodland development (Gurnell, 1997) and can lead to the formation of anastomosed channel patterns. The blockage of river channels inundates the floodplain during high flows, inundating multiple, smaller floodplain channels which create an anastomosed form with multi-directional flows (Brown *et al.*, 1995; Sear *et al.*, 2010).

Moulin and Piégay (2004) suggests that in regulated rivers, the volumes of large wood are much lower and therefore the increase of water levels caused by large wood accumulations is quite rare. They suggest that, due to the small large wood volumes in these regulated rivers, that the risk of flooding does not arise at the production site but rather the risk is transferred downstream particularly to structures, such as bridges and weirs, which are often associated with vulnerable land use areas such as urban developments. They claim that it is at structures where the accumulation of large wood leads to an increase in the elevation of the water surface upstream thus causing a flood risk and putting the structure under stress. This is contrary to the data in this chapter, which, for a semi-natural stream, suggests that the risk of flooding can occur at the production site where large wood is accumulated at natural jam points such as meander bends and next to overhanging riparian vegetation. Furthermore, the presence of large wood accumulations in semi-natural reaches is known to control the rate of large wood transport to downstream reaches (Piégay and Gurnell, 1997; Gurnell and Sweet, 1998; Millington and Sear, 2007) which can reduce the risk of it accumulating near bridges and weirs. The change in flow regime and in particular inundation of the floodplain can lead to the increase in large wood retention within the system (Gurnell, 2003). In a semi-natural river system such as the Highland Water, large wood can locally reduce the local inundation discharge and increase inundation frequency (by 166%) and inundation duration (45%) through the monitoring period.

The increase in inundation frequency due to the presence of large wood may seem to provide an unnatural flow regime to the reach however it is known that riverine woodland reaches are characterised by frequent flood pulse onto the floodplain, which cause sediment deposition and seed dispersion (Hughes and Muller, 2003). Vegetation patterns suggest that species distribution are largely controlled by the frequency, duration and intensity of flows (Hupp and Osterkamp, 1996) and the hydrological regime plays a key role in determining the level of diversity upon the floodplain (Petts, 1998). Inundation patterns have even been used to define limits of flood of different frequency (Hupp, 1987). Fetherston *et al.* (1995) highlighted the effect of disturbance flood events leading to conditions favourable for the development of riverine woodlands. Gurnell (1997) observes that the disconnection of the channel from its floodplain lead to channel entrenchment, reduces flood disturbance and lowers the floodplain water levels. This subsequently has a detrimental effect upon disturbance dependent landscapes which results in a homogenous alluvial forest. Similar observations were found in areas that were subject to clearance of large wood (Sedell and Frogatt, 1984) which led to disconnection of the channel from the floodplain. By improving the channel-floodplain connectivity using large wood, it is possible to restore these heterogeneous landscapes by re-creating the hydrological conditions favourable for the development of riverine woodland (Fetherston *et al.*, 1995; Tockner *et al.*, 1998; Tockner *et al.*, 2000; Tockner and Stanford, 2002; Hughes *et al.*, 2003). Walter and Merritts (2008) suggest that it is large wood accumulations which back up water and route flow into small floodplain channels and sloughs. Upstream of large wood accumulations, channels tend to widen, bank height reduce and depth reduce due to water being diverted around the obstruction (Keller and Swanson, 1979), This increases the frequency of floodplain inundation and through time, the occurrence of floodplain flow, will lead to the development of a multiple anabranching channels and riverine wetlands (Walter and Merritts, 2008). Streams with small anabranching channel within vegetated wetlands are suggested to be the pre-settlement condition of many rivers rather than the single meandering channel form (Sedell and Frogatt, 1984; Brown, 2002; Walter and Merritts, 2008; Francis *et al.*, 2008) which is often the target state selected when undertaking river restoration (Kondolf, 2006). Although the classic sinuous channel form has come to represent a natural ideal within river restoration this may not be entirely accurate (Montgomery, 2008). Many European systems prior to widespread settlement and woodland clearance were subject to blockages by large wood and their accumulations splitting flow into multichannel networks of anabranching streams (Harwood and Brown, 1993). Inter-channel flows were caused by variations in the water surface elevation due to the backwater effect at large wood accumulations and this is likely to be the origin of flow partitioning and the creation of shallow anabranching streams (Harwood and Brown, 1993). There were a number of reaches within the New Forest (such as that shown in Figure 8.7.2) in which the presence of large wood was found to correspond with anastomosed river reaches. Results presented later in this thesis (see Figures 8.11.2 and 8.11.4), suggests that large wood, through the initiation of out-of-bank flow can reactivate old side channels on the floodplain. This suggests that although the original goal of the EU LIFE 3 restoration project was to restore a sinuous channel and reconnect it to its floodplain to allow development of riverine woodland, the effect has actually been to allow blockages of the river channels through the use of large wood accumulations allowing flow to be distributed to multiple, smaller channels on the floodplain to restore and maintain an anastomosed river pattern (Sear *et al.*, 2010). This adds to those voices (Brown, 2002; Walter and Merritts, 2008, Montgomery, 2008; Sear *et al.*, 2010) who call for the reconsiderations of the assumptions underpinning river restoration and provides evidence for the role that large wood may play in allowing the evolution of multi-channel river systems (Walter and Merritts, 2008).

The use of large wood and its accumulations for restoration purposes requires management to ensure there are no adverse impacts upon people, fish, wildlife, flood control and bank erosion. The use of large wood to increase the frequency of out-of-bank flows can, in some cases, be detrimental and pose a risk to the river system stakeholders with potential impacts upon human populations, property, grazing animals and wildlife. Table 6.8.4 summarises potential impacts of the use of large wood as a restoration tool together with the potential risk of each impact.

The dynamic nature of large wood (Braudrick *et al.*, 1997) means that there is a risk of both direct debris strikes to people, property, structures and wildlife, and blow-outs of large wood accumulations which cause water to surge downstream (Gurnell and Gregory, 1981). The presence of large wood accumulations and multi-channel river patterns is known to significantly reduce the travel distance of mobilised large wood and increase retention of large wood in the reach where it was sourced (Millington and Sear, 2007). As a result, the risk of debris strikes and blowouts is rare in small headwater streams and potential impacts can be minimised through management of large wood in reaches adjacent to sensitive urban areas (Thomas and Nisbet, 2007).

| Potential Impact | Impacted | Risk | Note |
|---|---|---|---|
| Water Logging | People | Low | Large wood restoration is likely to occur in areas where increased inundation is beneficial. In some cases, increased inundation and water logging can lead to the leaching of nutrients and heavy metals from floodplain soils (Neumeister *et al.*, 1997) as well as the reduction in agricultural activity. Water-logging is less likely where inundation duration is short. |
| Flooding | People, Property, Grazing Animals | Medium | Floodplain Inundation can lead to stranding and in extreme cases drowning for both people and grazing animals. The storage of flow upon the floodplain could also lead to synchronisation of peak flows from tributaries increases downstream flood risk. |
| Breaching | People, Property | Medium | During extreme flood events, the force of water could lead to the blow out of large wood accumulations creating a surge of water. The stability of large wood accumulations within the New Forest has been shown at the Millyford Bridge accumulation which has been active for at least 25 years and experiencing the floods of the year 2000 which were estimated to be of a 100 year-200 year return period. The presence of a number of large wood accumulations can reduce the risk of blow outs. |
| Debris Strike | People, Property | Low | Large wood is known to create a hazard at bridge structures and culverts (Gippel *et al.*, 1992) and transported wood can be a hazard directly to property through debris strikes. Large wood restoration can be undertaken in areas of the catchment where impact of debris striking is minimal. Large wood management can be undertaken in reaches adjacent to sensitive urban areas to reduce the risk of debris strikes (Thomas and Nisbet, 2007). |
| Bank Erosion | People, Property, Grazing Animals | High | The presence of large wood can locally steer flow and can initiate significant bank erosion (Davis and Gregory, 1994). This can reduce the amenity value of the river channel as well as being a potential hazard to river users. |
| Quality of Pasture | Grazing Animals | Low | Anecdotal observations as part of this study suggested that increased inundation increased the amount and quality of pasture. Within the New Forest this was keenly welcomed by the forest verderers. The presence of deep pools upstream of large wood accumulations can also sustain drinking water for grazing stock during dry summers. |
| Blocked Passage | People, Fish, Grazaing Animals | Medium | The use of large wood results in the limiting of navigational use of river channels. There are also concerns over the impact of large wood accumulations upon migratory fish species. Anecdotal observations as part of this study suggest that fish can bypass blockages particularly in reaches with multiple channels. Furthermore, large wood is known to be of net benefit to many fish species (Dolloff and Warren, 2003). There is also a risk of grazing animals entering the river channel and becoming entangled within large wood accumulations. |
| Stranding of fish | Fish | Low | The presence of large wood has been shown to increase the number and depth of pool areas which can be significant habitats to fish during times of low flow and allow thermal refuge during periods of high temperatures. The Highland Water is reliant on rainfall for flow and often dries out during summer months, however no fish stranding was observed. |

**Table 6.8.4: Potential Impacts of river restoration using large wood.**

Increased overbank flow frequency is likely to impact on fish species that require seasonal access to the floodplain wetlands for spawning and nursery habitats (Gippel, 1995; Beechie *et al.*, 2005). Traditionally, large wood removal has been regarded as an engineering solution and as a result large wood removal was undertaken with little regard for effects upon aquatic fauna. There are often concerns that large wood can have a negative impact upon fish by blocking channels and the risk of stranding during low flow events. Reviews have shown that large wood accumulations can provide physical habitat to aquatic fauna, can retain fine particulate matter for biological processing and provide thermal refuge for fish (Harmon *et al.*, 1986) and as such provide a net benefit to fish. The EU Life 3 monitoring showed no adverse effects of the addition of large wood accumulations to the Highland Water. Other studies have shown that fish habitat is lost through the removal of large wood as pool habitat and flow complexity is lost (Dolloff and Warren, 2003). The life histories of more than 85 species of fish have some association with large wood for either cover spawning and feeding (Dolloff and Warren, 2003). However, Bisson *et al.*, (1987) suggests that although many studies suggest that with respect to fish populations, "*more is better*", there may be an optimum large wood accumulation frequency and loading which is currently unknown.

The role of large wood in bank erosion is currently uncertain with some believing that large wood accumulations are to be the main triggers for channel adjustments (Gurnell and Gregory, 1981; Davis and Gregory, 1994), which can results in significant amounts of bank erosion whilst others argues that the removal of large wood increases the flow velocity next to the bank reduces the resistance of the banks to flow resistance and as a result the introduction of large wood can be used to protect against bank erosion (Shields and Nunnally, 1984; Shields *et al.*, 2004). With the effect of large wood upon bank erosion unclear, the introduction of large wood should be assessed on a case-by-case basis and monitoring undertaken to ensure that adverse erosion is picked up early and remediated as appropriate.

The connection of the channel with its floodplain is beneficial as the floodplain plays several important roles within the catchment hydrological system (Burt, 1997) not least the storage of flow which can lead to a beneficial effect upon flood risk downstream through the attenuation of the flood wave and creating a lag in the timing of a flood hydrograph thus creating a link between the floodplain hydrology and the catchment flood hydrology (Archer, 1989; Bates *et al.*, 1996; Siggers *et al.*, 1999; Burt, 2000). However, storage of water upon the floodplain, during and after a flood event, can be problematic especially when the catchment is subject to further rainfall and subsequent flood discharges before the previous flow stored on the floodplain is able to drain away. The effect of flow storage of on the floodplain could delay the drainage of flood water and could compound the downstream flood risk as there is more water within the catchment. The occurrence of two flood events in quick succession may reduce the effectiveness of reconnecting the channel to its floodplain as a means of attenuating flood control.

The potential impacts of large wood restoration can be monitored and the risks managed to ensure that river restoration using large wood does not pose significant risk to people, property and wildlife.

## *6.9. Effect on Downstream Flood Hydrology*

### Millyford Bridge

The Millyford Bridge gauging station (GR 26981, 07575) is located downstream of the limit of the New Forest EU Life 3 restoration. It is the longest continuously recording gauging station within the New Forest and thus is useful for determining hydrological trends in the catchment. The digital data for this project began on the 11$^{th}$ March 1998 and gives a baseline data record of 5 years prior to restoration and 2 years after restoration. For this reason it is useful to assess the cumulative effect of restoration upon the downstream hydrology but difficult to separate the effects of channel restoration and large wood restoration. Figure 6.9.1 shows a time series of the mean daily discharge for the monitoring period.

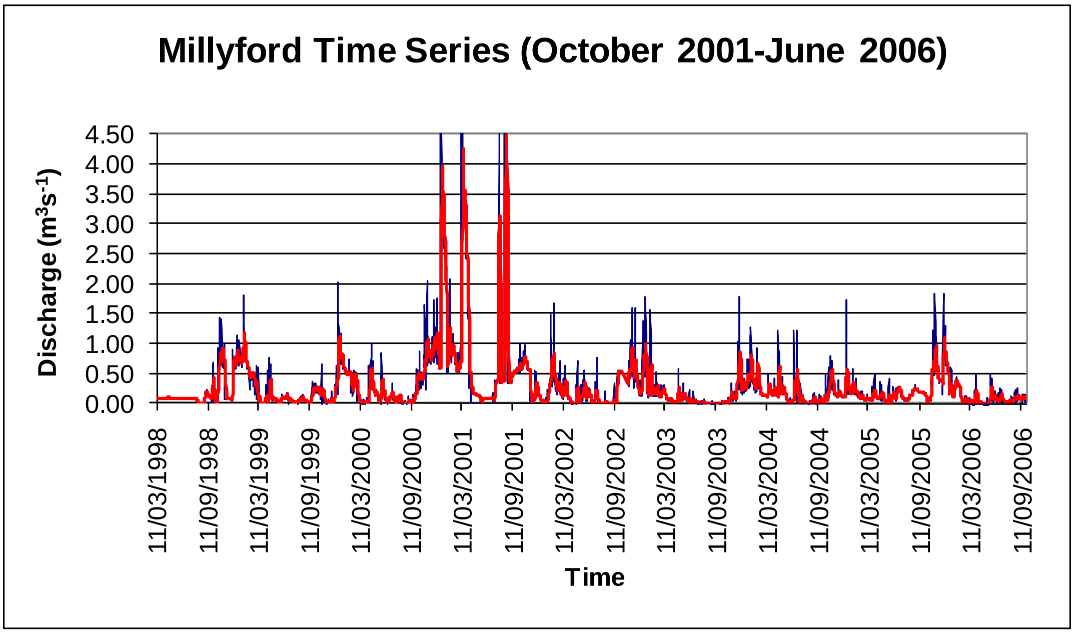



**Figure 6.9.1: The Hydrological Time Series at Millyford Bridge 1998-2006 with 7 day moving average (in red).**

It is difficult to pick trends from a hydrological time series due to the inherent noise in many hydrological systems. One clear pattern is the large peaks in the year 2000 which are associated with the 2000 floods which caused widespread damage in England and were caused by the highest rainfall since records began in 1776 (Environment Agency, 2001). Summary statistics provided in table 6.9.1 provide some information about the general trend before and after restoration. It is apparent that the 2000 floods have a large impact on the average values for the pre-restoration scenario. Therefore, the 2000-2001 flood season was removed from the average and it can be seen that there is a reduction in the mean value and in the $Q_5$ value. Although this suggests that the presence of large wood does affect the medium-term hydrological behaviour of the Highland Water, a T-Test shows that the difference is not statistically significant and therefore more data is required before it will be possible to claim the restoration has been successful in influencing downstream hydrological behaviour for a range of flows.

| Year | Mean Daily Discharge | SD | $Q_5$ | $Q_{95}$ |
|---|---|---|---|---|
| 97-98 | 0.09 | 0.06 | 0.18 | 0.01 |
| 98-99 | 0.26 | 0.33 | 0.85 | 0.01 |
| 99-00 | 0.2 | 0.26 | 0.69 | 0.01 |
| 00-01 | 0.98 | 1.27 | 3.67 | 0.09 |
| 01-02 | 0.21 | 0.27 | 0.69 | 0.01 |
| 02-03 | 0.18 | 0.29 | 0.78 | 0.01 |
| 03-04 | 0.19 | 0.25 | 0.72 | 0.01 |
| 04-05 | 0.16 | 0.15 | 0.38 | 0.01 |
| 05-06 | 0.18 | 0.27 | 0.69 | 0.02 |
| Pre-Restoration | 0.30 | 0.39 | 1.08 | 0.01 |
| Without 00-01 | 0.19 | 0.24 | 0.65 | 0.01 |
| Post-Restoration | 0.17 | 0.21 | 0.54 | 0.02 |
| Difference | 0.13 | 0.18 | 0.55 | 0.01 |

**Table 6.9.1: Summary Statistics for the Millyford Gauging Station**

## Effect on Flood Peak Magnitude

One of the goals of the restoration and of particular relevance to this thesis is whether the input of large wood has any impact on the catchment flood hydrology and, in particular, the flood peak magnitude and related flood probability and subsequent flood risk downstream of the restoration works.

Using the Millyford Bridge gauge, it is possible to assess the attenuation of a flood peak through the restored reach. Figure 6.9.2 shows the location of the two gauging stations, with the Highland Water 1 gauge just upstream of the upper limit of planform restoration and the Millyford Bridge gauging station downstream of the lower limit of pure large wood restoration. Between the two gauges, is a river length of 4km of which roughly a quarter had undergone planform restoration and half had undergone the addition of large wood. It is possible to evaluate the flood peak magnitude at the two gauging stations and determine a gross effect of the restoration works. Figure 6.9.3 shows two hydrographs of two flood events as recorded at the Highland Water 1 and the Millyford Bridge Gauges. The two events, shown in figure 6.9.3, took place on the 29/10/03 and 10/01/05 and show the attenuation of two similarly sized events before and after restoration. The discharges as measured at the Highland Water 1 gauge were 0.57m$^3$s$^{-1}$ and 0.56m$^3$s$^{-1}$ respectively. As they travel through the reach to the Millyford Bridge gauge, they were attenuated such that when the peak was measured at the gauge the discharges were 2.56m$^3$s$^{-1}$ and 2.2m$^3$s$^{-1}$ suggesting that the restoration had been responsible for attenuating 0.36m$^3$s$^{-1}$ of the flood event for this particular event.

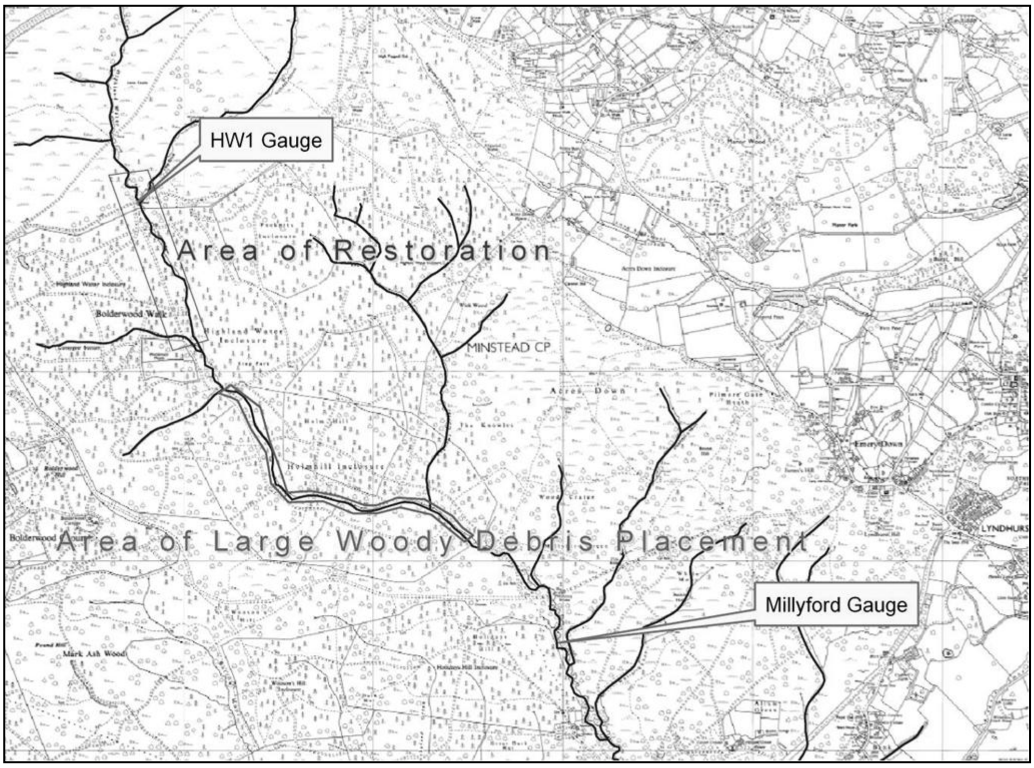



**Figure 6.9.2: The Reach over Which the Flood Peak Travel Time was measured.**

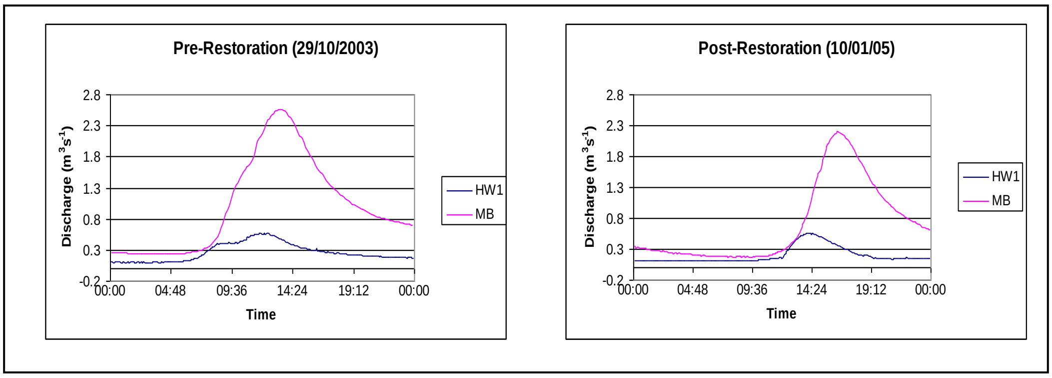



**Figure 6.9.3: Two Hydrographs Showing the Attenuation in Flood Wave Magnitude and Timing since Restoration**

A number of events were analysed to determine the effect of restoration on flood peak magnitude and travel time. The events were defined as an event which had a peak discharge greater than $0.15m^3s^{-1}$ at the Highland Water 1 gauging station. The value of $0.15m^3s^{-1}$ was chosen, as this was approximately commensurate with bankfull discharge at the Restored-Planform site after restoration. This threshold gave 47 flood events for which the analysis was undertaken (summarised in table 6.9.2). The data was plotted in Figure 6.9.4 which showed a general trend of higher discharges at Millyford Bridge gauging station for similar sized events at Highland Water 1 prior to restoration. In comparison, the post-restoration values appear to be lower at Millyford Bridge suggesting attenuation in the peak flow between the two gauges.

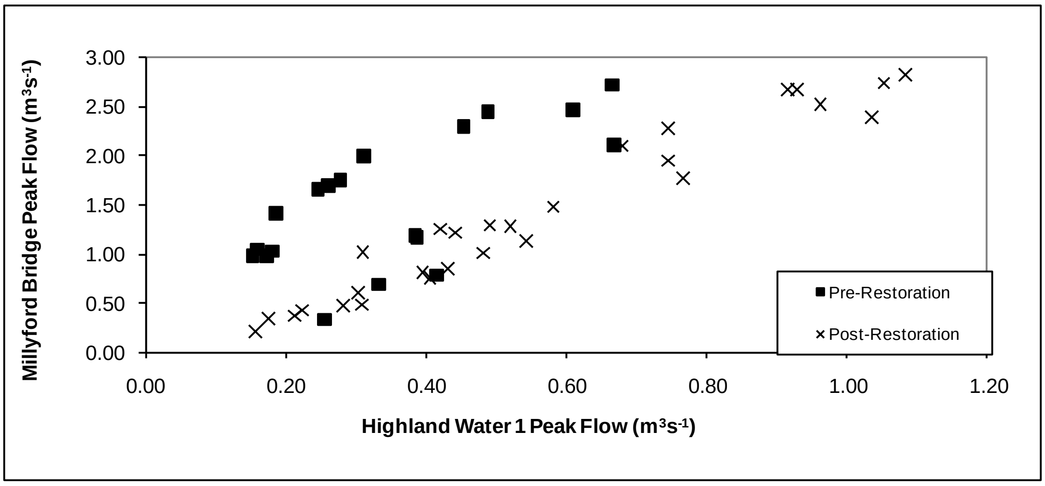



**Figure 6.9.4:- The relationship of peak flow at Highland Water 1 and at Millyford Bridge for identified flood peaks before and after restoration.**

There are a few pre-restoration values that lie within the post-restoration data cloud and this highlights the variability within the system and for a number of these particular flood events is a function of long duration multi-peaked flood events. The latter flood peaks in a multi-peaked event are influenced by the previous flood peaks due to the wetter antecedent conditions. Figure 6.9.4 shows the data points converging around a discharge of $1m^3s^{-1}$. The convergence at such a discharge of $1m^3s^{-1}$ suggests that the effect of the EU LIFE 3 restoration upon flood peaks may be limited to smaller floods events rather than those larger flood events which are associated with significant flood risk within the Highland Water catchment. Although, a discharge of $1m^3s^{-1}$ will result in some floodplain inundation there is little associated flood risk to property or infrastructure, with minimal impact upon people. The bulk of the flow for such a flood event is conveyed within the river channel and it is this portion which is retarded by the presence of in-channel large wood and their accumulations. Once floodplain flow is initiated, then the presence of large wood has less of an impact upon the attenuation of flood peak magnitude with data presented in Figure 6.9.4 showing a convergence in data at around $1m^3s^{-1}$. At this discharge, flow is conveyed via the floodplain as well as the river channel, and the roughness of the floodplain becomes critical in the attenuation of the flood peak. Therefore, to further the attenuation effect it may be necessary to roughen the floodplain through the presence of standing live wood, large wood and large wood accumulations on the floodplain surface.

Table 6.9.3 shows the average flood peak discharge for the two gauging stations before and after restoration. This shows that despite an increase in the average flood event peak discharge at the Highland Water 1 gauging station there is a slight decrease in the average flood event discharge at Millyford Bridge (statistically significant to the 10% level, t-statistic =1.99). This indicates that the restoration has been successful in mitigating some of the downstream flood probability with the peaks being attenuated on average by $0.24m^3s^{-1}$ or by 21%. Unfortunately, the nature of the restoration approach means that it is not possible to distinguish between the relative effects of the planform restoration and the large wood restoration. However, the flood events experienced during the study period were modest in nature, with the largest equivalent to a 2.2 year flood return period, and therefore the consequence of the observed reduction in flood probability cannot be said to have a significant impact upon the flood risk in the Highland Water catchment. Further monitoring of large flood events are required until it is possible to suggest that large wood restoration can attenuate large magnitude flood events and reduce flood risk.

| | Highland Water 1 | | Millyford Bridge | | | |
|---|---|---|---|---|---|---|
| Date | Time of Peak | Peak Discharge ($m^3s^{-1}$) | Time of Peak | Peak Discharge ($m^3s^{-1}$) | Difference | % Difference |
| **Pre-Restoration** | | | | | | |
| 30/10/2003 | 22:10 | 0.39 | 23:30 | 1.17 | 0.78 | 66.67 |
| 02/11/2003 | 10:55 | 0.38 | 12:10 | 1.19 | 0.81 | 68.15 |
| 03/11/2003 | 02:45 | 0.33 | 04:30 | 0.69 | 0.36 | 51.99 |
| 12/11/2003 | 07:40 | 0.26 | 09:20 | 0.33 | 0.07 | 21.09 |
| 21/11/2003 | 08:10 | 0.41 | 10:34 | 0.79 | 0.38 | 48.10 |
| 22/11/2003 | 14:40 | 0.67 | 16:04 | 2.11 | 1.44 | 68.25 |
| 11/12/2003 | 10:15 | 0.18 | 11:44 | 1.03 | 0.85 | 82.49 |
| 29/12/2003 | 11:50 | 0.19 | 13:22 | 1.41 | 1.22 | 86.57 |
| 01/01/2004 | 06:55 | 0.25 | 08:12 | 1.66 | 1.41 | 84.90 |
| 08/01/2004 | 08:45 | 0.49 | 10:42 | 2.44 | 1.95 | 79.94 |
| 11/01/2004 | 05:50 | 0.26 | 07:20 | 1.69 | 1.43 | 84.64 |
| 12/01/2004 | 10:15 | 0.66 | 12:10 | 2.72 | 2.06 | 75.77 |
| 14/01/2004 | 07:50 | 0.15 | 09:20 | 0.99 | 0.84 | 84.78 |
| 15/01/2004 | 19:20 | 0.16 | 20:40 | 1.05 | 0.89 | 84.69 |
| 31/01/2004 | 10:35 | 0.31 | 11:43 | 2.00 | 1.69 | 84.52 |
| 01/02/2004 | 18:25 | 0.61 | 20:13 | 2.46 | 1.85 | 75.23 |
| 18/04/2004 | 12:55 | 0.45 | 14:10 | 2.29 | 1.84 | 80.37 |
| 21/04/2004 | 14:45 | 0.28 | 16:30 | 1.75 | 1.47 | 84.00 |
| 04/05/2004 | 09:50 | 0.17 | 11:05 | 0.98 | 0.81 | 82.60 |
| **Average** | | 0.35 | | 1.51 | 1.17 | 73.41 |
| **Post-Restoration** | | | | | | |
| 19/12/2004 | 05:15 | 1.05 | 06:43 | 2.74 | 1.69 | 61.61 |
| 28/12/2004 | 03:15 | 0.54 | 05:08 | 1.13 | 0.59 | 52.04 |
| 08/01/2005 | 06:40 | 0.21 | 09:48 | 0.37 | 0.16 | 42.97 |
| 09/01/2005 | 19:10 | 0.22 | 21:58 | 0.43 | 0.20 | 47.38 |
| 10/01/2005 | 14:15 | 0.52 | 16:33 | 1.28 | 0.76 | 59.43 |
| 22/01/2005 | 23:15 | 0.43 | 01:36 | 0.85 | 0.42 | 49.06 |
| 12/02/2005 | 08:20 | 0.18 | 10:51 | 0.35 | 0.17 | 49.15 |
| 13/02/2005 | 14:50 | 0.16 | 17:41 | 0.21 | 0.05 | 24.43 |
| 22/03/2005 | 06:55 | 0.41 | 09:14 | 0.75 | 0.34 | 45.90 |
| 24/03/2005 | 02:40 | 0.30 | 04:55 | 0.60 | 0.30 | 49.33 |
| 29/03/2005 | 22:00 | 0.49 | 23:20 | 1.29 | 0.80 | 61.91 |
| 18/04/2005 | 05:00 | 0.48 | 06:55 | 1.01 | 0.53 | 52.31 |
| 24/04/2005 | 18:55 | 0.40 | 20:57 | 0.82 | 0.42 | 51.69 |
| 21/05/2005 | 12:10 | 0.58 | 13:42 | 1.48 | 0.90 | 60.73 |
| 24/10/2005 | 03:50 | 0.44 | 05:33 | 1.22 | 0.77 | 63.67 |
| 24/10/2005 | 20:20 | 0.92 | 22:18 | 2.67 | 1.75 | 65.70 |
| 30/10/2005 | 14:05 | 0.31 | 16:23 | 1.02 | 0.71 | 69.63 |
| 02/11/2005 | 01:05 | 1.08 | 03:18 | 2.82 | 1.74 | 61.62 |
| 02/11/2005 | 16:55 | 0.74 | 18:38 | 2.28 | 1.54 | 67.39 |
| 03/11/2005 | 07:15 | 1.04 | 09:08 | 2.39 | 1.35 | 56.59 |
| 03/11/2005 | 14:30 | 0.77 | 16:23 | 1.77 | 1.00 | 56.64 |
| 06/11/2005 | 12:30 | 0.74 | 14:23 | 1.95 | 1.21 | 61.84 |
| 02/12/2005 | 06:30 | 0.68 | 08:23 | 2.10 | 1.42 | 67.64 |
| 02/12/2005 | 20:15 | 0.93 | 22:03 | 2.67 | 1.74 | 65.20 |
| 07/12/2005 | 22:05 | 0.96 | 23:52 | 2.53 | 1.57 | 61.94 |
| 30/12/2005 | 12:50 | 0.42 | 15:32 | 1.25 | 0.83 | 66.41 |
| 01/01/2006 | 01:50 | 0.31 | 04:27 | 0.48 | 0.17 | 35.80 |
| 11/01/2006 | 09:25 | 0.28 | 11:32 | 0.48 | 0.20 | 41.07 |
| **Average** | | 0.56 | | 1.39 | 0.83 | 55.32 |

**Table 6.9.2: The difference between peak flows at Highland Water 1 and Millyford Bridge Gauging Stations.**

However, as well as the restoration, there are a number of factors that can influence the travel of a flood peak through the catchment system such as the antecedent conditions, urban development, and vegetation growth (Archer, 1989;

Wyzga, 1993). Vegetation is unlikely to have significant impact during the monitoring period due to the slow rate of tree growth and suppression of shrub growth due to the influence of grazing herbivores. The catchment is predominantly rural and this, together with the small monitoring timescales, means that urbanisation and other land-cover changes are unlikely to be responsible for the post-restoration attenuation in flood peaks. Therefore, the main influence is likely to be climatic; in particular the antecedent catchment conditions prior to the flood event.

| Site | Average Pre-Restoration Flood Magnitude ($m^3s^{-1}$) | Average Post-Restoration Peak Magnitude ($m^3s^{-1}$) | % Difference |
|---|---|---|---|
| **Highland Water 1** | 0.35 | 0.56 | 62.86% |
| **Millyford Bridge** | 1.51 | 1.39 | -2.11% |
| **Increase in Downstream Flood Magnitude** | 1.17 | 0.83 | |
| **Attenuation Effect ($m^3s^{-1}$)** | | | 0.24 |
| **Attenuation Effect (%)** | | | 21% |

**Table 6.9.3: The average flood event peak at Highland Water 1 and Millyford Bridge for the Pre- and Post-Restoration scenarios.**

Data from the nearby Ocknell Rainfall Gauge, operated by the University of Southampton, was used to determine the rainfall intensities and antecedent conditions. Both are important as similar sized floods may arise due to heavy rainfall falling on a dry catchment or a more moderate sized event falling on a wet catchment (Acreman and Boorman, 1993).

An analysis of the antecedent rainfall, as represented using the 5 day Antecedent Precipitation Index (API5) was performed. The API5 is commonly used in hydrological analysis to represent the antecedent conditions present within the catchment (Institute of Hydrology, 1999) and is given by:-

$$API5 = \sqrt{0.5[p_{d-1} + (0.5)p_{d-2} + (0.5)^2 p_{d-3} + (0.5)^3 p_{d-4} + (0.5)^4 p_{d-5}]} \quad \textbf{(6.3)}$$

Where $P_{d\text{-}n}$ is the rainfall for the $n^{\text{th}}$ day previous to the flood event.

The rainfall intensity and API5 analysis was undertaken for 39 of the 47 monitored flood events as, unfortunately, a gauge fault meant that rainfall data was unavailable for the period, 03/03/05 until the 30/05/05. The rainfall intensity and API5 value were plotted against the Millyford Bridge discharge and are shown in figures 6.9.5 and 6.9.6.

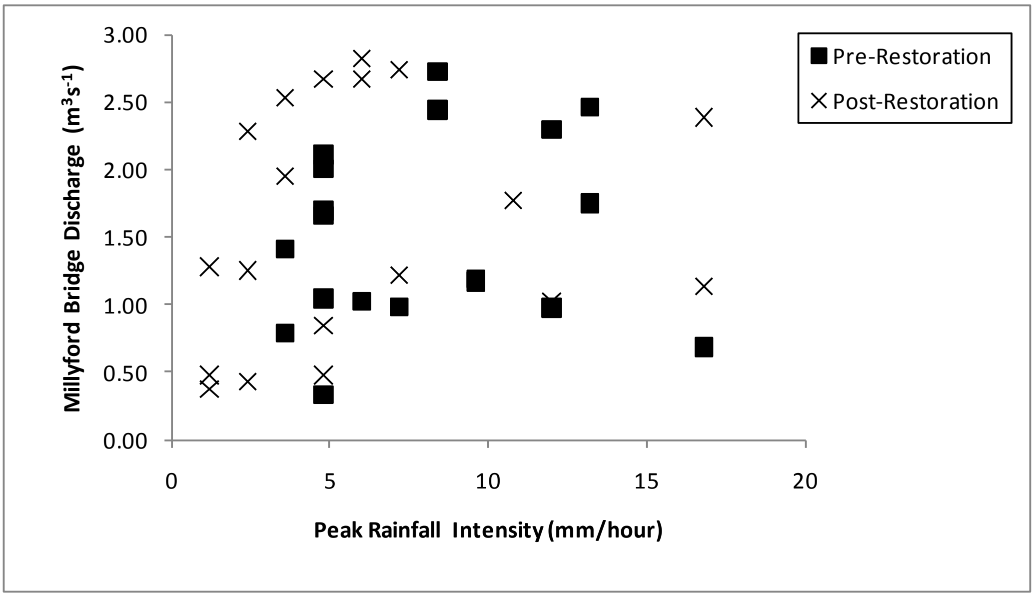



**Figure 6.9.5: Peak Rainfall Intensity plotted against discharge at Millyford Gauging Station for the Pre-Restoration and Post-Restoration Scenario.**

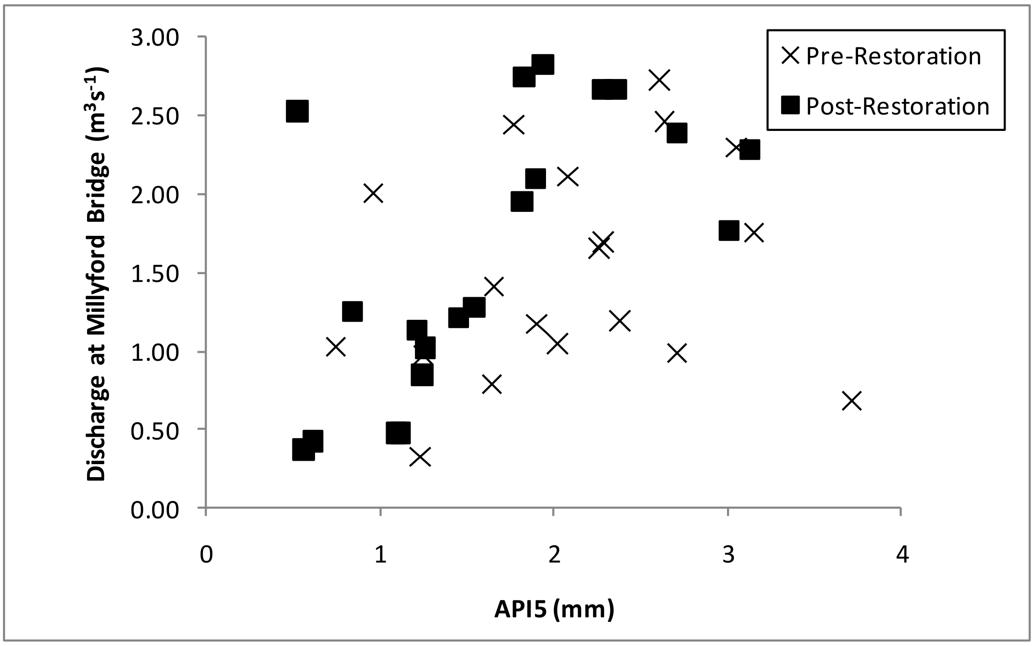



**Figure 6.9.6: The relationship between the 5 day Antecedent Precipitation Index and the Discharge at Highland Water 1 Gauging Station for the pre-restoration and post-restoration monitoring periods.**

The results show that the conditions post-restoration were slightly drier than those present prior to restoration, supporting data presented in Table 6.4.2. This difference is shown in the average peak rainfall intensity of 8mm/hour (St Dev=3.99mm/hour) for the pre-restoration and 6mm/hour (St Dev=4.7 mm/hour) for post-restoration however the t-test statistic shows the change is not significant at the 5% level (t-statistic=1.276). The average API5 value has also decreased from a pre-restoration value of 2.1mm (St Dev=0.78mm) to a post-restoration value of 1.62mm (St Dev= 0.78mm) although, again, this is not statistically significant (t-statistic=1.845). However, there appears to be no relationship between either peak rainfall intensity, or API5, and the difference in discharge between the Highland Water and Millyford Bridge gauging stations (shown in Figures 6.9.7 and 6.9.8). This result suggests that the hydrological impact of the restoration is independent of the prevailing climate. Therefore, it can be concluded that restoration can attenuate the flood peak magnitude for small flood events up to the 2.2 year return period flood observed as part of this study within the Highland Water catchment.

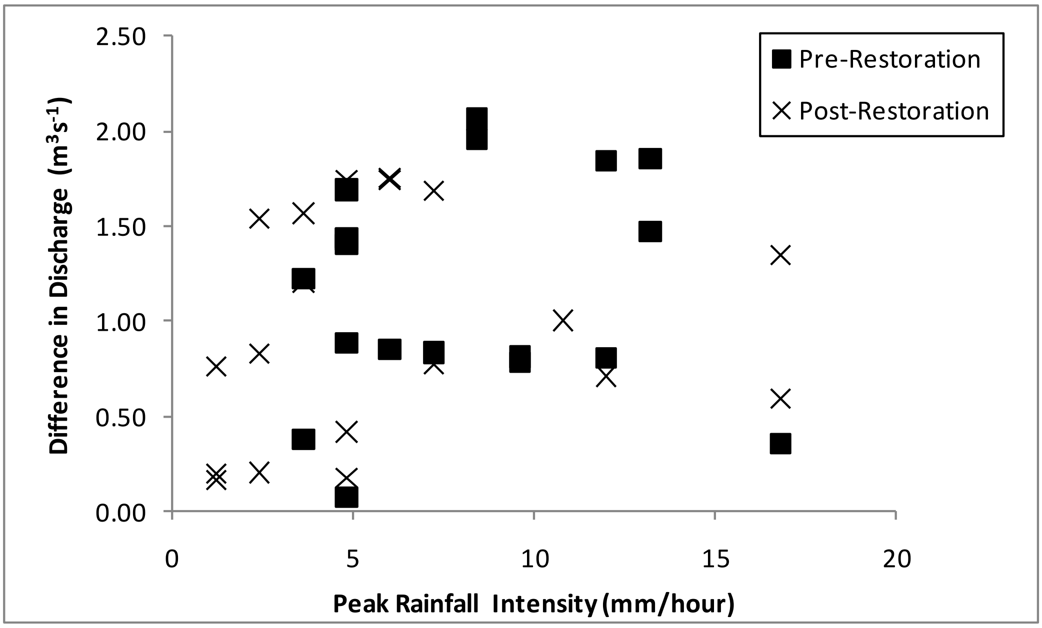



**Figure 6.9.7:- Peak Rainfall Intensity plotted against the difference in discharge between the Highland Water 1 and Millyford Bridge gauging stations.**

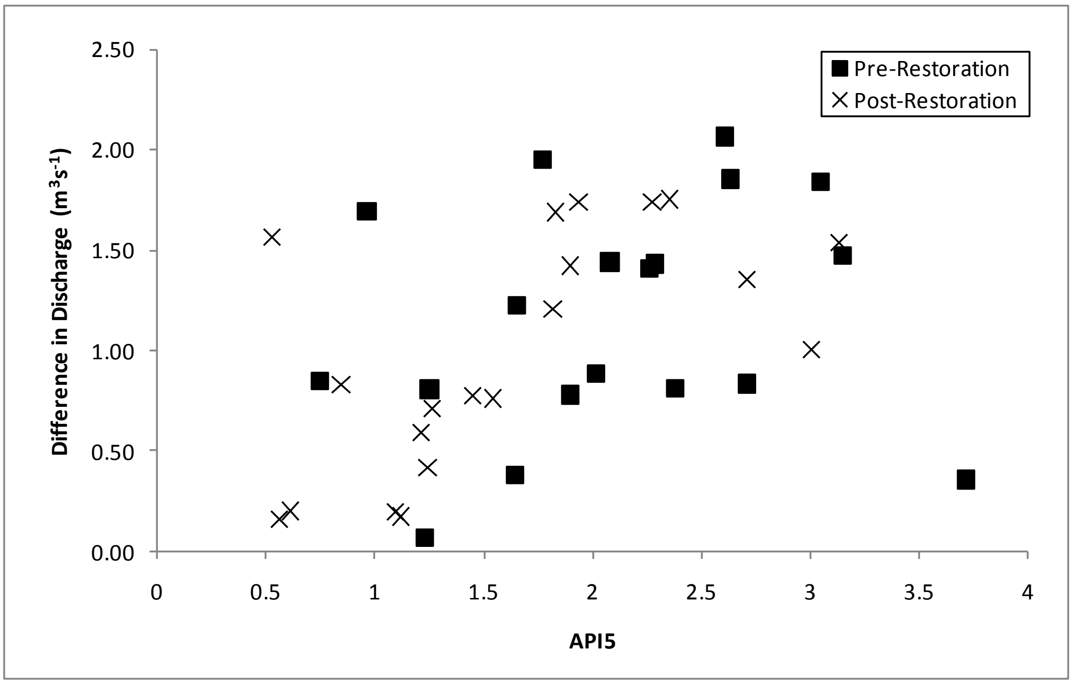



**Figure 6.9.8:- 5 Day Antecedent Precipitation Index (API5) plotted against the difference in discharge between the Highland Water 1 and Millyford Bridge gauging stations.**

## Effect on Flood Peak Travel Time

The effect on flood peak magnitude is not the only impact restoration can have on the catchment flood hydrology as any attenuation by restoration can impact on the time of travel of the flood wave. Using the two aforementioned flow gauges, it was possible to assess the time taken for flood waves to pass through the restored reach between the two gauging stations. By assessing the same flood events used in the flood peak magnitude analysis it was possible to determine the effect of restoration on the flood peak travel time. The combined effect of planform restoration and the input of large wood resulted in the average flood peak travel time increasing from 1hour 35 minutes to 2hours 10 minutes. This is an increase of 35 minutes, which can be important in the phasing of the other rivers present in the New Forest (Norton, 2003). A change in the flood peak travel time can lead to the synchronisation of flood peaks such that flood peaks from one river may coincide with another tributary and increase the flood risk. As part of the EU LIFE 3 project, catchment flood modelling was undertaken to understand how this impacted on flood risk and, although only undertaken for a limited range of 'design' flood events showed that downstream flood risk was not increased in the case of the Highland Water and other tributaries. It is suggested that, if restoration is used to slow the travel of the flood peak, then a catchment flood modelling exercise is imperative to determine the effect of synchronising flood peaks. It may be necessary to undertake modelling for more than the commonly used 'design' flood events to determine the impact of restoration upon the flood timing, synchronisation with other tributary inflows and the subsequent potential impact upon flood risk. This could be done using a probabilistic methodology such as a Monte-Carlo procedure which seeks to simulate a series of catchment flood events to determine which events may have an adverse impact upon downstream flood risk.

Such an analysis has been undertaken for this part of the Highland Water in the past by Gregory (1992). Figure 6.9.6 shows data from the current monitoring period added to data collected Gregory (1992). It can be seen that, in general, the higher discharge events have a shorter travel time between the two gauges as the effect of large wood accumulations is drowned out by the higher flows and the data points converge. This is a common effect that is also present in other friction elements within a river system (eg. sediment, bedforms and vegetation, see Jarrett, 1984; Prestegaard, 1983; Lee and Ferguson, 2002) and large wood is no exception (Petryk and Bosmajian, 1975). The convergence of data points, suggests that there is a limit to the effectiveness of the attenuation to smaller flood events which are carried within the river channel and thus affected by in-channel larger wood. Again, it may be possible to increase the effectiveness for larger flood events, by attenuating the flow conveyed on the floodplain through the addition of large wood and development of woodlands which would roughen the floodplain surface. The roughening of the floodplain surface will retard floodplain flow and may reduce the convergence of data points for the larger flow events.

Despite the noise present within the data due to the affect of antecedent catchment conditions and rainfall intensity, it is still possible to make out a number of trends. Firstly, that after 27th October 1987 the flood peak travel time increased. This was a direct result of the storms of the same date that led to an increase in the amount of large wood entering the Highland Water. The extra resistance offered by the large wood and the subsequent reduction in channel conveyance increased the flood peak travel time by 33 minutes. In 1989, there was a period of debris removal, which led to the reduction in flood peak travel times on average by 34 minutes. However as large wood management was stepped down there was again an increase in the flood peak travel time so that in the monitoring period prior to the restoration the flood peak travel time was at a similar level to that experienced after the great storm of 27th October 1987.

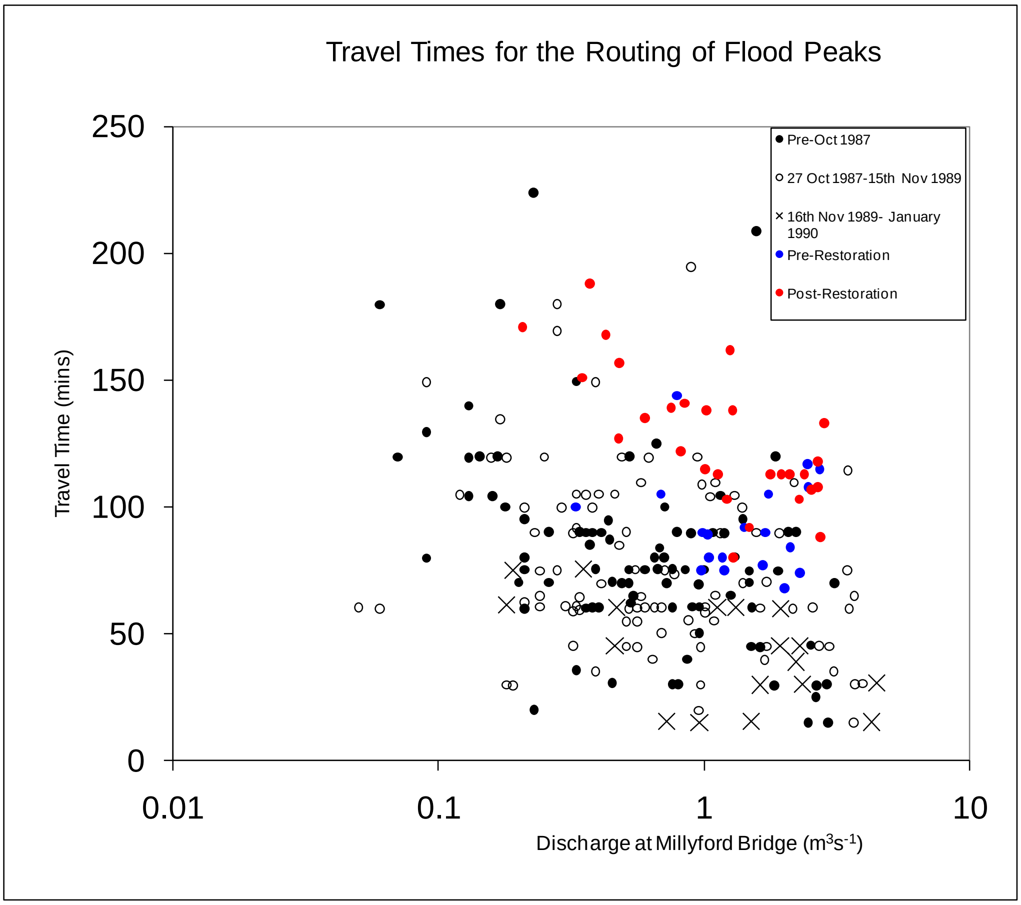



**Figure 6.9.9: Flood Peak Travel Times versus Discharge. Extra Data Added from Gregory (1992).**

This highlights the importance of large wood in attenuating flood peaks and highlights their use as a method of reducing downstream flood risk. Taking data from 1989/90 and that monitored pre-restoration, the increase in large wood density from 0.53 to 1.08 per 100m was responsible for a 50 minute increase in the average flood peak travel time. After planform restoration and the installation of large wood accumulations the flood peak travel times had further increased (shown by the data points (in red) being above the other data).

Solely on the basis of the gauge records, it is difficult to ascertain whether the planform restoration, reconnection of the channel with its floodplain or the input of large wood is the key component in reducing flow magnitude but they are all likely to play some role in influencing the flow hydrology.

Using the data from Gregory (1992) together with data from this study, it is possible to assess the impact of large wood upon the flood peak travel time. Table 6.9.4 provides a summary of the average travel time for each period shown in Figure 16.3 from Gregory (1992).

| Date | No of Large Wood Accumulation | Large Wood Accumulations per 100m | Average Flood Peak Magnitude | Average Flood Peak Travel Time |
|---|---|---|---|---|
| Pre-1987 | 154 | 1.77 | 0.86 | 81 |
| 1987-1989 | 141 | 1.61 | 0.99 | 77 |
| 1989-1990 | 46 | 0.53 | 1.58 | 43 |
| Pre-Restoration (2003-2004) | 92 | 1.08 | 1.42 | 93 |
| Post-Restoration (2004-2006) | 234 | 2.57 | 1.39 | 126.75 |

**Table 6.9.4: Average Flood Peak Magnitude and Peak Travel Time for 5 periods for the Highland Water, UK.**

Figure 6.9.10 shows some of this data and it is apparent that there is a trend of increasing flood peak travel time with an increase in large wood frequency. A trendline shows that there is a weak linear trend line showing an r-squared value of 0.43 which suggests that there are too few points to achieve a strong regression relationship.

The difference between the average flood peak travel time before and after restoration is significant at the 5% level (T-value is 4.7734) and suggests that large wood restoration is successful in increasing the flood peak travel time. This suggests a greater residence time of flow in the upper reaches of the catchment which produces flow hydrographs which are lower and broader than those river systems with little channel-floodplain connectivity which tend to have flashier flood regimes which are more responsive to rainfall events (Archer, 1989; Woltemade and Potter, 1994).

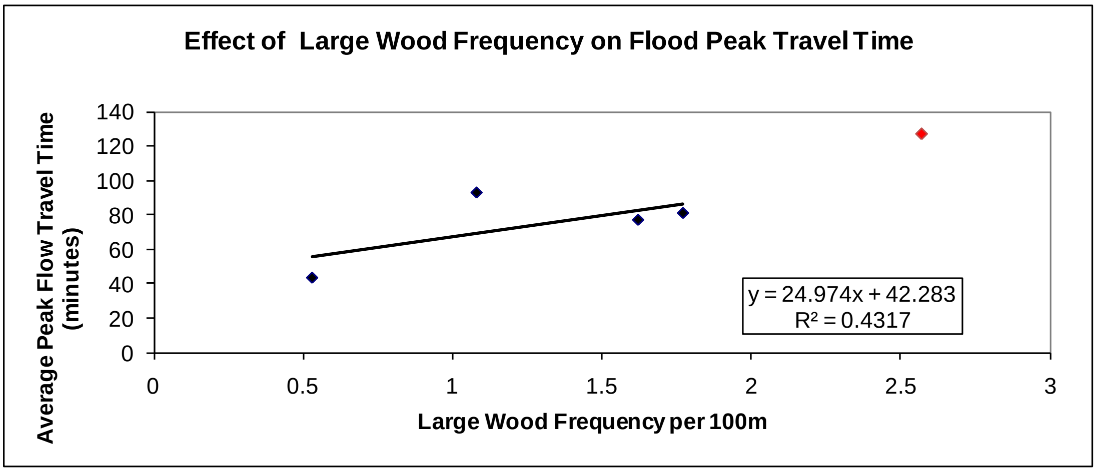



**Figure 6.9.10: Effect of the Large Wood Frequency upon Flood Peak Travel Time. The outlier in red is not included in the regression analysis as it was also subject to planform restoration.**

Due to the effect of the climatic factors, it is difficult to find a strong relationship between large wood frequency per 100m and flood peak magnitude. However, it is clear that large wood can significantly influence catchment flood hydrology in the Highland Water catchment. However, it should be noted that the Highland Water is a small catchment and data presented in Figure 6.9.4 and Figure 6.9.9 suggest the influence is restricted to those floods less than $1m^3s^{-1}$ in magnitude which is equivalent to a 1.3 year return period.

## 6.10. Catchment Hydrology: Planform versus Large Wood Restoration

Due to the method of catchment hydrological monitoring it is has not proven easy to distinguish between the effects of the planform restoration and those of the large wood restoration. At the catchment scale, it is likely that the planform restoration is responsible for the majority of the peak magnitude attenuation and flood peak timing increase. An increase in channel length of 40%, together with the input of a number of large wood accumulations, caused flood peak magnitude to decrease by 21% and flood peak travel time to increase by 33%. This is a similar magnitude to that found by Acreman *et al.* (2003) on the River Cherwell in south-east England, where modelled restoration of the channel to pre-engineered dimensions led to a reduction in peak flow of 10-15%. This is largely due to the increased connectivity between the channel and its floodplain, which leads to the storage of water upon the floodplain. This connectivity was achieved through channel restoration. It is also known that large wood can improve the connectivity between the channel and its floodplain (Jeffries *et al.*, 2003) with large wood being responsible for up to a 175% increase in floodplain inundation frequency in the present study.

Gregory (1992) found that the ponding of water by large wood accumulations resulted in increased water depth, reduced velocity and thus significantly increasing the flood peak travel by 2-3 times the average travel time prior to large wood clearance. A similar effect has been observed in the current study with a statistically significant relationship being demonstrated between large wood frequency per 100m and flood peak travel time. This potential downstream flood relief is one of the many benefits of the use of large wood and this can be further developed through the development of riverine woodland (Brown, 1997). The effect is drowned out at higher flows and this is similar to the findings of Shields and Smith (1992) who found that friction factors for cleared and uncleared reaches converged at high flows of over $20m^3s^{-1}$. This attenuation pattern is similar to the effect of seasonal in-channel vegetation (Hamill, 1983; Sellin and Beesten, 2004).

Rehabilitation of the channel-floodplain link either through planform restoration or with large wood can be used as a valuable part of flood management strategy for river catchments. Hoijer (1996) calculated that flooding of 3500ha of floodplain in the Shannon Valley, Ireland to an average depth of 1m represented the storage equivalent to 1 day of peak discharge ($400m^3s^{-1}$). This can have significant impacts on downstream flood risk and flood management. The US Army Corps of Engineers (1972) calculated that floodplain storage of 3800ha on the Charles River, Massachusetts could reduce downstream flood damage costs by up to US$17 million. Therefore, there is real benefit to connecting the channel with its floodplain for flood management purposes. Woltemade (1994) suggested that the impact of floodplain storage on flood peak is subject to the size of the river catchment. Attenuation effects were limited in small catchments ($<10km^2$) where there are steep slopes, an absence of well-developed floodplains and short flood wave travel times. The opposite occurs in larger floodplains ($>10^4km^2$) where floods are attenuated by complex processes operating at much larger spatial scales. However, they may occur at similar spatial scales as commonly floodplains fill at the 2-10 year flood return period and thus store water but at larger flood return periods the floodplains begin to transmit flow (Bhowmik and Demissie, 1982).

Another way in which large wood accumulations can influence flood hydrographs is the pulse of flow that occurs when large wood accumulations are blown out during floods (Gurnell and Gregory, 1981). These blow-outs are rare and, within small headwater streams like the Highland Water, unlikely to have a significant impact on the downstream hydrograph. Furthermore, the presence of a number of large wood accumulations throughout the reach can suppress the effect of any flow pulse in the event of a collapse of one large wood accumulation.

## 6.11. Summary

The work presented in this chapter suggests that the EU Life 3 restoration was successful in reconnecting the channel with its floodplain through the use of planform restoration and large wood. Key within the EU Life 3 approach was the use of large wood accumulations to locally increase water levels, leading to increases in the frequency of inundation of the floodplain by up to 175%. Data shows that the role of large wood is affected by local variability such as in bank height, channel capacity and also the type of large wood accumulation. The performance of different large wood accumulations in influencing floodplain inundation frequency and magnitude is crucial to the understanding of their use as a restoration tool for restoring flood pulses and conditions favourable for riverine woodland.

Storage of flow on the floodplain during high flow events is linked to the channel: -floodplain connectivity. Storage of flood waters leads to suppression of the floodwave, reducing flood peak magnitude and increasing the time of travel for the flood wave. Unfortunately, it was not possible to separate the downstream hydrologic effects of large wood on flood peak magnitude from those of planform restoration. Using data from Gregory (1992) and that from the present study it was possible to access the average travel time for a number of large wood loading scenarios. The results showed that there was a statistically significant relationship between the large wood frequency and flood peak travel time.

# 7. The Hydraulic role of in-channel Large Wood Accumulations

## *7.1. Introduction*

The results from the EU LIFE 3 restoration works showed how significant large wood can be in influencing floodplain hydrology as well as reach-scale hydraulics within a semi-natural forested river channel. This was shown through the influence on the inundation frequency and duration at the monitored sites as well as the impact upon downstream flood hydrology. To improve understanding of this effect it is necessary to study the processes that occur at the large wood scale and how they influence the reach-scale hydraulics. The effect is likely to vary depending upon the type of large wood accumulation and this work seeks to assess the roughness offered by each type.

Attempts to predict the flow resistance contributed by large wood have relied upon the drag force approach first used by Petryk and Bosmajian (1975) for floodplain vegetation. Any object submerged in a flow is likely to experience two distinct forces, those forces due to the frictional shearing between the object and the flow and those forces that arise from flow separation around a ‘bluff’ object (Chadwick and Morfett, 1999). The latter is the form drag that is accounted for using the drag force approach. It relies on the specification of the energy lost per unit channel length due to large wood as a result of the associated drag. The method has subsequently been used to predict large wood resistance by Shields and Smith (1992), Gippel *et al.* (1992), Shields and Gippel (1995), Manga and Kirchner (2000), Curran and Wohl (2003) and Wilcox and Wohl (2006). The approach assumes that the effect of the large wood can be treated as a boundary roughness component that is uniformly distributed along a reach. However, in practice, large wood can cause local accelerations and decelerations of flow (Abbe and Montgomery, 1996). Results from low gradient sand- and gravel-bed rivers showed that the approach could account for 84% of the variation in the data (Shields and Gippel, 1995). The same approach was used in a step-pool system where there were large percentage residuals (average = 96.2%) which were attributed to the spill resistance associated with the high gradient step-pool processes (Curran and Wohl, 2003). Curran and Wohl (2003) explain that form resistance may be more important in lower-gradient channels whereas in higher-gradients and in step-forming large wood accumulations the spill resistance contributes significantly more to the total flow resistance. At present little has been done to tie in the data from a range of studies to examine trends across a variety of environments. This work seeks to rectify this and provide a review of previous studies, adding new data from the Highland Water, a low-order forested stream, and comparing it to existing data from the literature. It will also provide an understanding of the role of in-channel large wood accumulations and a methodology for assessing the resistance offered. This is important for the understanding of channel conveyance, flood risk and also for hydraulic modelling which relies on an accurate representation of the resistance coefficient for simulations of floodplain inundation (Wu *et al.*, 1999).

## 7.2. Methodology

In order to assess the roughness contribution of large wood to the reach-scaled hydraulics of a lowland forested stream it was necessary to partition the total roughness into a series of constituent parts which could be estimated using well studied formulas (Einstein and Barbarossa, 1952). This required the collection of a range of field data in order to calculate the Darcy-Weisbach friction factor. The Darcy-Weisbach friction factor was used as it is dimensionally correct and has a sound physical reasoning when compared to other commonly used roughness coefficients (Hey, 1979; Sellin *et al.*, 2003).

Channel morphology was characterised by producing a cross-section profile at the upstream and downstream boundaries of the reach and one immediately upstream of the large wood accumulation (see Figure 7.2.1). Channel morphology measurements were taken using a Geodimeter Total Station and used to obtain values of reach-averaged channel cross-sectional area (A), wetted perimeter (WP), hydraulic radius (R), channel width (W), and water surface slope (S). The measurement error associated with the total station is within 0.5-1cm and therefore the derived channel dimensions are estimated to be accurate to approximately 1-2.5cm.

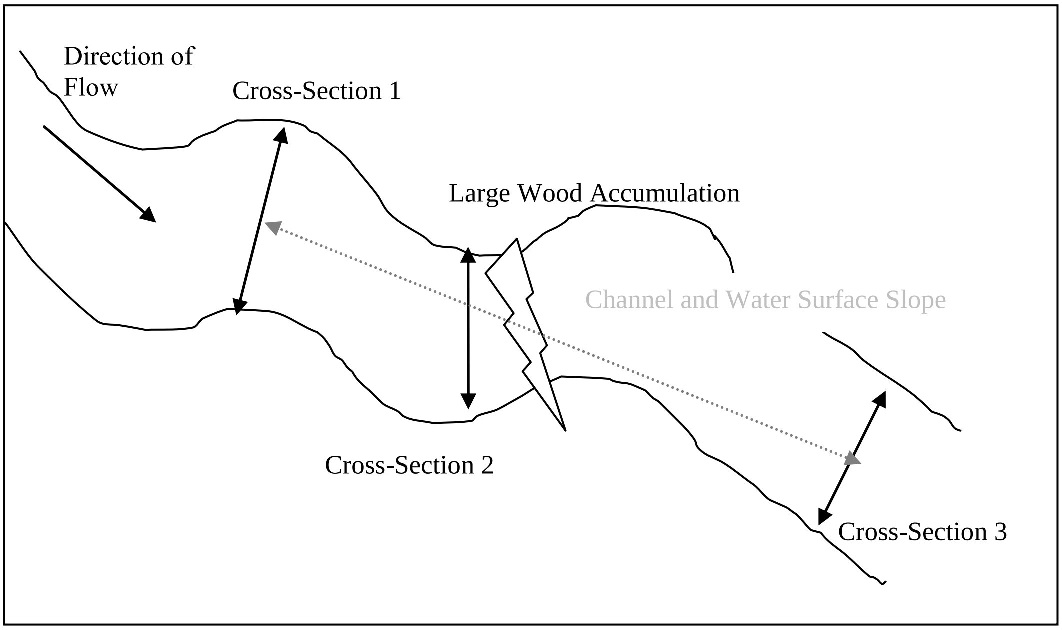



**Figure 7.2.1: The Location of the Surveyed Cross-Sections to Characterise Channel Morphology**

It was necessary to calculate the reach-averaged velocity, which was done using a salt dilution-gauging technique. The mean travel time of the tracer was used with the reach length to calculate the mean reach velocity using:-

$$v = 0.5\int_0^\infty \left(Con_d(t) - Con_b\right)\partial t \qquad \textbf{(7.1)}$$

Where $Con_d$ ($t$) is the tracer conductivity at the downstream limit as a function of time ($t$) and $Con_b$ is the background conductivity of the flow. The dilution gauging was done at as close to bankfull conditions as was practical and safe. Dilution gauging was conducted twice at each site and an average velocity taken.

Accuracy of the dilution gauging method is typically ±5% (Whiting, 2003). Notes were taken as to any features associated with the large wood accumulation and photographs were taken upstream and downstream of the accumulation.

Using the reach-averaged velocity ($\bar{v}$) and channel dimensions it was possible to calculate the Darcy-Weisbach friction factor:-

$$f = \frac{8 * g * R * S}{\bar{v}^2} \qquad \textbf{(7.2)}$$

Where $g$ is the gravitational constant ($9.81ms^{-2}$). This measured Darcy-Weisbach friction factor is a composite term, which represents the retarding influences that cause energy loss in fluid motion (Richards, 1982).

## *7.3. Roughness Partitioning*

The Darcy-Weisbach friction factor, $f$ can be partitioned into the different types of resistance in a commonly used roughness partitioning technique (Einstein and Barbarossa, 1952; Bathurst, 1982) which for the purpose of this study is split into bed resistance, bend resistance and resistance from large wood. Many studies of resistance partitioning use the same basic method whereby total resistance is divided into a number of components, which can be calculated using empirical formulas. Differences between the calculated components and the total roughness are then attributed to immeasurable components such as bedform resistance (Parker and Peterson, 1980; Prestegaard, 1983) or spill resistance (Curran and Wohl, 2003; Wilcox *et al.*, 2006).

$$f_{total} = f_{bed} + f_{bends} + f_{LWD} \qquad \textbf{(7.3)}$$

Bed resistance was originally estimated using Hey's (1979) formula for gravel-bed rivers, which is recommended as most satisfactory by Bathurst (1997)). However, as described later, following the flume experiments the bed resistance was estimated using the formula of Griffith (1981) which showed a better fit with observed data. The Griffith (1981) equation is:-

$$\frac{1}{\sqrt{f}} = 0.76 + 1.98 Log_{10}\left(\frac{R}{D_{20}}\right) \quad \textbf{(7.4)}$$

Where $D_{20}$ is the 20th percentile of the bed sediment size, which is 0.013m.

To sample bed sediment size a Wolman (1954) pebble count was conducted in which 100 pebbles were selected from the river bed surface at 10 different sections within the reach. The pebbles were selected blind to reduce sampling bias. The Wolman pebble count is a widely used technique used in fluvial geomorphology to sample grain-size distribution without the need for bulk samples, which can prove impractical when sampling a number of sites (Manners *et al.*, 2007)

Bend resistance was approximated using head loss coefficients, as this has been found to give the best values when used in other work involving large wood (Shields and Gippel, 1995 and subsequent discussion by Marriott, 1996 and reply from Shields and Gippel, 1996). The resistance at bends can be calculated using head loss coefficients (Henderson, 1966) which, for a river with a width to depth ratio above 10 and Froude number below 0.5, can be approximated by:-

$$C_i = \frac{2B_i}{r_c} \quad \textbf{(7.5)}$$

Where $C_i$ is the head loss coefficient for bend $i$, $B$ is the channel width at bend $i$ and $r_c$ is the radius of curvature of the bend. Using the head loss coefficient, it is possible to approximate the resistive forces due to bends in steady flow as:-

$$\sum f_{bends} = \sum \rho A \left[\frac{B_i}{r_c}\right] \alpha \bar{V}^2 \quad \textbf{(7.6)}$$

Where $\rho$ is the density of water and α is a kinetic energy correction factor assumed to equal 1.15 in uniform flow (Henderson, 1966). Curran and Wohl

(2003) used a value of one to account for the effect of a non-uniform velocity distribution across the section. However, table 7.3.1 shows the values of the kinetic energy correction factor suggested by Chow (1959). As the Highland Water is a natural channel with turbulent flow especially around large wood accumulations where there are flow accelerations and decelerations, the present study used a value of 1.15. Shields and Gippel (1995) also used this value in the original derivation of the drag coefficient approach to estimate the resistance offered by large wood.

| **Channel** | **α** | | |
|---|---|---|---|
| | **Minimum** | **Maximum** | **Average** |
| Regular channels, flumes, spillways. | 1.10 | 1.20 | 1.15 |
| Natural streams and torrents. | 1.15 | 1.50 | 1.30 |
| Rivers under ice cover. | 1.20 | 2.00 | 1.50 |
| River valley, over flooded. | 1.50 | 2.00 | 1.75 |

**Table 7.3.1: Kinetic Energy Correction factor, α, for a range of environments from Chow (1959).**

Bend resistance parameters were measured using a combination of total station data and tape measures in the field and compared with large-scale maps and Light Detection And Ranging (LiDAR) imagery for accuracy (see Figure 7.3.1 for a definition of the curvature of radius parameter). It was thought prudent not to rely on one source of information as there are issues with each method. It is difficult to identify the radius of curvature for large bends when on the ground due to trees and other floodplain vegetation. The large-scale maps may not have picked up recent erosion and deposition, and the nature of the forested environment caused problems when interpreting the LiDAR imagery.

With the bed and bend components of the reach scale resistance accounted for it was then possible to look at the large wood resistance.

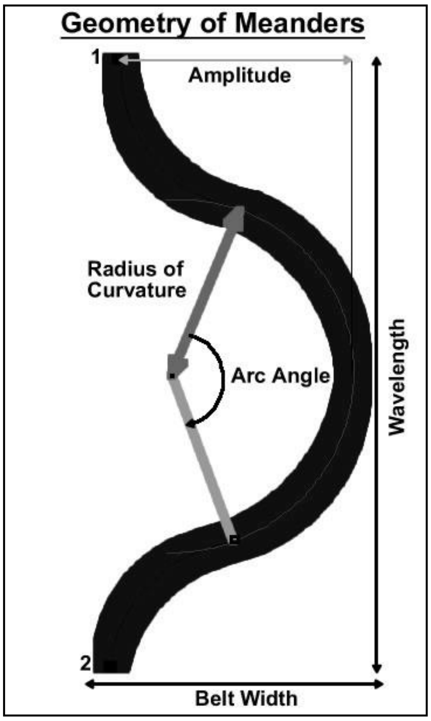



**Figure 7.3.1:- Meander Geometry Terms.**

## *7.4. Large Wood Resistance*

A methodology suggested by Gippel *et al.* (1992) was implemented to predict the resistance offered by the large wood within the reach using the drag coefficient approach specified in chapter 2.

To take into account the finite nature of the channel width and the impedance effect of the large wood it is necessary to calculate a blockage ratio from which a drag coefficient is approximated (Shields and Gippel, 1995). The first part is to calculate the flow facing area of the large wood, which is calculated by:-

$$A_i = l * d \tag{7.7}$$

$$A^{'} = A_i * Sin(\theta) \tag{7.8}$$

Which is then corrected for its angle of orientation by the following:-

Where θ is the orientation of the large wood accumulation to the flow direction. An angle of 90º is defined as parallel to the predominant flow direction. This is used to calculate a blockage ratio, which is a ratio of the frontal area of the wood to the reach-averaged channel cross-sectional area.

$$BR = \frac{A^{'}}{A} \qquad \textbf{(7.9)}$$

Shields and Gippel (1995) used the product of channel width and the hydraulic radius as a method of calculating area in the above expression but due to the nature of the data collected in the present study it was thought that area calculated directly would be more accurate.

The drag coefficient is a parameter that represents the drag of an object, in this case a piece of large wood represented by a cylinder, in a moving fluid. Shields and Gippel (1995) determined experimentally that the drag coefficient was a function of the blockage ratio see below:-

$$C_d = \frac{C_d^i}{a\left[1 - BR\right]^b} \qquad \textbf{(7.10)}$$

$C^i_d$ is a drag coefficient of a cylinder in flow of infinite extent (i.e., no boundary effects) and *a* and *b* are experimentally determined coefficients. Shields and Gippel (1995) found that $a$=0.997, $b$=2.06 and $C^i_d$ =0.6 from flume experiments thus giving the expression below for the drag coefficient for a given large wood accumulation:-

$$C_d = \frac{C_d^i}{0.997\left(1 - BR\right)^{2.06}} \qquad \textbf{(7.11)}$$

It should be noted that in the present study, the blockage ratios are likely to be much higher due to the quantity of large wood and the relatively small cross-sectional area of the channel. This presents a problem as equation (7.11) will be extrapolated outside the range over which it was originally developed. However, this approach has been applied in other field environments where the blockage ratios were higher (Curran and Wohl, 2003). The drag coefficient is relatively insensitive to the blockage ratio when the blockage ratio is less than 0.8 (see Figure 7.4.1).

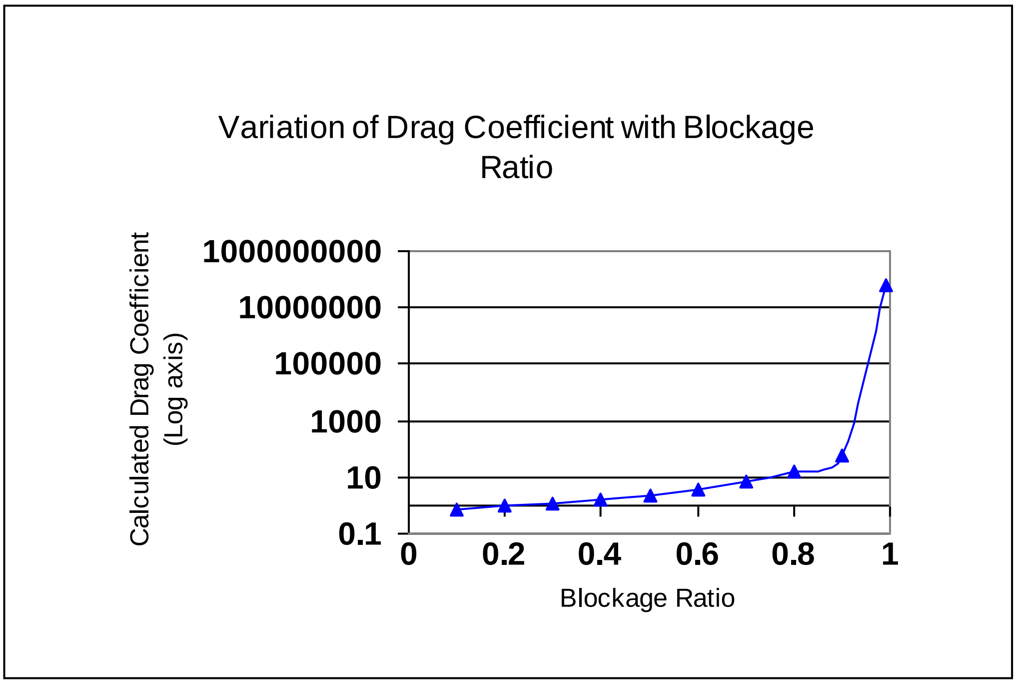



**Figure 7.4.1:-The variation of drag coefficient with blockage ratio for the function of Shields and Gippel (1995).**

The drag coefficient only changes significantly when the blockage ratio is greater than 0.8. In this scenario, the drag coefficient can tend to infinity. Shields and Gippel (1995) calculated the drag coefficient for all large wood pieces within their reaches, which were not densely choked with large wood. However, this can cause a problem in densely blocked reaches where the sum of all the frontal areas of large wood may be larger than the channel cross-sectional area, which means that the blockage ratio loses its true meaning. To overcome this problem, Curran and Wohl (2003) used an estimate of a constant blockage ratio of 0.6 and a subsequent drag coefficient of six for all large wood accumulations within their study reach. This approach is considered inappropriate and an over-simplification for the current study, as within the Highland Water there are a range of different types of large wood accumulations that have different blockage ratios. As a result, a visual estimate of blockage ratio was taken for each large wood accumulation from the upstream face using photos and field observations.

The drag coefficients are then multiplied by the blockage area for the large wood accumulation and then expressed as a ratio over the reach volume. This gives a measure of large wood density, $\chi$.

$$\chi = \frac{\sum_{i=1}^{n} Cd^i A^i}{BL} \tag{7.12}$$

It is then possible to estimate the resistance offered by the large wood accumulation according to the following equation:-

$$f_{lwd} = \frac{4}{\alpha} * \chi \tag{7.13}$$

This drag coefficient approach to assessing vegetative roughness does assume that the resistance is dominated by drag and is uniformly distributed along the reach. This does not take into account local flow accelerations and decelerations that are commonly associated with large wood accumulations (Abbe and Montgomery, 1996; Shields *et al.,* 2001; Daniels and Rhoads, 2003). The drag coefficient approach also treats large wood accumulations as solid objects rather than as a permeable structure of trunks, branches and leaf litter. Many large wood accumulations have a more complex architecture than the simple, single trunk debris described in other studies. However, it is still considered the best approach in quantifying the resistance offered by large wood (Kadlec, 1990; Shields and Gippel, 1995).

## *7.5. Field Data*

The data collected from the field was collated and the resistance was partitioned in order to gain an insight into the behaviour of different types of large wood accumulations. To do this, each large woody accumulation was classified according to the scheme published by Wallerstein *et al.* (1997). Figure 7.5.1 shows the measured resistance of each large woody accumulation plotted against slope for each classification. As can be seen there is a slight pattern to the resistance offered by each type of large wood accumulation with a general continuum from the low resistance offered by underflow accumulations (Average $f$=10.7), through the increased resistance offered by deflector accumulations (Average $f$=16.2) to the large resistance offered by overflow accumulations (Average $f$=230.7). These values may seem high although they are similar to those obtained by Beven *et al.* (1979) who found values of $f$ between one and 48, with an extreme value of 1328 for an upland river channel in the UK. The pattern displayed shows an increase in Darcy-Weisbach friction factor with increasing slope which is concurrent with the findings of Jarrett (1984) in mountain rivers without large wood. This relationship between resistance and slope is explained as the interrelation between channel slope and bed material particle size (Jarrett, 1984). As channel slope increases finer particles are removed and larger particles remain within the channel. This results in increased turbulence and resistance which increases the friction slope (Jarrett, 1984). In the case of the Highland Water, it is the presence of large wood which increases the friction slop rather than large particles.

This pattern gives an indication of the influence that each large wood accumulation type has upon the local flow hydraulics with underflow and deflector accumulations having a minor effect on retarding flows and with overflow accumulations blocking the channel leading to the ponding of flow and weiring of the flow over the accumulation. However, despite a general trend being present there is some scatter within the data that hints at the variability and uncertainty inherent in measuring field environments and large wood hydraulics in particular.

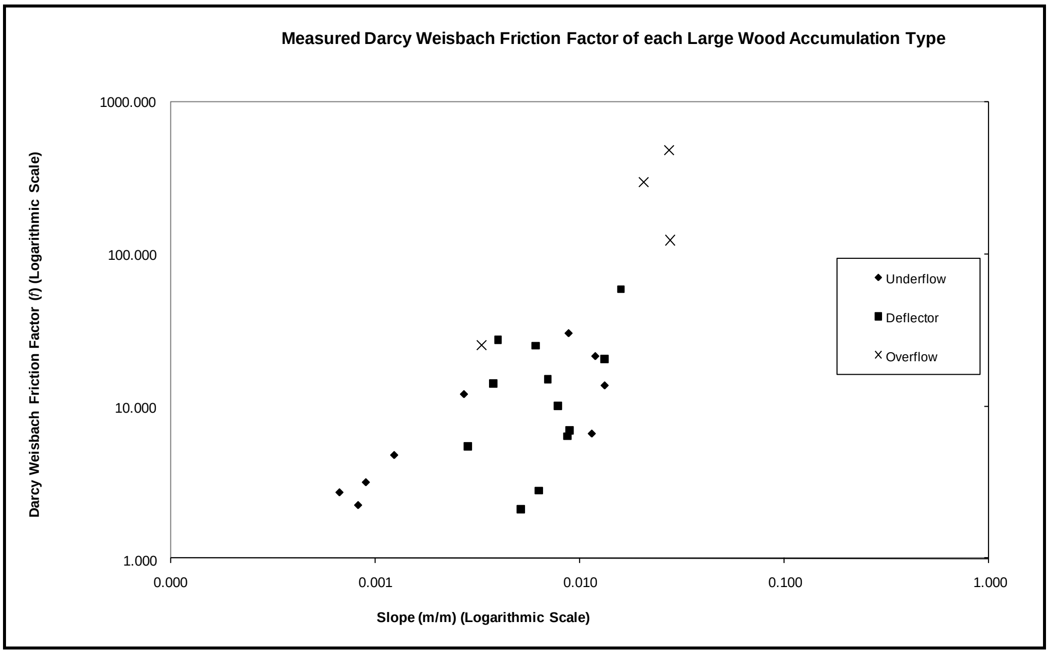



**Figure 7.5.1: The Measured Darcy Weisbach Friction Factor for Each Large Wood Accumulation Type.**

There are a number of factors that are difficult to control within the field environment with discharge being one of the most fundamental. Figure 7.5.2 shows the scatter which is present when plotting Darcy Weisbach friction factor against Discharge. The scatter gives little indication of any trend because there are other factors that cannot be isolated when in the field.

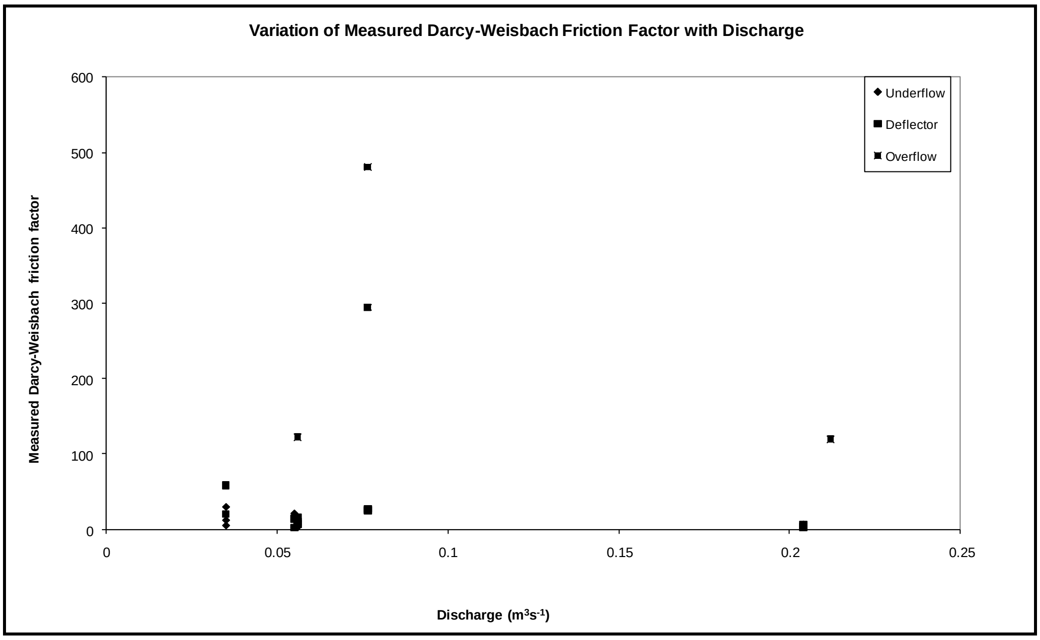



**Figure 7.5.2: Darcy-Weisbach Friction Factor versus Discharge for 4 different classifications of Large Wood Accumulation.**

For this reason, it is difficult to assess factors that may influence the resistance offered by large wood in isolation from other contributory factors. To eliminate some of the variables present within a natural environment it was decided to set up a flume experiment whereby certain variables could be controlled. This provided a framework within which to test the effect of different factors such as discharge, blockage ratio and the different types of large wood that are present within the Highland Water research catchment. The semi-natural woodlands are a source of deciduous large wood that usually enter the river channel with branches and an intact canopy whereas large wood from the conifer plantations was usually shorn of its branches and were single pieces of large wood.

## 7.6. Flume Scaling

In order to more precisely understand the factors contributing to large wood accumulation roughness a flume study was conducted in which roughness could be measured, with bed and bend resistance kept constant. Thus, the roughness contributed by large wood accumulations could be isolated.

The flume has one major advantage over field experiments; processes can be observed in a reduced time frame within a controlled laboratory environment (Peakall *et al.*, 1996). In most applications, the physical hydraulic model (usually a Flume) is usually smaller in size than that of the prototype channel. In order to allow comparison between the flume simulations and those conditions encountered in natural channels the flume dimensions are scaled to achieve geometric, kinematic and dynamic similarity which means that there is form, motion and force correspondence between the model and prototype (Yalin, 1971; Peakall *et al.*, 1996).

Geometric similarity implies that the ratios of prototype character lengths to model lengths are equal:

$$L_r = \frac{W_p}{W_m} = \frac{d_p}{d_m} \tag{7.14}$$

Where $L$ is the scale ratio, $W$ is the width, and $d$ the depth of the channel, subscripts $p$ and $m$ refer to the prototype and model parameters, respectively, and the subscript $r$ refers to the ratio of prototype to the model. When the flow patterns and velocity in the model are scaled proportionally to those in the prototype kinematic similarity is achieved:

$$V_r = \frac{V_p}{V_m} \tag{7.15}$$

Where $V$ is velocity.

Dynamic similarity is where the model forces are scaled proportionally to those in the prototype and thus:

$$F_r = \frac{F_1}{F_2} \tag{7.16}$$

Where $F$ is the force quantity used. The quantities $L_r$, $V_r$ and $F_r$ are the basic scale ratios from which several other scale ratios such as mass, time, discharge and pressure can be determined. In open channel flows such as those encountered in natural channels, the presence of a free surface means that the effects of gravity are important, thus the ratio of inertial forces to gravitational forces represented by the Froude number (equation 7.17) is significant (from Chanson, 1999).

$$Fr = \frac{V}{\sqrt{gd}} \tag{7.17}$$

Where $V$ is the velocity, $g$ is the gravity constant ($9.81 ms^{-2}$) and $d$ is the flow depth.

As it is impractical to alter the effect of gravity, the gravitational acceleration is assumed constant in both the model and the prototype, which allows the derivation of other secondary scale ratios such as:-

$$V_r = \sqrt{L_r} \tag{7.18}$$

$$Q_r = V_r L_r^2 = L_r^{5/2} \tag{7.19}$$

$$F_r = \frac{M_r L_r}{T_r^2} = \rho_r L_r^3 \tag{7.20}$$

Where:-

$$M_r = \rho L_r^3 \tag{7.21}$$

$$T_r = \frac{L_r}{V_r} = L_r^{1/2} \tag{7.22}$$

and $\rho$ is the fluid density.

Mass ($M_r$), length ($L_r$) and Time ($T_r$) scale ratios, based upon the unity of the Froude number between the model and prototype have now been defined which means that if the prototype is scaled using the above equations it is said to achieve Froude similitude.

One of the main concerns of Froude scaled hydraulic modelling is the effect of viscous forces. The Reynolds number is used to describe the ratio of viscous to inertial forces in a flow and the only way to take account of the viscous forces is to ensure that the Froude number and Reynolds number (*Re*, shown in equation 7.23) are the same in the model as the prototype.

$$\mathrm{Re} = \frac{\rho V R}{\mu} \tag{7.23}$$

where $\mu$ is the fluid viscosity and $\rho$ is the water density.

However, in reality it is impractical to vary the fluid viscosity to enable similarity of Reynolds numbers as the fluid used in both model and prototype is usually water. In order to overcome the problem of viscous forces the flow must be fully turbulent with the same relative roughness ($K_s$) as the prototype:

$$(k_s)_r = L_r \tag{7.24}$$

Several authors have given guidelines on the minimum Reynolds number required to overcome viscous effects with Allen (1947) stating 1400, Peakall *et al.* (1996), 500 and Chanson (1999) stating 5000 although it is accepted that turbulent flows in natural channels are associated with a Reynolds number of above 2500 (Knighton, 1998).

The Reynolds number is also important when considering the drag coefficient of any large wood. The drag coefficient for a cylinder is defined as:-

$$C_d = \frac{F_d}{\frac{1}{2} v^2 \rho A_d} \tag{7.25}$$

where $F_d$ is the drag force (N) and $A_d$ is the projected area of body facing the flow (m$^2$). The drag coefficient varies with increasing Reynolds number according to Figure 7.6.1 which was populated by experimental data from various authors.

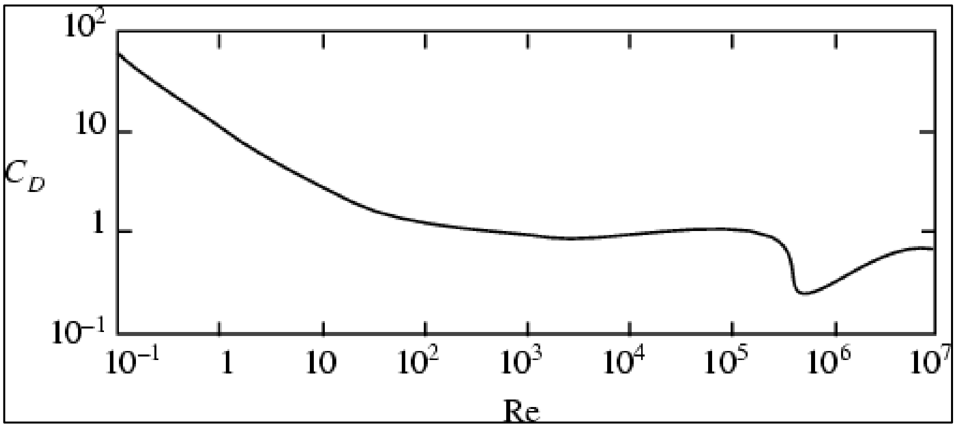



**Figure 7.6.1: Variation of drag coefficient with Reynolds number for circular cylinder (from Triton (1988))**

At low Reynolds numbers the drag coefficient decreases with increasing Reynolds number such that:-



**(7.26)**

$$C_d \propto \frac{1}{\mathrm{Re}}$$

which for a given body in a given fluid with fixed $d$, $\rho$ and $\mu$ corresponds to:-

$$D \propto V \qquad \textbf{(7.27)}$$

This direct proportionality of the drag to the approach velocity is a characteristic behaviour at low velocities (Tritton, 1988). At higher Reynolds numbers ($10^2$ to $3*10^5$) the drag coefficient varies little with the Reynolds number. However, there is a shift in the trend as, as Reynolds numbers reach approximately $3*10^5$, the drag coefficient drops by a factor of over 3. This occurs because the flow over the object changes from laminar to turbulent and as a result, the wake narrows. This leads to reduced momentum extraction from the flow and therefore results in less drag (Tritton, 1988). As a result, skin drag becomes less important and form drag is the important factor, which remains almost constant with increasing Reynolds number when flow is turbulent (Wallerstein, 1999). Therefore, as long as the flow is turbulent the problem of viscous forces can be overcome as the drag coefficient will be similar in the model and prototype even though the Reynolds number does not match.

## *7.7. Scaling the Highland Water*

The prototype is described in the field settings section of this chapter. In order to scale the model to fit the prototype characteristics the following routine from Chanson (1999) is used.

The preparatory stage is to acquire the relevant topographic and hydrological field data to describe the prototype dimensions and forces (see Table 7.7.1). Then the dominant effects (ie, viscosity, gravity or surface tension effects) need to be considered to select the appropriate scaling criterion. In the case of the Highland Water, gravitational forces are likely to be most important so Froude scaling is chosen, however viscous forces are likely to be present and need to be recognised.

In practice, most river models are scaled with a Froude similitude and as the liquid used in both model and prototype is the same (i.e., water) viscous forces are minimised by ensuring fully turbulent conditions (i.e., ensure a high Reynolds number). Once this has been established, then an iterative process is undertaken to select the relevant scales.

The first step is to select the smallest geometric scale ratio $L_r$ to fit within the constraints of the flume. As this study is looking at high flow events, it was decided that a channel width smaller than the flume constraints should be chosen to allow high flows and some overbank flow onto the floodplains.

| Variable | Value | Flume Constraint |
|---|---|---|
| **Width (*W*)** | 1.88m | 1.37 |
| **Depth (*d*)** | 0.73m | 0.61 |
| **Hydraulic Radius (*R*)** | 0.41m | N/A |
| **Slope (*S*)** | 0.0057m/m | 0-0.005m/m |
| **$84^{th}$ percentile of the Sediment ($D_{84}$)** | 65.32mm | 23mm |
| **$Q_{max}$** | N/A | $0.47m^3s^{-1}$ |

**Table 7.7.1: Highland Water Characteristics and Flume Constraints**

An arbitrary channel width of 0.8m was chosen to allow some floodplain on either side. This then gives:-

$$L_r = \frac{W_p}{W_m} = \frac{1.88}{0.8} = 2.35 \tag{7.28}$$

Using this ratio and equation (7.14) the depth of the model channel can be established as 0.31m

Secondly, for the chosen $L_r$ it needs to be checked whether the maximum model discharge is large enough to model the prototype flow conditions according to Froude scaling. Using equation (7.19) and the maximum discharge that can be achieved in the flume ($0.47m^3s^{-1}$) allows the maximum prototype event capable of being simulated is:-

$$\begin{aligned} Q_r &= L_r^{5/2} = 2.35^{5/2} = 8.4658 \\ 0.47*8.4658 &= 3.98m^3s^{-1} \end{aligned} \tag{7.29}$$

$3.98m^3s^{-1}$ is larger than any discharge events that have currently been observed and is larger than the bankfull discharge of a reach with large wood accumulations measured by Jeffries *et al.* (2003) of $0.55m^3s^{-1}$. Therefore, the model should be adequate to simulate all but the most extreme discharges that occur in the Highland Water.

Once it has been established that the model achieves geometric similarity and can simulate the range of prototype discharges then the next stage of the process is to determine whether the flow resistance scaling is achievable in the model. To do this one must first calculate the roughness coefficients for the prototype. As the model sediment, in this experiment, is practically constrained, it is possible to measure the roughness factor for the flume. The Darcy-Weisbach friction factor (*f*) was used as this is a non-dimensional factor and has a sound physical reasoning when applied to a model environment compared to other roughness coefficients (Hey, 1979; Sellin *et al.*, 2003).

The flow resistance within the model is limited to the sediment present within the flume which is fine gravel ($D_{84}$=0.02). Although the model flow resistance is not exactly the same as that of the prototype, the similarity should be enough to enable accurate flow patterns to be reproduced. The ratio of prototype flow resistance (*f*= 2.04, *n*=0.1043) to model flow resistance (*f*= 1.72, *n*=0.0845) is 1.18 and if the roughness is expressed in terms of Manning's *n* the ratio is 1.22 which is better than that of other published Froude scaled flume studies of large wood (Wallerstein *et al.*, 2001). It was therefore decided that, before the addition of large wood elements, the prototype and model flow resistance factors were appropriately similar and therefore no scaling of the roughness coefficients was required.

Once the flow resistance scaling has been achieved, then the model Reynolds number was checked for the test flow rate to ensure that if the prototype flow is turbulent. Using equation (7.23) and assuming a water density of 1000kgm$^{-3}$ (Knighton, 1998), a kinematic fluid viscosity of 0.0001 it is possible to calculate the Reynolds number for the bankfull discharge. Using the rearranged continuity equation:

$$V = \frac{Q}{A} \tag{7.30}$$

and assuming a bankfull discharge of 0.55 m$^3$s$^{-1}$ (Jeffries *et al.*, 2003) for the prototype and scaling the discharge for the model to 0.0649m$^3$s$^{-1}$, the Reynolds numbers are 164,360 and 45,832 for the prototype and model respectively. Although the difference between the two Reynolds numbers is quite large this is not that great a problem because, as long as the Reynolds number is larger than 2500 then the flow is considered fully turbulent (Knighton, 1998). Again, the ratio between the two numbers (111) is lower than that which has been used in the published literature (158 by Wallerstein *et al.*, 2001).

Now that the model has been Froude scaled to achieve similitude with the prototype, scaling of the large wood elements is necessary. To scale the large wood element, Froude number should be similar for the model and prototype. The large wood element Froude number ($Fr_e$) is given by the equation:-

$$Fr_e = \frac{V}{\sqrt{gd_{lwd}}} \tag{7.31}$$

where $V$ is the approach velocity, and $d_{lwd}$ is the large wood element's diameter (from Wallenstein *et al.*, 2001). The average diameter of large wood in the Highland Water is 0.3cm, which gives a Froude number of 0.233. In order to give a similar model Froude number a large wood element diameter of 0.12m is required.

The large wood element Reynolds number can also be calculated using the following equation:-

(7.32)

$$\mathrm{Re}_e = \frac{V\,d_{lwd}}{v}$$

where $v$ is the kinematic viscosity of water, which is the ratio:-

$$v = \frac{\mu}{\rho} \qquad \textbf{(7.33)}$$

and is approximately $1*10^{-6}$ at 20 ºC (Richards, 1982). Using equation (7.32) the large wood element Reynolds values are 120,000 and 34,047 for the prototype and model respectively. As has been discussed earlier, Reynolds similitude is difficult to achieve as the same fluid is used within both the model and the prototype. However, as the large wood element Reynolds number is shown to be in the turbulent region this is not considered an overriding issue. Table 7.7.2 shows the original prototype values for a number of hydraulic and hydrologic characteristics as well as the corresponding values for the model together with the scaling factors used.

Using the values shown in Table 7.7.2 ensures that the model is Froude scaled and therefore it is justifiable to scale up the model results to the prototype scale using the scaling ratios presented.

### Practical Issues with Froude Scaling

When creating the channel dimensions in the flume it was soon evident that the angle of repose of the gravel did not allow a rectangular channel cross-section that was first envisaged. The scaling assumed a rectangular channel cross section with a width of 0.8m and a depth of 0.31m. However, the gravel rested at an angle of 50º thus giving a trapezoidal channel. This, in turn, led to a reduction in the channel cross-section and other channel geometry descriptors. It was decided to keep the channel cross-section and other geometry descriptors constant and this was done by ensuring that the average width at a cross-section was 0.8m, this resulted in channel dimensions shown in figure 7.7.1. This set up was considered to be a more accurate representation of the prototype channel where bank angle is variable. As channel cross-sectional area, average depth and average width were not changed, there was no requirement for rescaling of the flume.

| Variable | Symbol (units) | Prototype | Model | Ratio |
|---|---|---|---|---|
| **Channel Width** | W (m) | 1.88 | 0.8 | 2.35 |
| **Flow depth** | D (m) | 0.73 | 0.31 | 2.35 |
| **Bed Slope** | S (m/m) | 0.0057 | 0.005 | 1.14 |
| **Bed angle** | θ (º) | 0.326 | 0.286 | 1.14 |
| **Cross-sectional area** | A ($m^2$) | 1.3724 | 0.248 | 5.53 |
| **Wetted perimeter** | P (m) | 3.34 | 1.42 | 2.35 |
| **Hydraulic radius** | R (m) | 0.4109 | 0.175 | 2.35 |
| **Bankfull discharge** | $Q_b$ ($m^3s^{-1}$) | 0.55 (from Jefferies *et al.*, 2003) | 0.0649 | 8.47 |
| **Derived mean flow velocity at $Q_b$** | V ($ms^{-1}$) | 0.4 | 0.2619 | 1.53 |
| **Representative grain size** | $D_{84}$ (m) | 0.065 | 0.02 | 3.25 |
| **Cross-sectional shape factor** | A | 13.295 | 13.28 | 1 |
| **Manning's *n*** | *N* | 0.1043 | 0.0845 | 1.23 |
| **Darcy-Weisbach friction factor** | *f* | 2.04 | 1.72 | 1.18 |
| **Flow Froude number** | Fr | 0.15 | 0.15 | 1 |
| **Flow Reynolds number** | Re | 164,360 | 45,832 | 3.59 |
| **Large wood diameter** | $d_{lwd}$ (m) | 0.3 | 0.12 | 2.31 |
| **Large wood Froude number** | $Fr_e$ | 0.233 | 0.233 | 1 |
| **Large wood Reynolds number** | $Re_e$ | 120,000 | 34,047 | 3.52 |

**Table 7.7.2:- Prototype and model variables and dimensions.**

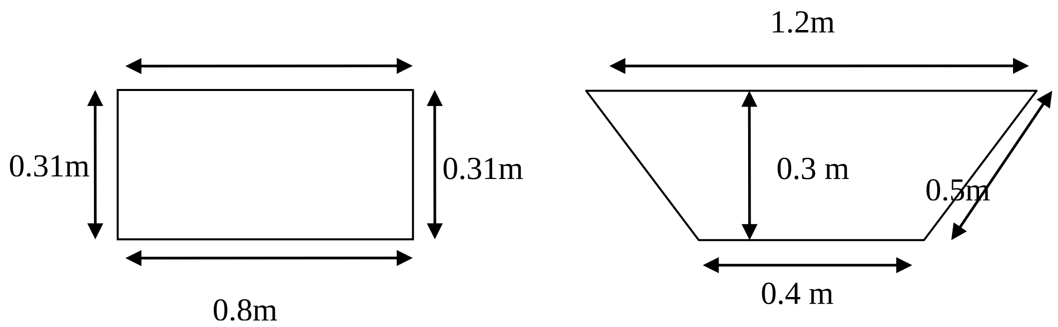



**Figure 7.7.1:-The scaled model channel cross-section and actual model channel cross-section**

## *7.8. Flume Methodology*

Once the channel had been formed in the flume, flow was pumped through using electronically driven centrifugal pumps and the tailgate set to ensure a normal depth condition downstream of the large wood accumulation which assumes that the slope balances with friction forces to create a non-varying depth. The discharge was set at $0.045m^3s^{-1}$ and was left to run until the channel morphology and flow depths were stable. Once the channel and flow depth were stable, a few tests were conducted to assess whether the scaling ratios had correctly reproduced the prototype conditions. Firstly, discharge was increased steadily until it reached bankfull flow conditions. This was achieved at a discharge of $0.065m^3s^{-1}$ which was similar to the value that had been scaled ($0.0649m^3s^{-1}$). Using the mean velocity, derived from dilution gauging ($0.273ms^{-1}$), and the geometric properties of the flume channel it was possible to calculate the roughness coefficient. Manning's *n* and Darcy-Weisbach friction factor, *f*, were both calculated and were found to be 0.080 and 1.58 respectively. The value for the Manning's roughness coefficient closely mirrored that which was present in the prototype although a little lower than was previously predicted by the scaling. The Darcy-Weisbach friction factor was also a little lower than that which was expected from the Froude similitude with a residual of 8.14% of the predicted value. This may be due to errors with the dilution gauging techniques, which have been found to have an uncertainty of around 5% (Whiting, 2003).

Once the flume channel was constructed to scale with the prototype, the large wood resistance experiment could take place. The experimental design was to assess the effect of large wood with and without fine wood (smaller than 0.1m diameter) and various volumes of large wood. Figure 7.8.1 shows an example of a large wood accumulation within the flume. One, two and three pieces of large wood were used to assess the effect of varying large wood loadings. Due to instability of the channel bed sediment, only underflow accumulations were assessed as due to the nature of the flume material, deflector and overflow accumulations produced sufficient scour around the large wood accumulation to cause the accumulation to blow out. Each large wood accumulation configuration was measured at a range of discharges, 15, 30, 45 and 60$ls^{-1}$ (0.015, 0.03, 0.045 and 0.06$m^3s^{-1}$ and equivalent to prototype discharges of 0.12$m^3s^{-1}$, 0.25$m^3s^{-1}$, 0.38$m^3s^{-1}$ and 0.51$m^3s^{-1}$). The experimental matrix is summarised in Figure 7.8.2.

**Figure 7.8.1: Large Wood Accumulation in a flume environment. The arrow shows the direction of flow.**

| | | | Without Fine Wood | | | With Fine Wood | | |
|---|---|---|---|---|---|---|---|---|
| **\|Model Discharge** | **Equivalent Prototype Discharge** | **No LW** | **1 Piece of LW** | **2 Pieces of LW** | **3 Pieces of LW** | **1 Piece of LW** | **2 Pieces of LW** | **3 Pieces of LW** |
| **$0.015m^3s^{-1}$** | **$0.12m^3s^{-1}$** | X | X | X | X | X | X | X |
| **$0.03m^3s^{-1}$** | **$0.25m^3s^{-1}$** | X | X | X | X | X | X | X |
| **$0.045m^3s^{-1}$** | **$0.38m^3s^{-1}$** | X | X | X | X | X | X | X |
| **$0.06m^3s^{-1}$** | **$0.51m^3s^{-1}$** | X | X | X | X | X | X | X |

**Figure 7.8.2: The Flume Experimental Matrix**

A range of discharges were used to assess the effect of discharge upon large wood resistance ranging from low flow conditions to bankfull flow. This meant that there were sixteen runs with large wood and four runs at each of the discharges with no large wood, as a control. Each run was set up and left to run for about an hour to allow channel morphology to stabilise. Once the flume material had settled, two dilution-gauging measurements were taken to establish mean velocity. Water surface slope, upstream of the large wood accumulation, and channel dimensions were measured using a total station in order to determine the Darcy-Weisbach friction factor.

## *7.9. Flume Results*

The flume environment allowed the controlled measurement of the effect of certain factors on the reach-scaled resistance and the three investigated in this study were discharge, blockage area and type of wood within an accumulation. Discharge is an external factor, which varies in the field, but as was seen in the previous chapter is a controlling influence of the inundation of the floodplain. How the resistance offered by large wood varies through a range of discharges is important in the understanding of how large wood influences floodplain inundation. The latter two controlling factors can be varied as part of any restoration measures and therefore it is important to understand their role in influencing the reach scale resistance to provide recommendations for restoration practitioners.

## Effect of Discharge upon Reach Scale Large Wood Resistance

Perhaps the most fundamental parameter that can be controlled in the flume environment, which varies in semi-natural river systems, is the discharge of flow entering a reach. By controlling the discharge, the relationship between resistance and discharge can be explored for a number of large wood accumulations.

Discharge was varied systematically for each large wood accumulation set-up from 0.015 $m^3s^{-1}$, which represented a low to medium flow condition up to 0.060 $m^3s^{-1}$, which represented a bankfull condition. Measurements were also taken at discharges of 0.045 $m^3s^{-1}$ and 0.030 $m^3s^{-1}$. Figure 7.9.1 shows the variation of Darcy-Weisbach friction factor *f* with Discharge for a plain channel and three different large wood scenarios. The plain channel resistance is purely a function of the channel sediment. The large wood accumulation in each was an underflow accumulation from the classification of Wallerstein *et al.* (1997). The general trend in figure 7.9.1 is a reduction in the resistance with an increase in the discharge and this is similar to that observed in the field (eg. Shields and Smith, 1992). This is because the increasing flow and the related increase in flow depth effectively drown out the resistance as the relative submergence of the large wood piece increases.

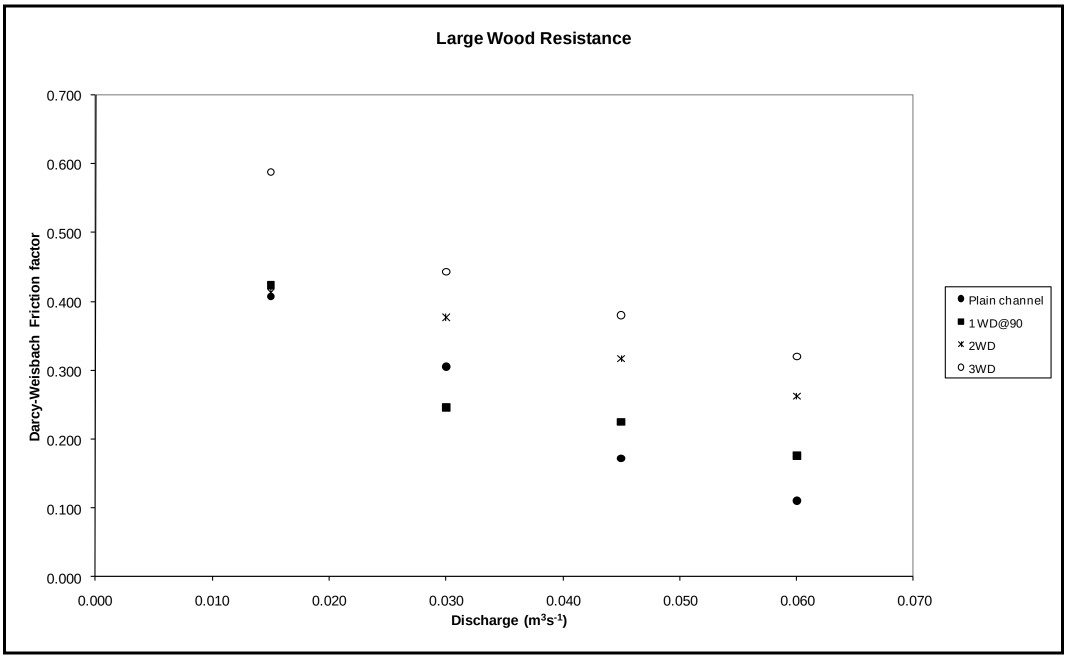



**Figure 7.9.1: Effect of Discharge on Reach Resistance (the prototype resistance is 1.18 times the model resistance shown in the figure).**

In terms of hydraulics, it is known that when the flow depth exceeds the bed material size by a factor of 10 then the vertical velocity profile is approximated by the logarithmic distance from the bed (Bathurst, 1997). That is, flow closer to the bed is more disturbed with velocity being more retarded than flow that is further from the bed (eg. the law of the wall see Wilcock, 1996). A similar pattern is likely to occur with large wood where the velocity is disturbed in the near vicinity of the large wood but is less disturbed further from the obstruction. With an increasing discharge and a subsequent increase in velocity, the influence of the roughness element decreases. Thus, there is a clear downward trend for all large wood accumulations with an increasing discharge. This is despite the fact that with an increase in stage the amount of wood in contact with the flow may increase (increased blockage area) which may influence the blockage ratio such as may occur in the case of an underflow accumulation. The trend is complicated by the presence of large wood that does not come into contact with the flow for the $0.015m^3s^{-1}$ scenario only. The model scenario with three key pieces of large wood within the accumulation is in contact at the lowest discharge. This means that the

0.015m$^3$s$^{-1}$ data points, with the exception of the 3 pieces of large wood scenario, are fairly closely clustered as they all represent a simple channel with no large wood.

To test the performance of the approach commonly used to predict flow resistance in reaches where large wood is present, the predicted flow resistance was compared with the measured flow resistance. On plotting the predicted total resistance (from equation 7.3) against the measured resistance, it became apparent that there was a general under-prediction of the resistance at all discharges. Figure 7.9.2 shows the plot of the measured versus the predicted resistance.

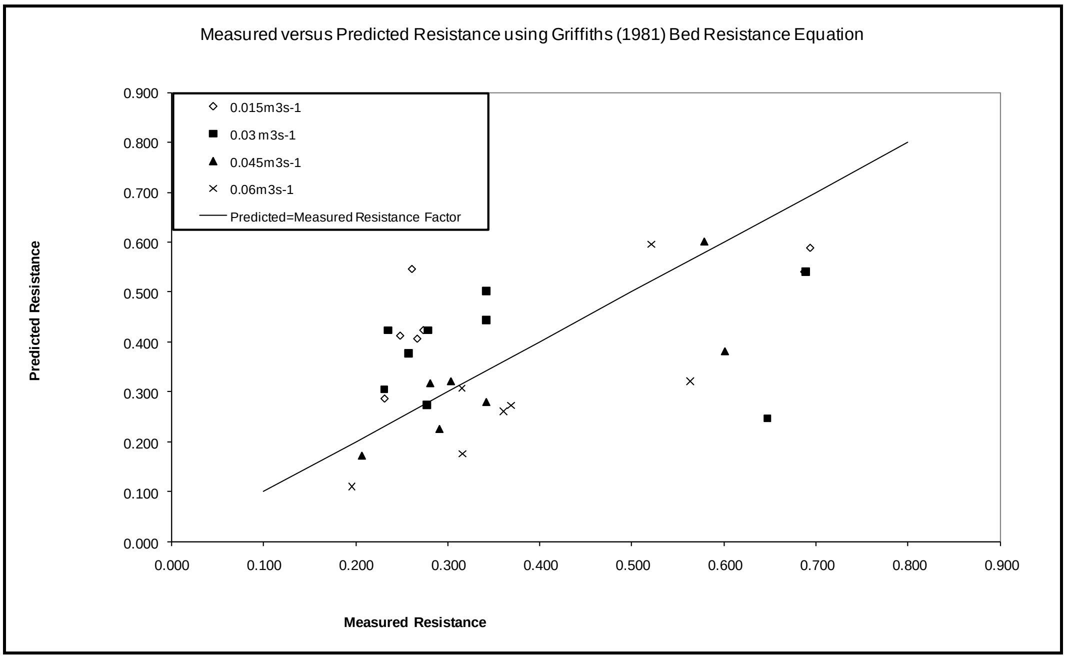



**Figure 7.9.2: Measured Darcy-Weisbach Friction Factor versus Predicted Resistance.**

As can be seen there is some scatter of the data around the Measured=Predicted trend line with the majority of the predicted resistance under predicting the measured resistance by an average of 0.127 which expressed as a percentage is 32.3%. Table 7.9.1 shows this split by the measured discharge. From this, it can be seen that there is some under-prediction of the 0.015m$^3$s$^{-1}$ scenario where, as mentioned above, there was no wood influencing the resistance as it was not in contact with the flow. As the flume channel was straight and there were no bedforms or bank vegetation then the reach resistance is purely a function of bed resistance.

| **Discharge** | **Average Absolute Error** | **Average Absolute Percentage Error** | **Maximum Error** | **Root Mean Squared Error** |
|---|---|---|---|---|
| $0.015m^3s^{-1}$ | 0.217 | 46.1 | 0.543 | 0.286 |
| $0.03m^3s^{-1}$ | 0.148 | 38.6 | 0.316 | 0.328 |
| $0.045m^3s^{-1}$ | 0.066 | 19.4 | 0.164 | 0.182 |
| $0.06m^3s^{-1}$ | 0.076 | 25.1 | 0.19 | 0.133 |

**Table 7.9.1: The Differences between Observed and Predicted Resistance split by Discharge.**

Marriott (1996) suggested that the bed resistance equation may have been the source of residuals in the data of Shields and Gippel (1995) which Shields and Gippel (1996) concurred was likely the choice of bed resistance formula that resulted in low values of bed resistance. Church *et al.* (1990) found that site-specific characteristics are major factors in the differing performance of particle resistance formulas and as such different bed resistance equations are valid at different sites.

As bed resistance equations were a possible source of uncertainty it was decided that a number of bed resistance equations would be used to calculate bed resistance in order to determine that which was most appropriate. Two commonly used particle resistance equations for gravel-bed rivers, that of Hey (1979) and Bray (1979), shown below, were therefore used, as well as the Griffiths (1981) equation, to estimate the bed resistance in the bed-only flume runs:-

Hey 1979
$$\frac{1}{\sqrt{f}} = 2.03 Log\left(\frac{a_{shape}R}{3.5D_{84}}\right) \qquad \textbf{(7.34)}$$

Bray, 1979
$$\frac{1}{\sqrt{f}} = 1.26 + 2.16 Log_{10}\left(\frac{d}{D_{90}}\right) \qquad \textbf{(7.35)}$$

Where $D_{84}$ and $D_{90}$ are the 84th and 90th percentile of the sediment grain size distribution (0.023m and 0.028m) respectively and $a_{shape}$ is a shape factor given by:-

$$a_{shape} = 11.1\left(\frac{R}{d_m}\right)^{-0.314} \tag{7.36}$$

Figure 7.9.3 shows the predicted Darcy-Weisbach friction factor plotted against the measured resistance factor for those flume runs where there was no large wood presence or the large wood was not influencing the flow (ie, Blockage area is equal to 0 and measured resistance is considered equal to bed resistance).

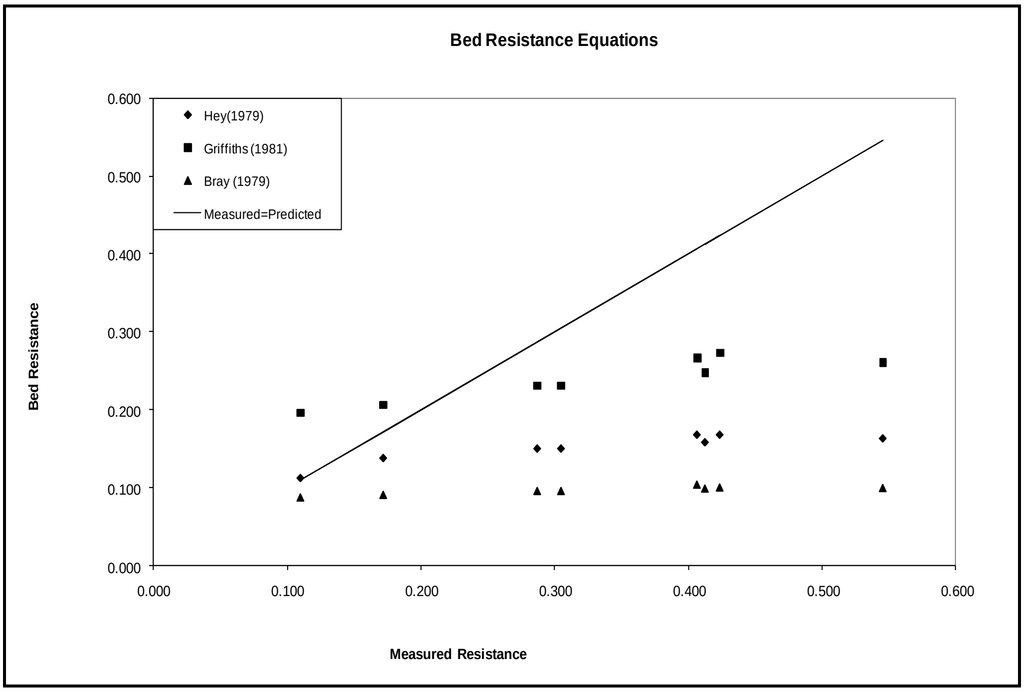



**Figure 7.9.3: Comparison of the different bed resistance equations used to predict resistance in the flume runs with no large wood present.**

As can be seen from Figure 7.9.3, the equation provided by Griffiths (1981) provided the best fit with the predicted equals measured line of the bed resistance equations used although the particle resistance equation was still under-estimating the particle resistance (by almost 50% in some cases). This must be considered in the following sections especially as this may lead to the over-prediction of the residual between measured and predicted total resistance which is assigned to immeasurable components or spill resistance.

Despite the relatively large residuals, the Griffith (1981) particle resistance equation was used for the large wood scenarios as it provides a better fit with measured resistance than the other equations assessed. Shields and Gippel, (1995) also used the equation of Griffiths (1981) as they found that it better represented the gravel bed channels in their study sites. They used the Brownlie (1983) equation for the sand-bed channels in their range of study sites.

### Influence of Large Wood Density and Blockage Area on Reach Scale Resistance

As identified in the previous chapter, large wood loadings can vary from catchment to catchment or within a catchment. Therefore, it is imperative to gain an understanding of the role that wood volume plays in influencing large wood resistance.

To simulate the different wood loadings within a reach the flume was run with a number of different configurations with one, two and three key pieces of large wood within a single large wood accumulation. Figure 7.9.4 shows the Darcy-Weisbach friction factor for a number of discharges ($0.015 m^3 s^{-1}$, $0.03 m^3 s^{-1}$, $0.045 m^3 s^{-1}$ and $0.06 m^3 s^{-1}$) for flume runs with no wood, one, two and three key pieces of wood. The resistance factor increases with an increase in the number of pieces of wood for a given discharge. The number of pieces of large wood can be used as a proxy for wood volume so in general the amount of wood present within a reach is influential in the resistance present within a reach. However, the number of key pieces is a simple quantification and does not portray the actual loadings present, as some of the key pieces could be larger than others. The submerged wood volume was thus calculated for each run, converted to a large wood density and plotted against the reach scale resistance (see Figure 7.9.4). In general, there is an upward trend in measured resistance with an increase in the large wood density as expected. This is because there are more roughness elements within a reach that act to retard the flow.

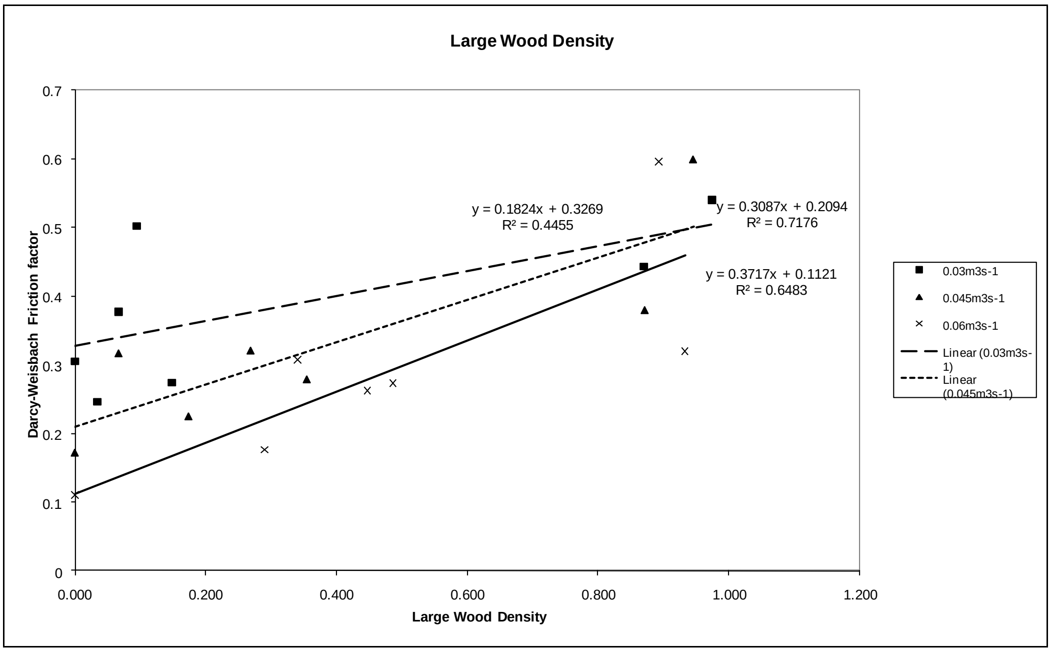



**Figure 7.9.4: Effect of Large Wood Density versus Darcy-Weisbach Friction Factor**

Wood volume is a term commonly used when describing the geomorphological effect of large wood and is generally reported to be a good indicator of wood loading within a reach (Gregory *et al.*, 1993; Erskine and Webb, 2003). However, the hydraulic effect is likely to be different. Gippel *et al.* (1996) found that multiple large wood elements interacted to induce wakes and turbulence structures which reduced drag and hence resistance. They found that when using two cylinders the drag of the two cylinders is lower than would be expected if there was one isolated cylinder. This is because the front cylinder causes a wake, which creates increased turbulence in the boundary layer of the rear cylinder and the rear cylinder acts to reduce vortex formation (Gippel *et al.*, 1996). This produces the counter-intuitive scenario whereby the combined drag of two cylinders is less than that of a single isolated cylinder up to a separation distance of up to two diameters of the large wood element. As the spacing increases the drag approaches that expected from isolated cylinders with the effect insignificant when the spacing was greater than 6-9 diameters (Young, 1991). In the flume, the average large wood diameter was 0.12m and in the field 0.3m. Therefore, in most cases the large wood accumulation size was in the region of 4-8 diameters. This means that the drag coefficient is commensurate with that which would be expected of the front cylinder. Therefore, it is appropriate to use a blockage ratio to calculate the drag coefficient as any large wood behind the frontal blockage area does not impact upon the drag coefficient.

The blockage ratio of each configuration was estimated using the flow cross-sectional area and the blockage area of the submerged wood. The blockage ratio thus represents the two-dimensional blockage represented by each large wood accumulation to the general direction of the flow. Figure 7.9.5 shows the blockage ratio as plotted against the measured Darcy-Weisbach friction factor for the $0.03m^3s^{-1}$, $0.045m^3s^{-1}$ and $0.06m^3s^{-1}$ scenarios.

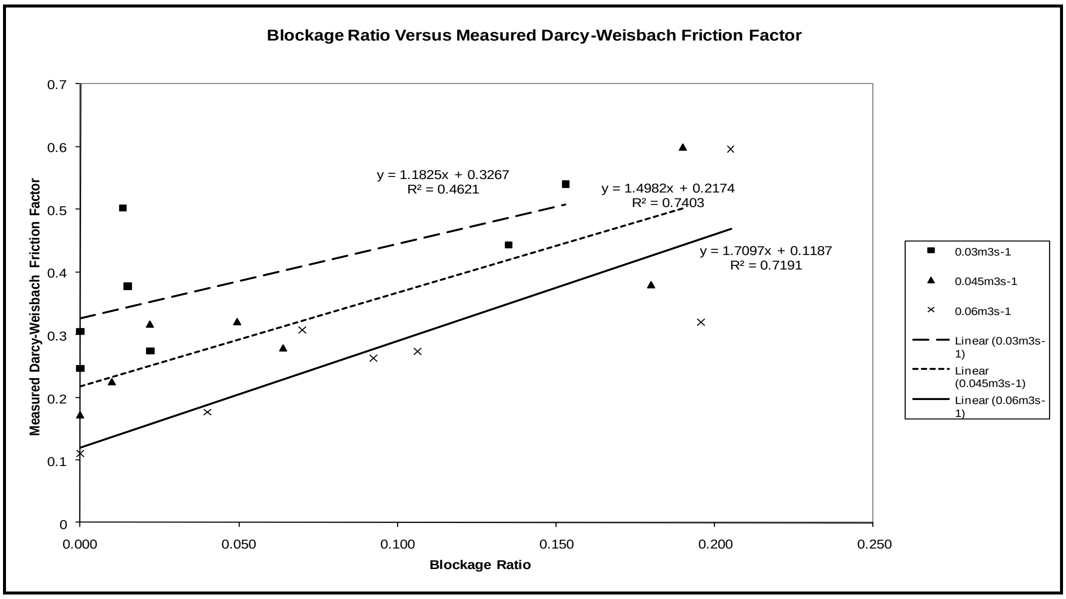



**Figure 7.9.5: Effect of Blockage Ratio versus Darcy-Weisbach Friction Factor.**

It can be seen that with an increase with blockage ratio there is an associated increase in the Darcy-Weisbach friction factor. This is expected and is a critical component in the estimation of predicted resistance. Therefore, those large wood accumulations that block more of the channel (such as overflow accumulations), will have a higher resistance and more of an impact upon channel hydraulics than those accumulations, which partially block the channel (underflow and deflector accumulations). This is important in the functioning of the large wood accumulations and the role they have in initiating floodplain inundation. It will also be important in a restoration context because although overflow accumulations impact influence channel hydraulics the most, the complete blockage of the channel to achieve these goals may be undesirable especially for sediment transport and the migration of fish species.

## Source of Large Wood

The flume was run for two other scenarios to account for the different input of large wood to the channel within the study catchment:-

1) Single Large Wood piece to simulate wood sourced from conifer plantations within the study catchment,
2) Branched large wood to simulate deciduous large wood input from natural riparian forests areas within the study catchment.

Figure 7.9.6 shows the data for this experiment which shows that for a given discharge the roughness contributed by an accumulation with fine wood present is likely to be larger than that with one without. The figure shows that there is more scatter in the resistance provided by large wood accumulations with fine wood. This is summarised in Table 7.9.2 which shows the standard deviation for the different discharges. On average the standard deviation for the 'with fine wood' scenario is double that of that 'without fine wood'. This suggests that the presence of fine wood, leads to a more complex interaction with flow resistance due to the small-scale interference it has upon the flow structures.

Table 7.9.3 summarises the measured reach scale Darcy Weisbach resistance for the 2 scenarios, for the four discharges ($0.015m^3s^{-1}$, $0.03m^3s^{-1}$, $0.045m^3s^{-1}$ and $0.06\ m^3s^{-1}$). This shows that the presence of fine wood can increase the Darcy-Weisbach measured resistance by up to 1.463 (for 2 pieces of large wood and a discharge of $0.15m^3s^{-1}$). For a single key piece, two and three key pieces of large wood the presence of fine wood, when averaged over the sample discharges, can increase measured resistance values by 46%, 26% and 30% respectively with an average impact of 34%. This can have important implications for the use of large wood accumulations as a restoration tool because often sawn logs are used which have been shorn of their branches and associated fine wood.

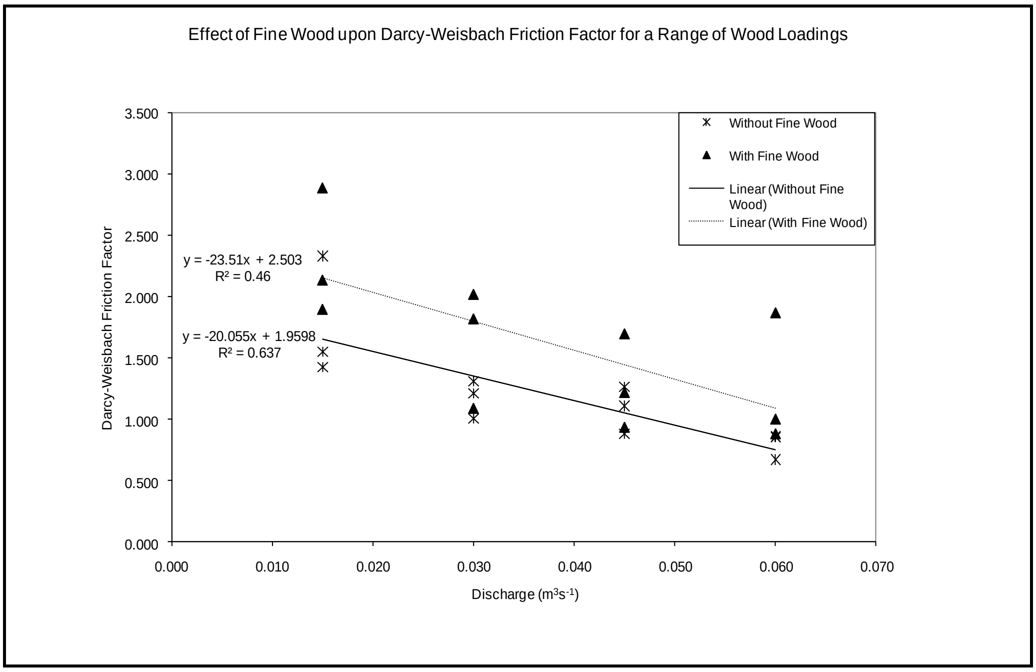



**Figure 7.9.6: Darcy-Weisbach Friction Factor for a range of discharges for a with fine wood and without fine wood scenario**

| **Discharge** | **0.15m$^3$s$^{-1}$** | **0.3m$^3$s$^{-1}$** | **0.45m$^3$s$^{-1}$** | **0.6m$^3$s$^{-1}$** | **Average** |
|---|---|---|---|---|---|
| **Without Fine Wood** | 0.49 | 0.16 | 0.19 | 0.11 | 0.24 |
| **With Fine Wood** | 0.52 | 0.49 | 0.39 | 0.54 | 0.48 |

**Table 7.9.2: Standard Deviation of the Resistance versus Resistance for the 'with fine wood' and 'without fine wood' scenarios.**

This result concurs with the results of Manners *et al.*, (2007) who found that velocity increased by up to 23% through a large wood accumulation once fine wood was removed leaving the key pieces. An increase in velocity is symptomatic of a reduction in roughness. Manners *et al*. (2007) found that this increase in velocity was related to the increase in porosity and therefore the type of wood can be loosely related to the blockage ratio.

| Number of Key Pieces of Large Wood | Discharge ($m^3s^{-1}$) | Without Fine Wood | With Fine Wood | Difference (%) |
|---|---|---|---|---|
| **1** | **0.15** | 2.334 | 2.136 | 0.198 |
| | **0.3** | 1.005 | 2.019 | 1.014 |
| | **0.45** | 0.886 | 1.219 | 0.333 |
| | **0.6** | 0.674 | 1.002 | 0.328 |
| | **Average** | 1.225 | 1.594 | 0.370 (30%) |
| **2** | **0.15** | 1.425 | 2.888 | 1.463 |
| | **0.3** | 1.214 | 1.090 | 0.125 |
| | **0.45** | 1.112 | 0.935 | 0.177 |
| | **0.6** | 0.854 | 0.882 | 0.028 |
| | **Average** | 1.151 | 1.449 | 0.298 (26%) |
| **3** | **0.15** | 1.550 | 1.897 | 0.348 |
| | **0.3** | 1.311 | 1.819 | 0.509 |
| | **0.45** | 1.267 | 1.698 | 0.430 |
| | **0.6** | 0.862 | 1.869 | 1.008 |
| | **Average** | 1.247 | 1.821 | 0.574 (46%) |

**Table 7.9.3: The Measured Darcy-Weisbach Friction Factor for the 'with fine wood' and 'without fine wood' scenarios for a number of different discharges.**

What was observed in the field was that large wood that entered the channel with canopies intact was better at retaining transported wood elements (see the Semi-Natural Control Site of Millington and Sear, 2007). This enabled the accumulation of wood, which reduced porosity and improved the hydraulic performance of the large wood accumulation. Therefore, this has to be considered when introducing large wood for the purpose of river restoration.

## *7.10. Flume Summary*

A Froude scaled flume experiment was conducted initially as a pilot project to ascertain key factors which influenced the resistance offered by a number of large wood accumulations of different architecture. Three main factors were assessed, discharge, wood volume (and subsequently blockage area) and large wood source. All three were found to be significant in affecting the resistance offered and therefore it is important they are considered when using large wood as a restoration tool. The flume experiments also provide further data on large wood resistance that can be added to that obtained in the Highland Water catchment and compared in the next section with those in the academic literature to further improve our understanding of the role of different large wood accumulations in influencing resistance in a range of environments.

## *7.11. Comparison with other Published data*

Data collected for the present study was compared with data in the literature for the Obion River, a sand-bed channel in a tributary of the Mississippi River in western Tennessee, the Tumult river, a gravel-bed tributary of the Murrumbidgee River in New South Wales, Australia from Shields and Gippel (1995) and seven boulder bed step-pool channels in the Cascade Range, Washington (Curran and Wohl, 2003). Table 7.11.1 shows characteristics of these different channels with Figure 7.11.1 showing the measured resistance at each site. Figure 7.11.1 suggests that there is a continuum of points from the low-gradient streams of Shields and Gippel (1995) with relatively low resistance to the high-gradient channels of Curran and Wohl (2003) with larger resistance coefficients, albeit with some variability. This is reflected in the dominant type of large wood accumulation with deflector accumulations being common in the low gradient streams of Shields and Gippel (1995) and the accumulations present in the field sites of Curran and Wohl (2003) being associated with significant steps in the water surface profile and are thus classified as overflow accumulations. The data from the Highland Water and the flume experiment fit between these two other environments with a range of large wood accumulation type covering underflow, deflector and overflow accumulations. This shows the value of the data collected and collated in this study in providing further data on large wood resistance in an environment where data was previously lacking.

| | **Drainage area ($km^2$)** | **Slope (m/m)** | **Average Channel width (m)** | **D50 (m)** | **Hydraulic radius** | **Dominant Large Wood Accumulation Type** |
|---|---|---|---|---|---|---|
| Obion River (Shields and Gippel, 1995) | 927 | 0.0006 | 17.62 | 0.0044 | Not Specified | Deflector |
| Tumult River (Shields and Gippel, 1995) | Not specified | 0.001 | 38 | 0.022 | 2.85 | Deflector |
| Coweeman River (Curran and Wohl, 2003) | 0.635 | 0.115 | 2.05 | 0.0345 | 0.0935 | Overflow |
| Deschutes River (Curran and Wohl, 2003) | 2.2 | 0.093 | 4.8 | 0.087 | 0.18 | Overflow |
| Puyallup River (Curran and Wohl, 2003) | 0.943 | 0.114 | 3.16 | 0.0598 | 0.116 | Overflow |
| White River (Curran and Wohl, 2003) | 1.2 | 0.15 | 2.8 | 0.073 | 0.1 | Overflow |
| Cle Elum River (Curran and Wohl, 2003) | 1.74 | 0.0865 | 3.225 | 0.084 | 0.0915 | Overflow |
| Taneum River (Curran and Wohl, 2003) | 2.95 | 0.145 | 2.5 | 0.038 | 0.0605 | Overflow |
| North For Ahtanum Creek (Curran and Wohl, 2003) | 5.625 | 0.114 | 3.375 | 0.07 | 0.124 | Overflow |
| Highland Water | 11.2. | 0.0057 | 1.88 | 0.065 | 0.4109 | Deflector |
| Flume | N/A | 0.005 | 0.8 | 0.02 | 0.175 | Underflow |

**Table 7.11.1: Channel characteristics from which the large wood data was obtained.**

The measured resistance provided by large wood can increase 100 fold between low gradient channels ($s$<0.005) and higher gradient ($s$>0.1). This is a similar finding to that of Jarrett (1984) who found that particle resistance in mountain river channels was strongly influenced by channel slope. This means that the ability of large wood to influence the reach scale resistance will vary depending on the environment that it is present.

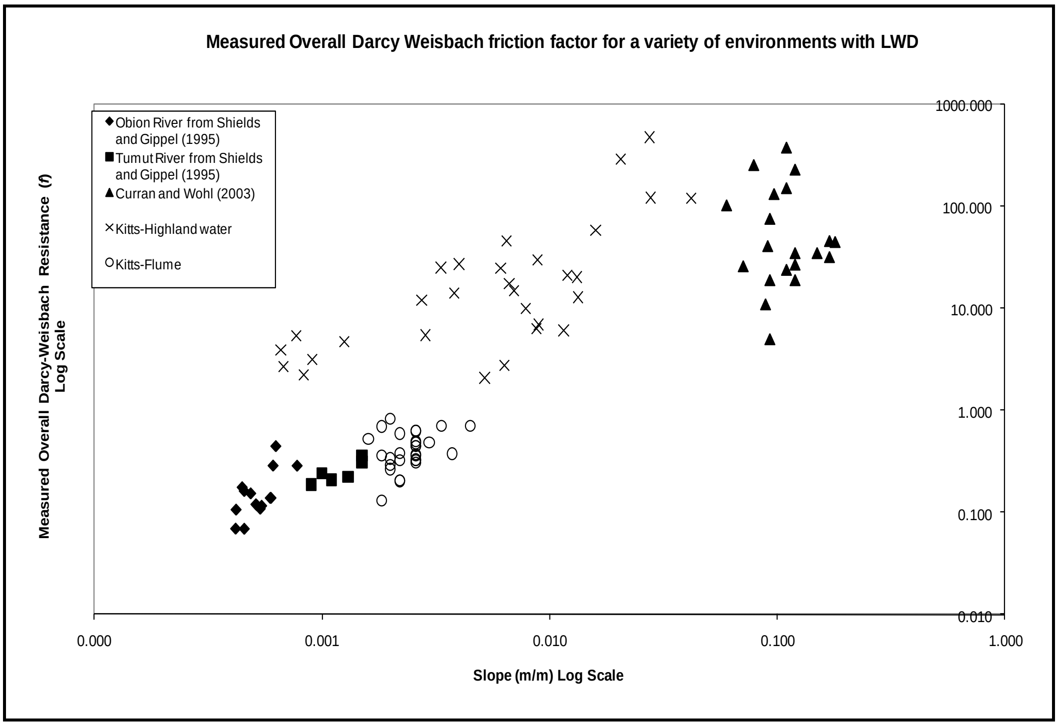



**Figure 7.11.1: Measured Overall Darcy-Weisbach Friction Factor for large wood reaches in a number of different environments**

Restoration using large wood is possible in most riverine environments and has been used for various purposes such as bank erosion prevention (Shields *et al.*, 2004) and ecological reasons (Lehane *et al.*, 2002). However, the role that large wood plays in influencing the reach scale hydraulics is strongly influenced by slope and this should be an important consideration in considering the environments where large wood is likely to have a significant impact upon channel hydraulics.

By adding in the resistance due to bed material and head loss at bends to the large wood resistance it is possible to come up with a predicted total resistance. The same trend is shown in the predicted resistance contributed by large wood shown in Figure 7.11.2 which shows that slope is an important factor in the absolute resistance offered by large wood. Figure 7.11.3 shows the difference between the measured and predicted resistance. It is apparent that there are some large differences between the predicted and measured resistance and that the differences again generally increase with an increasing slope.

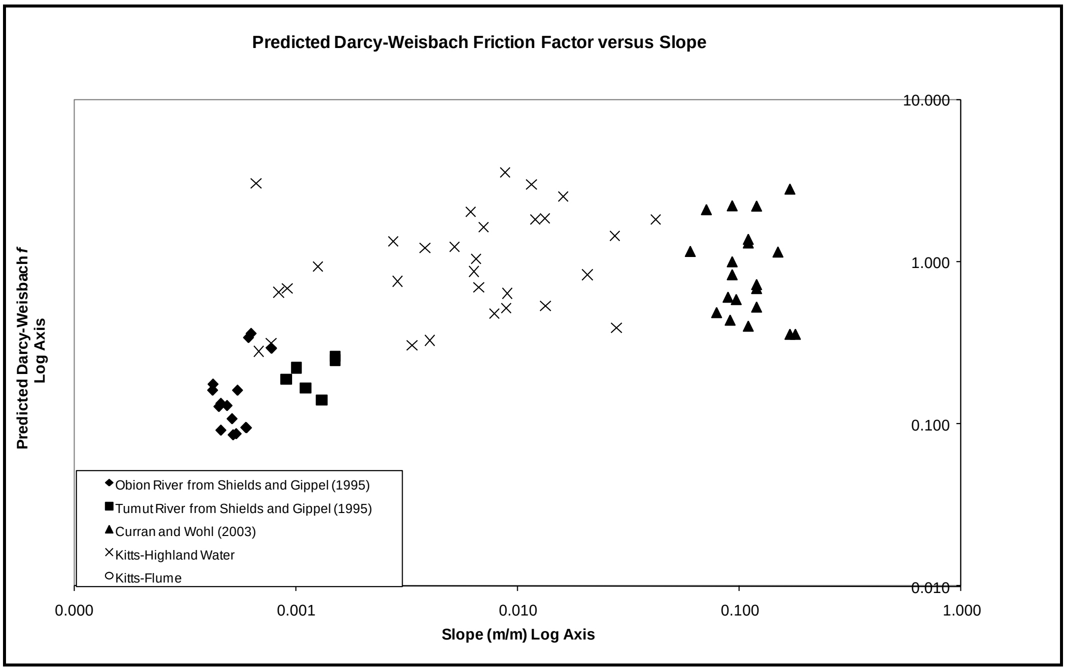



**Figure 7.11.2: Slope versus predicted Large Wood Resistance (based on Equation 7.13) for a range of environments with large wood present.**

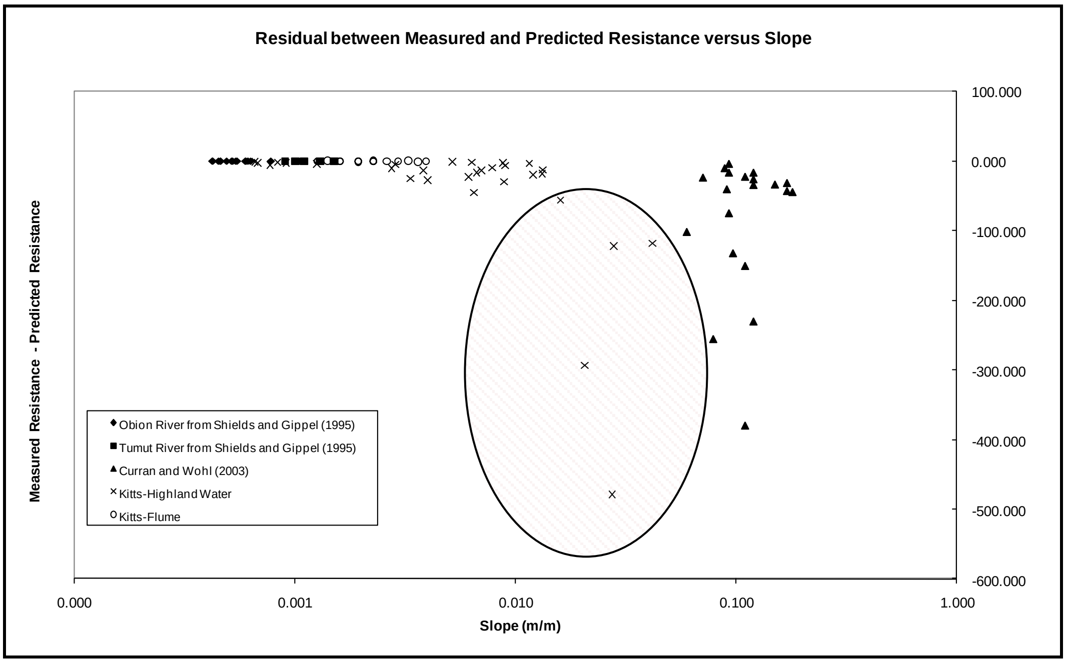



**Figure 7.11.3: Difference between measured and predicted roughness for a number of environments with large wood present. The scatter present in the Curran and Wohl (2003) data and the Highland Water overflow accumulations (highlighted in the graph) is hypothesised to be due to spill resistance.**

Differences between observed and measured values for bed resistance are often attributed to bed form effects (Parker and Peterson, 1980; van Rijn, 1984; Prestegaard, 1983). There are no commonly used approaches to predict the roughness contribution due to bed forms such as bars within the academic literature. Methods similar to the partitioning of resistance, used in this present study, have been used to quantify bar form resistance (Parker and Peterson, 1980; Prestegaard, 1983) and there has been some attempt at predicting bed form resistance in gravel-bed rivers (Hey, 1988). It is unlikely that such forms will have had such a large effect in the high-gradient boulder bed channels studied by Curran and Wohl (2003). The sand bed nature of the low gradient streams of Shields and Gippel (1995) may mean that dune features may have been present although these were not accounted for in the original study. Bed forms may have a slight influence on resistance in the Highland Water although small reaches with no bars were chosen which attempted to avoid the issue of bar form resistance.

The resistance offered by bank vegetation and root structures is another component that may contribute to the difference between measured and predicted resistance coefficients. Jarrett (1984) found that, for a high gradient mountain stream, as stage rose with discharge there was a threshold where the Manning's *n* roughness coefficient, despite initially decreasing with discharge, started to rise. This rise was attributed to the influence of bank vegetation at a certain bank height. It was noted in field data from the Highland Water, where a range of large wood accumulations were repeatedly measured, that there was a general trend where measured Darcy-Weisbach resistance decreased with a rising discharge. Although this general trend does portray some variation due to the differing blockage ratios of large wood accumulations with a rising stage with discharge (see Figure 7.11.4). Shields and Gippel (1995) suggested this was because large wood promoted energy dissipation through flow contraction and pool development processes, which became drowned out at higher discharges. This kind of pattern is similar to those in sand bed rivers (Chow, 1959), and also boulder bed rivers (Bathurst, 1978). This suggests that bank vegetation and roots structures present within the bank had a negligible impact upon the total reach scale resistance. It is not known how bank vegetation and root structure may have affected the total resistance in the studies by Shields and Gippel (1995) and Curran and Wohl (2003).

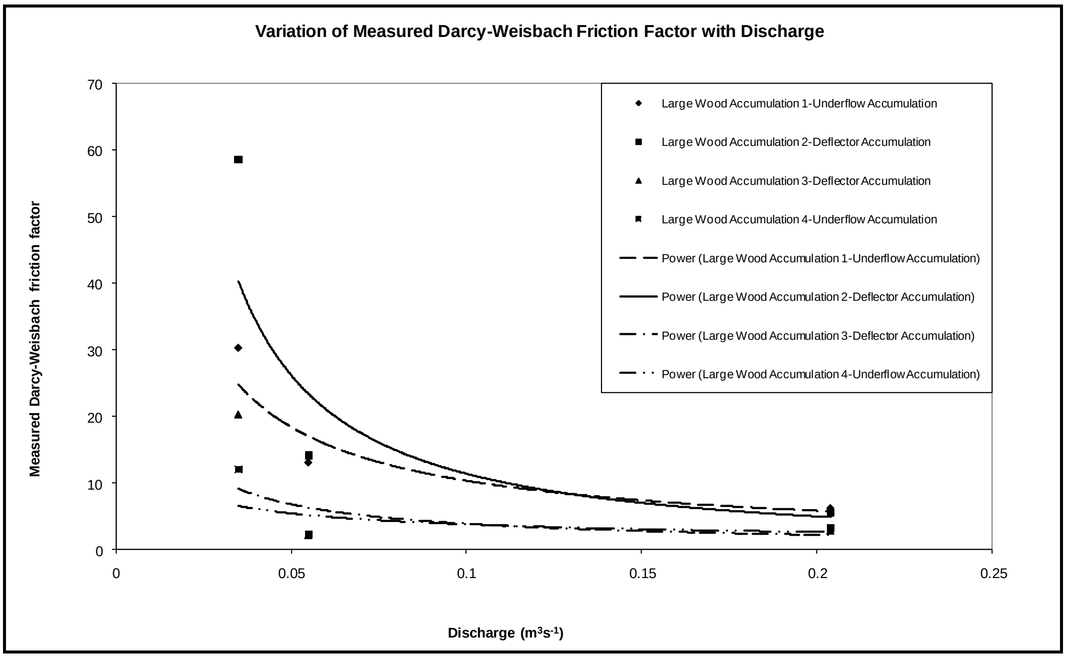



**Figure 7.11.4: The variation of Darcy-Weisbach friction factor over a range of Discharges for four different large wood accumulations in the Highland Water.**

Despite there being the possibility that a small proportion of the residual error between observed and predicted resistance may be attributed to bed form and bank vegetation resistance it is likely that there is another source of resistance, which is not accounted for.

## *7.12. Spill Resistance*

Curran and Wohl (2003) postulated that the large errors present within their data were likely to be due to spill resistance where spill resistance is that resistance which is associated with turbulence at locations of rapid velocity deceleration (Leopold *et al.*, 1960). In a high gradient boulder bed channel, velocities are typically high and boulders and large wood form significant steps in the channel and water surface profile. This, they argue, is where large wood accumulations can significantly influence total flow resistance. This present study supports this hypothesis in that overflow accumulations, which result in spill and white-water, are associated with large residual errors between predicted and observed resistance. However, in the present study this spill is not a result of high-gradient bed slopes but comes about from a large abundance of large wood relative to the channel dimensions that creates high blockage ratios and can, in the instance of overflow accumulations, lead to a significant head of water.

The highlighted data in figure 7.11.3 are from the Highland Water and in particular, overflow accumulations, which create a step in the water surface profile (see figure 7.12.1) and subsequently flow spills over the top during high flow. As the large wood accumulation blocks the whole channel, the flow is ponded upstream reducing the conveyance before it accelerates over the large wood accumulation in critical and supercritical flow. This flow then plunges into a pool where velocity plummets to zero. It is this rapid velocity deceleration that causes the spill resistance identified by Leopold *et al.* (1960).

Such spill resistance may also occur in the lower gradient, low-energy streams such as those studied by Shields and Gippel (1995) although due to the relatively low tree height to channel width ratio it is unlikely that the large wood causes a significantly large blockage (BR>0.6) and/or creates a significant step in the water surface profile to make spill resistance a dominant component in the reach scale resistance.

When the average contribution of different roughness elements ($f_{bed}$, $f_{bends}$, $f_{lwd}$ and $f_{spill}$) to the total measured reach resistance is plotted it shows that in high-gradient streams of Curran and Wohl (2003) and the present study the large wood resistance is minimal whilst spill resistance dominates (see Figure 7.12.2). This fits in with the findings of Wilcox and Wohl (2006) who found that spill resistance is significantly influenced by slope with higher contributions and magnitudes of spill resistance to total resistance occurring in reaches with steeper slopes.

Three Photographs of large wood accumulation USB6 at Grid Reference (SU 426658, 108043). Top Left is looking down at the accumulation. Notice the white-water associated with a 0.3m head. Top Right is from the right bank looking across the accumulation. Bottom left is on the right bank looking upstream. The spill is hidden in this image by some large wood but the difference between the upstream and downstream water surface levels is noticeable

**Figure 7.12.1:- Photos of the step in profile at large wood accumulation USB6 at Grid Reference (SU 426658, 108043) on the Highland Water, New Forest, UK.**

In lower-gradient streams, such as those presented in Shields and Gippel (1995), it is the form resistance that accounts for a much greater proportion of the total resistance (see Figure 7.12.2). This shows that the hydraulic role of large wood varies depending on the environment of interest. The different type of hydraulic resistance in channels of differing gradients is nothing new. Standard approaches to predicting flow resistance in low-gradient channels, relating friction factor to submergence ratios, often assume that resistance is dominated by grain roughness (Comiti *et al.*, 2007). In low-gradient channels with large wood such as those of Shields and Gippel (1995), the form resistance offered by large wood can be predicted and thus the total predicted resistance (bed resistance + large wood resistance) is commensurate with the measured resistance. In high-gradient channels, spill resistance contributes a significant amount of the total measured resistance, which previous studies have tried to relate to step geometry (Comiti *et al.*, 2007).

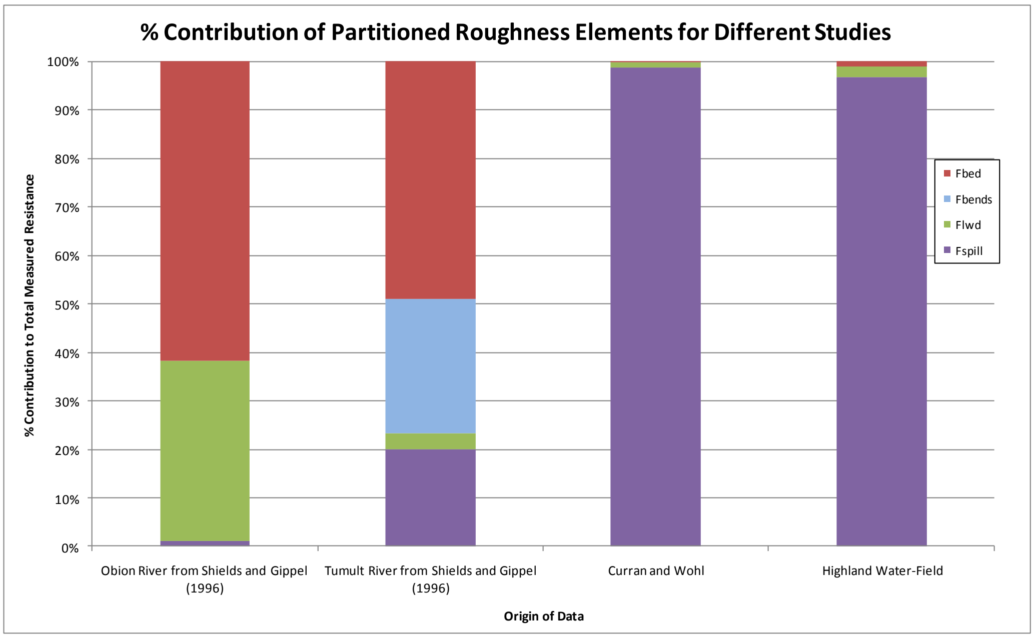



**Figure 7.12.2: The Contribution of different resistance components upon total resistance value in a number of different environments.**

However, although Curran and Wohl (2003) showed that spill resistance was important in step-pool channels, Wilcox *et al.* (2006) demonstrated using flume experiments that part of this spill resistance was attributable to the presence of large wood. They undertook experiments with bed resistance and steps in the long profile (assumed to be responsible for spill resistance) and found that in runs with large wood present the increase in resistance was beyond what would be calculated using the form drag approach. They also found that in experiments with plane beds and large wood, and stepped beds with large wood, total resistance was better predicted than in the cases with plane beds. This suggests that the cylinder drag approach put forward by Shields and Gippel (1995) is most appropriate for calculating the form drag resistance offered by large wood on plane beds rather than for large wood on steps because of the additional resistance caused by the large wood step interaction (Wilcox *et al.*, 2006). This shows the importance of the interaction effects between different resistance components: The resistance offered by large wood can also increase spill resistance offered by steps in the water surface profile. This is important in the Highland Water, as there are a number of overflow accumulations that significantly block the channel and form steps in the water surface profile.

As alluded to earlier in Figure 7.5.2, different large wood accumulations will also impact upon the total resistance in different ways with various factors influencing different accumulation types. Figure 7.12.3 shows the contribution of each roughness element to the total measured resistance for three different types of large wood accumulation (data summarised in table 7.12.1). This shows that the contribution of each partitioned roughness element varies for each type of large wood accumulation. For all cases it is the spill resistance which dominates contributing between on average 85% (for deflector accumulations) and 99% (for overflow accumulations) of the total flow resistance. However, this spill resistance is a function of the presence of large wood and would not be present in reaches without large wood.

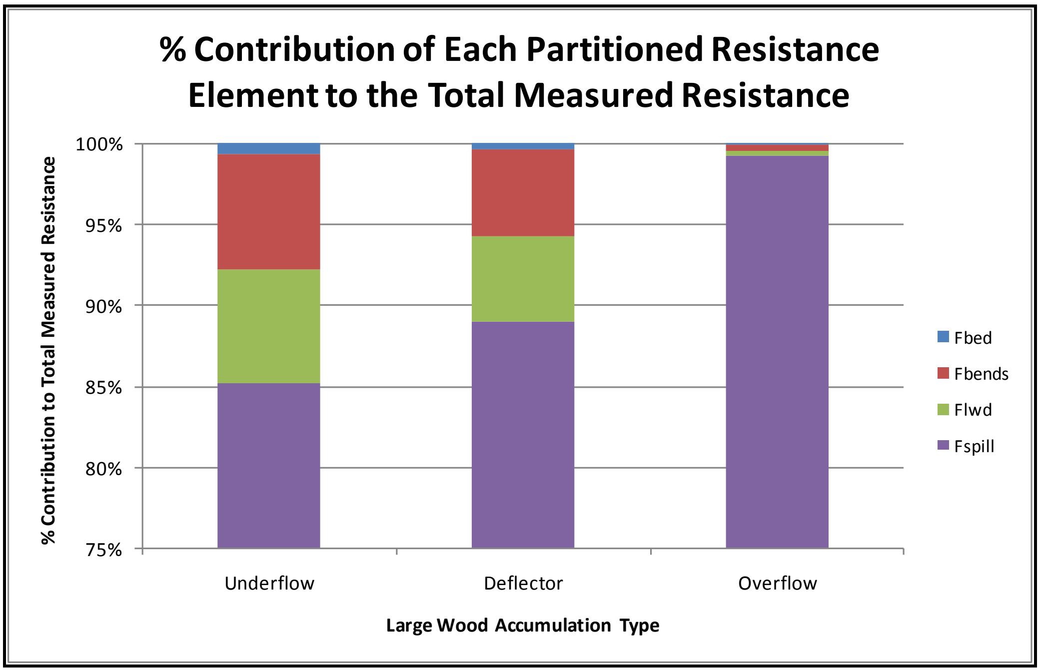



**Figure 7.12.3: The Contribution of different resistance components upon total resistance value for reaches with different large wood accumulations. In the case of the overflow accumulations, the spill resistance dominates although the spill resistance is strongly linked to the presence of large wood.**

To understand the initiation of spill resistance provided by the large wood it is useful to draw analogies with other hydraulic structures. As expected the overflow accumulation has the highest contribution from spill resistance as flow spills over the accumulation into a plunge pool where effectively flow velocities tend to zero.

| | | Average Contribution | Minimum Contribution | Maximum Contribution |
|---|---|---|---|---|
| **Underflow** | **Fbed** | 0.23 (4.21%) | 0.17 (0.77%) | 0.29 (9.65%) |
| | **Fbends** | 0.07 (2.22%) | 0.00 (0.00%) | 0.09 (9.39%) |
| | **F LW** | 1.93 (11.00%) | 0.11 (0.95%) | 2.82(46.46%) |
| | **Fspill** | 9.50 (82.57%) | 1.57 (50.0%) | 29.68 (98.28%) |
| **Deflector** | **Fbed** | 0.50 (5.46%) | 0.16 (0.59%) | 1.67 (17.54%) |
| | **Fbends** | 0.07 (2.05%) | 0.00 (0.00%) | 0.41 (14.68%) |
| | **F LW** | 0.87 (10.66%) | 0.09 (0.45%) | 3.27 (51.65%) |
| | **Fspill** | 14.72 (81.83%) | 0.85 (40.75%) | 56.05 (98.79%) |
| **Overflow** | **Fbed** | 0.13 (0.18%) | 0.10 (0.02%) | 0.16 (0.65%) |
| | **Fbends** | 0.05 (0.03%) | 0.00 (0.00%) | 0.23 (0.08%) |
| | **F LW** | 0.75 (0.62%) | 0.14 (0.17%) | 1.72 (1.44%) |
| | **Fspill** | 207.55 (99.08%) | 24.89 (98.47%) | 479.35 (99.72%) |

**Table 7.12.1: The contribution of different resistance components to the total resistance for reaches with different large wood accumulation types.**

The turbulent jets which flow over the large wood accumulation and the sharp velocity reductions lead directly to spill resistance (Leopold *et al.*, 1960). The large wood accumulation acts similar to a broad crested weir and cylindrical weirs by obstructing the channel and significantly deforming the flow field. Upstream of the accumulation the flow is subcritical, accelerates over the top of the weir and spills over into a supercritical nappe (White, 1999) where nappe flow is characterised by flow tumbling over as an overflow. Downstream of the accumulation the flow is recirculated leading to strong thee-dimensional flow structures (see figure 7.12.4) which can be responsible for scour downstream of the large wood accumulation (Wallerstein, 1999)

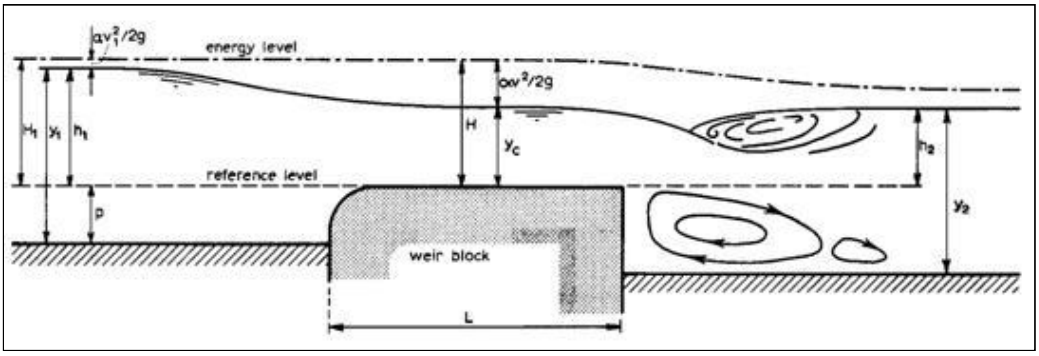



**Figure 7.12.4: Flow over a broad crested weir. Note the recirculation zone downstream of the weir block (from https://public.deltares.nl/display/HYMOS/05+With+measurement+ structure accessed August 08).**

The spilling nature of the nappe flow and the recirculation zones at the downstream end of the weir lead to an abrupt change in velocity which is where the spill resistance is present. The presence of large wood can initiate this step by creating the overflow processes but also can exacerbate it by increasing the height of the step.

The second highest average contribution by spill resistance was from the underflow accumulations. Underflow accumulations create turbulence by forcing flow underneath the key large wood pieces locally accelerating near-bed flow (Hickin, 1984). This process can be analogous to those that occur around underwater pipelines (for example see the three vortex system presented by Chiew, 1990 shown in Figure 7.12.5).

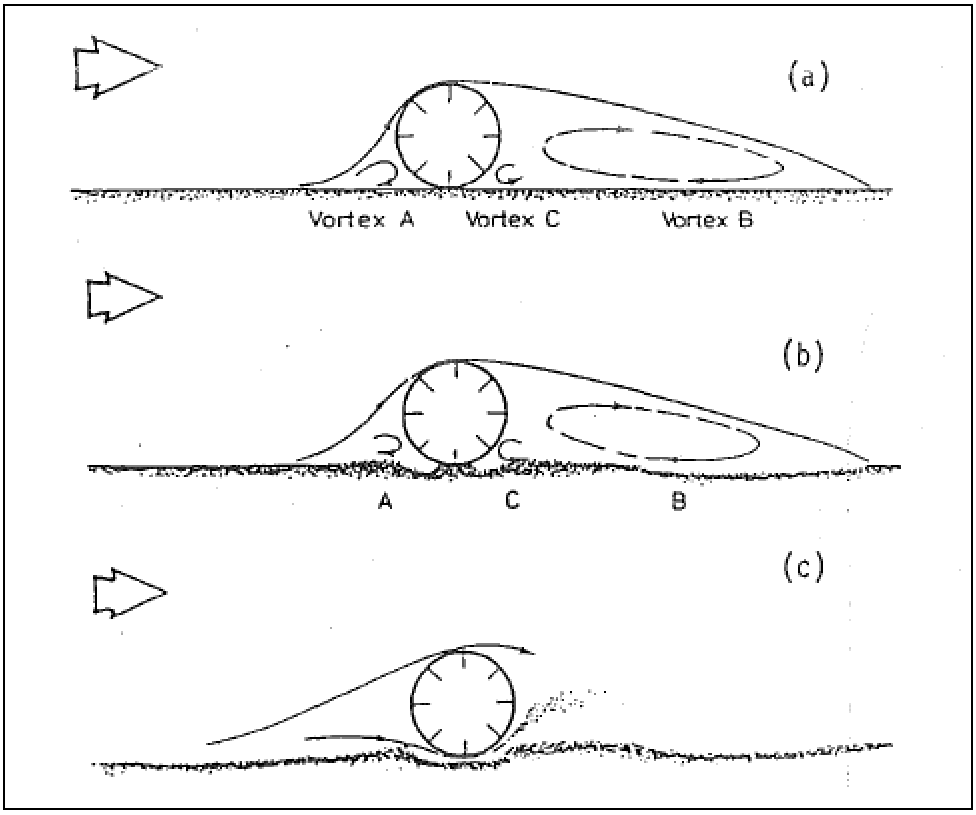



**Figure 7.12.5: The Three-Vortex System and Onset of Scour (from Chiew, 1990).**

Scour was observed in single pieces of large wood which were artificially added to reaches within the Highland Water and it is likely that the same processes were operating as described by Chiew (1990). The large wood accumulations, like the submerged pipeline, increases form drag which creates a low-pressure zone downstream of the large wood element. The pressure gradient between upstream and downstream leads to the increase of flow under the large wood accumulation and the upwelling of flow downstream of the accumulation. This upwelling in the low-pressure zone downstream of the large wood accumulation can lead to localised turbulent flow, which influences the amount of spill resistance.

Deflector accumulations deflect flow around the key large wood pieces and in some ways act in a similar way to the underflow accumulations albeit deflecting flow towards banks rather than beds. Manners *et al*. (2007) found that velocities adjacent to a large wood accumulation were greater than those either upstream or downstream of it. Daniels and Rhoads (2003) found that flow around large wood accumulations near meander bends intensify helical motion by locally enhancing the cross-stream pressure gradient. Thus a small amount of spill resistance is present.

As the original methodology was developed by Shields and Gippel (1995) it can be argued that the large wood resistance methodology is not suited for all environments especially those where spill resistance is the dominant process. Wilcox *et al.* (2006) found that the cylinder drag based approach is not appropriate in step-pool channels as it underestimates large wood resistance because the step-large wood interaction effects are not accounted for. Data from this study show that the approach underestimates resistance in a gravel bed environment which contrasts with successful applications in lower-gradient gravel bed, sand-bed and spring-dominated rivers (Shields and Gippel, 1995; Manga and Kirchner, 2000).

Curran and Wohl (2003) suggested that the step-pool feature is the source of the spill resistance however they did not find significant relationships between resistance and step geometry such as $H$ (step height), $L$(step length) and $H/L$. Results from this study where large wood accumulations do not create significant steps in the water surface profile (such as underflow and deflector accumulations) suggests that step geometry does not influence the spill resistance. As a result, an alternative approach is required, which assesses the role of spill resistance offered by large wood accumulations. One approach taken by Colosimo *et al.* (1998) was to use the Froude number.

## *7.13. Froude Number*

Residuals between measured total resistance and predicted resistance, which were attributed to spill resistance, were plotted against Froude number shown in Figure 7.13.1 which is known to affect the friction factors when changes in the free-surface configuration occur (Colosimo *et al.*, 1988). Objects such as large wood can protrude through the water surface and like other free surface disturbances can lead to energy dissipation (Rouse, 1963).

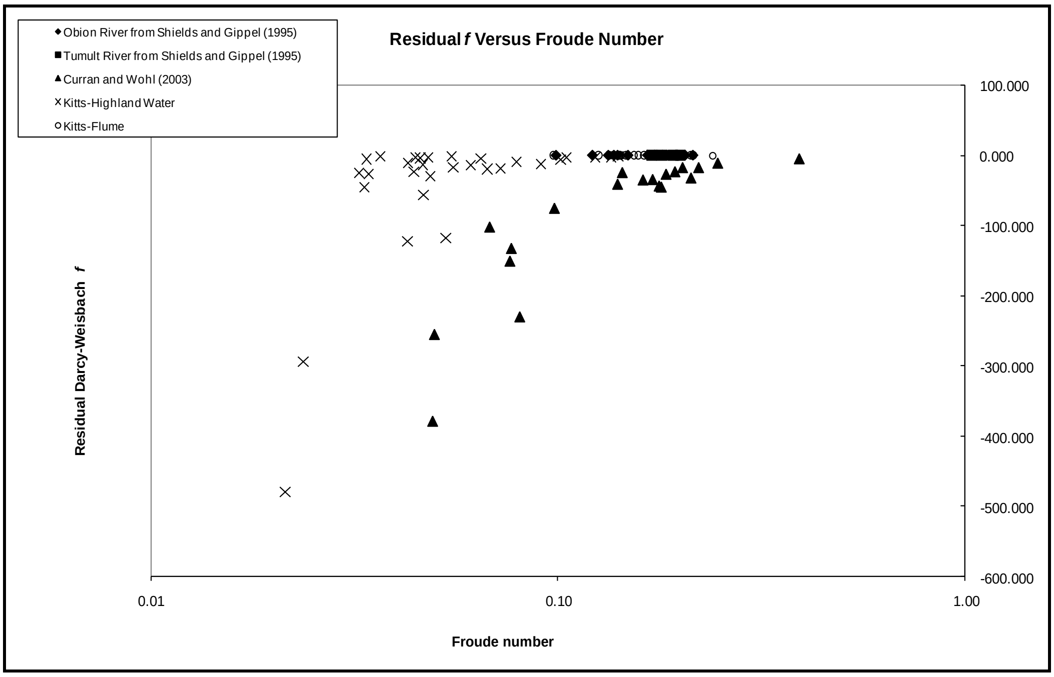



**Figure 7.13.1: The Residual Darcy-Weisbach Friction Factor (attributed to spill resistance) versus Froude Number.**

The plot shows that the residual attributed to spill resistance is inversely proportional to Froude number, which is similar to the findings of Colosimo *et al* (1988) when looking at gravel bed channels. If data from Curran and Wohl (2003) and overflow accumulations from the present study, which are characterised by high spill resistance, were plotted against the Froude value, a power relationship can be responsible for almost 70% of the variation in the data (statistically significant at the 1% level).

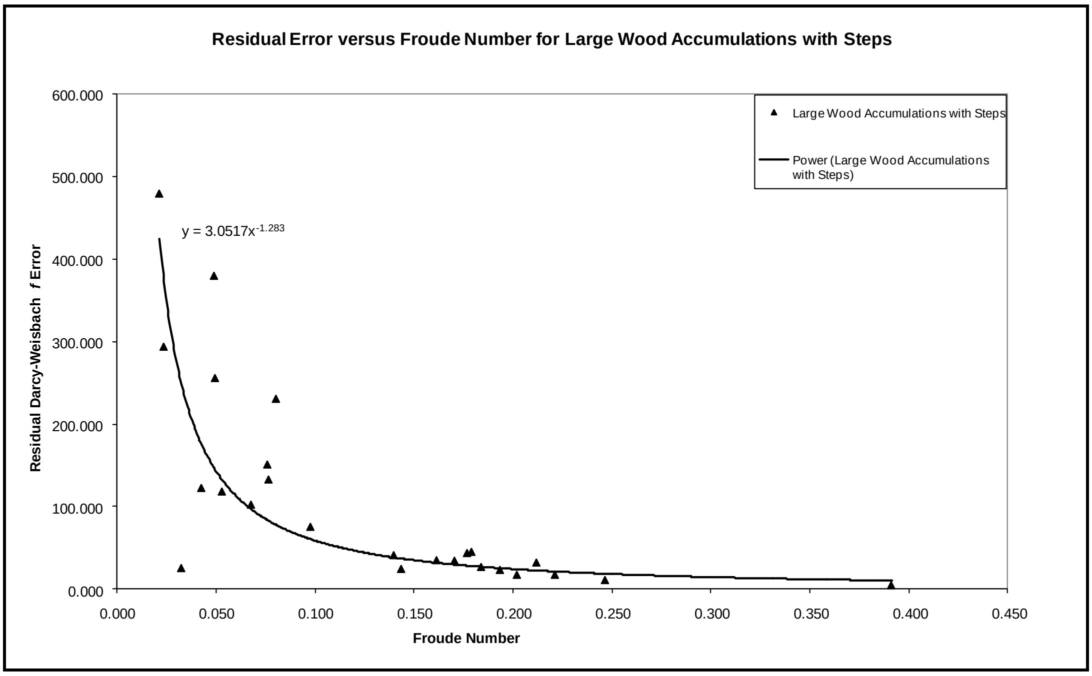



**Figure 7.13.2: Residual Error versus Froude Number for Large Wood Accumulations with steps in the water surface profile (overflow accumulations).**

The form of this relationship for those with steps in the water surface profile is:-

$$\text{Spill Resistance}=3.0517Fr^{-1.283} \qquad \textbf{(7.37)}$$

For those accumulations that do not cause a step in the water surface profile, the relationships are shown in figure 7.13.3. As can be seen there is a strong relationship for deflector accumulations ($r^2$ = 0.766, statistically significant at the 0.05 level) but an extremely weak one for the underflow accumulations. The reason for this is unknown but it could be due to the formation of standing waves downstream of the large wood accumulations which lead to further distortion of the free surface.

The format of the relationship for the deflector accumulations is:-

$$\text{Spill Resistance}=0.0186Fr^{-2.309} \qquad \textbf{(7.38)}$$

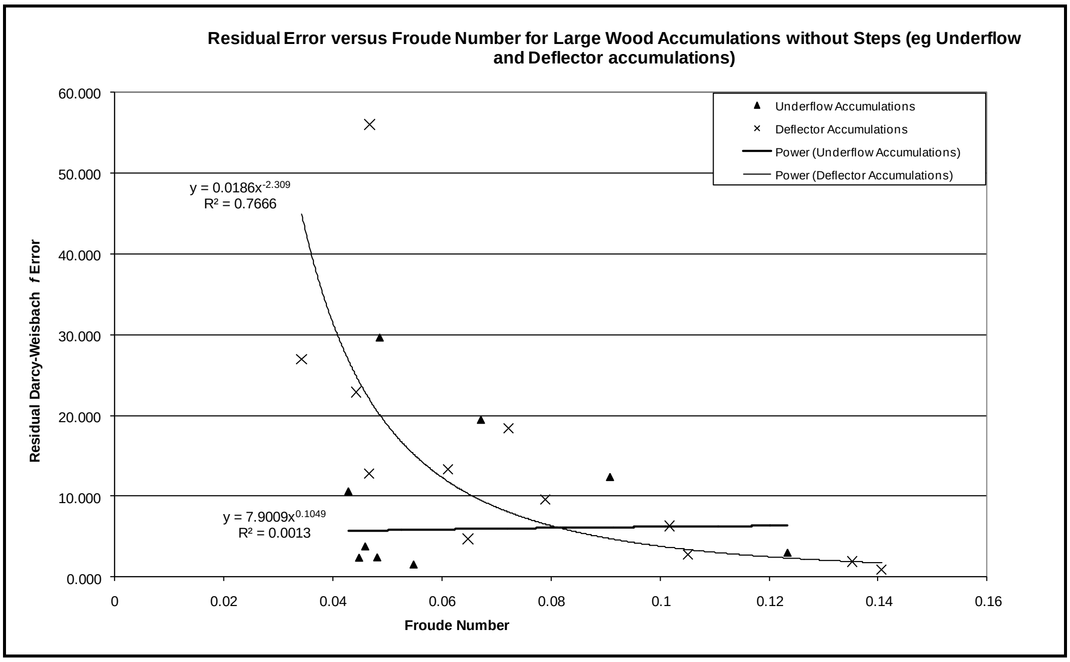



**Figure 7.13.3: Residual Error versus Froude Number for Large Wood Accumulations without steps in the water surface profile (underflow and deflector accumulations).**

The relationship between the Froude number and the residuals between the measured and predicted *f* values is not unexpected as the reach scale Darcy-Weisbach friction factor, *f*, expressed in a functional equation obtained by dimensional analysis is:-

$$f = f\left(\frac{R}{d_{\phi}}, \Phi, \mathrm{Re}, \xi, Fr, Y\right) \quad \textbf{(7.39)}$$

Where R is the hydraulic radius, $d_{\Phi}$ is the particle size for which $\Phi$ percentage of the particles are smaller, *Re* the Reynolds number, ξ the flow sinuosity, *Fr* the Froude number and *Y* a sediment mobility parameter (Yalin, 1972). The Reynolds number does not have any impact on the friction flow in channels with rough granular beds (Graf *et al.*, 1983). The relative submergence $R/d_{\Phi}$ is accounted for using the bed resistance equations used, (ie in this study that of Griffiths, 1981) and the flow sinuosity was calculated using the head loss of Henderson (1966). The sediment mobility parameter is considered irrelevant for fixed-bed channels

(Yalin, 1972). This leaves us with the Froude number, which has so far not been accounted for. The Froude number affects the friction factor when free-surface distortions occur which can occur in the presence of large roughness elements (Colosimo *et al.*, 1988) such as large wood accumulations. Bathurst (1982) suggested, for particle resistance, that increases in Froude number are associated with increases in relative submergence which leads to a reduction in the number of particles interacting with the free surface and the drag of the roughness elements. This is because of the development of surface wave drag around protruding bed elements (Bathurst, 1985) which could be a similar scenario to that experienced near large wood accumulations.

Colosimo *et al.* (1988) found that differences (Δ) between observed and predicted friction factors ($1/\sqrt{f}$) for a gravel bed river were related to the Froude number according to the following equation:-

$$\Delta = -1.65 + 2.54 Fr \tag{7.40}$$

This is significantly different to the regression equations in the current study for large wood accumulations although this could be an indication of the high relative roughness produced by the large wood or a function of the high gradient.

Both Bathurst (1985) and Colosimo *et al.*, (1988) however, suggest that the Froude number is a function of the resistance rather than *vice versa*. This can also be illustrated for large wood accumulations. The large wood accumulation retards water leading to reduced flow velocity whilst at the same time, ponding upstream leads to high flow depths which together lead to a reduction in Froude number. Therefore although the Froude number can account for some of the variation between measured and predicted resistance, it may not lend itself for use as a predictive tool. Further work is necessary to further the understanding of the contribution of spill resistance to the reach scale resistance in channels of high gradients and where large wood accumulations are present.

## 7.14. Summary

The flow resistance offered by large wood is extremely difficult to quantify. Previous workers have used an approach suggested by Shields and Gippel (1995) which is used within this work. A number of large wood accumulations were sampled within the New Forest and were compared against those from other environments. The results show that large wood does not have a singular effect on flow resistance with different large wood accumulations having different effects and large wood having different effects within different environments. The importance of spill resistance identified within the present study supports findings from Curran and Wohl (2003) and Wilcox and Wohl (2006) in step-pool boulder bed streams and suggests a difference in the role large wood plays in high-gradient environments and low-gradient environments where spill resistance is essentially absent.

Flow resistance partitioning is complicated by the interaction effects that occur between roughness variables. The presence of large wood can influence spill resistance but this is not accounted for in the cylinder-drag-based approach used by Shields and Gippel (1995). Data presented showed that up to 76% of this variation could be assigned to the Froude number (relationship significant at the 5% level), which is known to be influenced by free surface effects (Colosimo *et al.*, 1988), for the deflector accumulation and up to 70% for overflow accumulations (relationship significant at the 1% level).

This has important implications for the understanding of large wood, as it is necessary to quantify the effect of large wood on flow conveyance and hydraulics as large wood profoundly disrupts the flow structure (Daniels and Rhoads, 2003). The reduction in conveyance as a result of large wood within the channel can increase the frequency of inundation and in increase shear stresses, which can lead to bed or bank erosion and sediment transport. Vegetation such as large wood provides a high resistance and has a large impact on water levels within rivers and therefore the estimation of the friction factor is important (Kouwen and Fathi-

Moghadam, 2000). The present study shows that resistance can vary depending on the type of large wood accumulation that is present within a reach. Standard equations used to determine large wood resistance rely on a drag force approach although this is more suited to those environments and large wood accumulations where form resistance dominates and spill resistance is limited. Quantifying the spill resistance component of the total reach scale resistance is a significant challenge in reaches with an abundance of large wood and in high-gradient river systems. In the previous chapter, it was shown that the presence of large wood can have an impact in increasing flood inundation frequency, reducing flood peak magnitude and travel time. It is shown in this chapter that this effect is achieved through the blockage of the channel by large wood accumulations and the dissipation of flow energy mainly through spill resistance, although the mechanism depends on the particular type of large wood accumulation. The type of large wood accumulation is important in any use as a restoration tool and being able to predict the effect of each large wood accumulation upon flow hydraulics is important. Therefore, in the next chapter, a hydrodynamic model is setup to assess the impact of different types of large wood accumulations and configurations upon the inundation extent, velocity patterns and flow depth patterns. A number of average resistance values have been derived for each type of large wood accumulation from the Highland Water as shown in table 7.14.1.

| **Large Wood Accumulation Type** | **Average Darcy-Weisbach Friction Factor (SD)** | **Min. Darcy-Weisbach Friction Factor** | **Max. Darcy-Weisbach Friction Factor** | **Average Manning's *n* from field data (SD)** | **Min. Manning's *n* from field data** | **Max. Manning's *n* from field data** |
|---|---|---|---|---|---|---|
| Underflow | 10.7 (9.7) | 2.24 | 30.20 | 0.27 (0.128) | 0.139 | 0.505 |
| Deflector | 16.16 (15.8) | 2.10 | 58.59 | 0.32 (0.147) | 0.123 | 0.609 |
| Overflow | 230.73 (200.4) | 25.20 | 480.80 | 1.42 (0.82) | 0.475 | 2.329 |

**Table 7.14.1: Resistance Values for Different Types of Large Wood Accumulations.**

These values will be carried forward to hydrodynamic modelling part of this thesis as accurate simulations of floodplain inundation rely on an accurate estimate of the resistance coefficient.   These have been converted to a Manning's *n* value, which is a more widely used resistance coefficient and also one used within the Hydro2de modelling code.  However, it should be noted that due to the units of Manning's *n* and the dimensionless Darcy-Weisbach friction factor, caution should be used when converting between the two as they are not dimensionally correct.

# 8. Hydrodynamic Modelling of Riverine Woodland Environments.

## *8.1. Introduction*

Riverine woodlands are known to be sources of large wood and its presence is critical in achieving the mosaic of inundation typical of wet riverine woodland (Jefferies *et al.*, 2003). Large wood increases the local flow resistance and increases both the inundation frequency and magnitude, which can create the development of conditions favourable for the development of riverine woodland (Brookes, 1996; Hupp and Osterkamp, 1996; Tockner *et al.*, 1998; Richards *et al.*, 2002) as well as directly influencing the floodplain geomorphology (Lewin and Hughes, 1980; Zwolinski, 1992). For these reasons, it has been suggested that large wood can be used as a restoration tool to promote the multi-directional flow patterns that are observed in riverine woodland (Brown *et al.*, 1996). However, currently little work has assessed the ability of large wood to initiate inundation and its role in influencing inundation patterns or how different types of large wood accumulations can influence the floodplain hydraulics of such systems. Each type influences local flow hydraulics differently and it has been shown to have different contributions to the local reach flood hydrology. In order to fulfil the linkage between the large wood accumulation scale and the reach scale it is useful to assess the impact of large wood accumulations on the reach-scale flood hydraulics. Floodplain flow can be investigated using a range of methods from descriptive observations to more complex methods designed to simulate instantaneous flood flows (Jeffries, 2002). One such method is using hydrodynamic numerical models with the benefit of gaining a synoptic view of inundation patterns and metrics and it is this which is implemented in this study to investigate the floodplain flows within the Restored-Planform site. The role of large wood accumulations in routing flow is important and the effect of different types of large wood accumulations on flood inundation extent and patterns can also be assessed using a hydrodynamic modelling framework. The outputs will be assessed in terms of inundation extents, patterns and velocity vectors.

Before it is possible to set up numerical experiments a calibrated hydrodynamic model is required from which a number of numerical experiments could be conducted. The following sections describe the setup, calibration, validation of the hydrodynamic model before describing the results of the numerical experiments.

## *8.2. Two-Dimensional Hydrodynamic Model*

The modelling of flows on a riverine woodland surface is made difficult due to the specification of complex surface topography. Therefore, it was necessary to use a model that was primarily designed for use in complex environments and was frequently applied to floodplain environments. One such code that allows the input of such complex geometry in raster format is Hydro2de, which has been used in braided river channels (Connell *et al.*, 2001) and in floodplain environments (Nicholas, 2003; Nicholas and Mitchell, 2003; Sweet *et al.*, 2003).

**Hydro2de**

Hydro2de is a two-dimensional floodplain flow model (Beffa and Connell, 2001). It uses a finite volume scheme to model flows over a uniform grid. Hydro2de is based on the depth averaged shallow water equations that can be written in conservative form as:-

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}+\frac{\partial r}{\partial y}=0 \qquad \textbf{(8.1)}$$

$$\frac{\partial q}{\partial t}+\frac{\partial\left(\frac{q^2}{h}\right)}{\partial}+\frac{\partial\left(\frac{qr}{h}\right)}{\partial y}+\frac{g}{2}\frac{\partial\left(h^2\right)}{\partial x}+gh\frac{\partial z}{\partial x}-\frac{1}{\rho}\frac{\partial\left(h\tau_{xy}\right)}{\partial y}-\frac{1}{\rho}\frac{\partial\left(h\tau_{xx}\right)}{\partial x}+\frac{\tau_{by}}{\rho}=0 \quad \textbf{(8.2)}$$

$$\frac{\partial r}{\partial t}+\frac{\partial\left(\frac{r^2}{h}\right)}{\partial y}+\frac{\partial\left(\frac{qr}{h}\right)}{\partial x}+\frac{g}{2}\frac{\partial\left(h^2\right)}{\partial y}+gh\frac{\partial z}{\partial x}=\frac{1}{\rho}\frac{\partial\left(h\tau_{yx}\right)}{\partial x}-\frac{1}{\rho}\frac{\partial\left(h\tau_{yy}\right)}{\partial y}+\frac{\tau_{by}}{\rho}=0 \quad \textbf{(8.3)}$$

Where *h* is flow depth, *q* and *r* are unit discharge in the x and y directions respectively, *t* is time, *z* is bed elevation, *g* is gravitational acceleration, *ρ* is the fluid density, $\tau_{xx}$, $\tau_{yy}$, $\tau_{xy}$ and $\tau_{yx}$ are turbulent stresses, and $\tau_{bx}$ and $\tau_{by}$ are bed shear stresses. Turbulent normal stresses are assumed to be negligible, whilst shear stresses are modelled using the Boussinesq approximation:-

$$\tau_{xy}=\tau_{yx}=\rho v_t\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \quad \textbf{(8.4)}$$

Where *u*=q/h and *v=r/h* and $v_t$ is the eddy viscosity, which is estimated by the following:-

$$v_t=0.07u_*h \quad \textbf{(8.5)}$$

Where $u_*$ is the friction velocity. The value of 0.07 is the default eddy coefficient recommended as a good estimate for river flow in the Hydro2de manual (Hydro2de, 2001), although this value can be defined by the user. It is also possible to estimate the eddy coefficient using a mixing length model after Prandtl (1925). A sensitivity analysis was conducted to assess the most appropriate turbulence method and this is described later in this chapter. Bed shear stresses are determined as a function of velocity:

$$\frac{\tau_{by}}{\rho} = gn^2 \frac{v\sqrt{u^2 + v^2}}{h^{\frac{1}{3}}} \tag{8.6}$$

Where $n$ is the Manning's roughness coefficient.

Hydro2de uses a finite volume method and solves equations 8.1-8.3 using an explicit integration method to calculate the flow depth and two horizontal unit discharge components. This leads to shorter and less laborious program codes (Beffa and Connell, 2001). Numerical fluxes between cells have to be interpolated by the values given in the cell centres. Taking the arithmetic mean of the adjacent points would lead to spurious oscillations in the solution (Hirsch, 1988). In order to dampen these oscillations a flux difference splitting scheme (FDS) proposed by Roe (1981) was used. The Roe (1981) scheme introduces an upstream weighting for the flux evaluation and effectively propagates waves across a cell face. In order to achieve a second order of accuracy for the solution a variable extrapolation approach (MUSCL) (van Leer, 1977) is used which is better at representing the upstream wave front in any dam break problems (Beffa and Connell, (2001). This is useful in the current application to flows in the presence of large wood accumulations as there are often sharp drops in the water surface elevation and therefore spill resistance.

## *8.3. Field Data Required for Model Setup*

All hydrodynamic models require the input of certain data in order to model flow structures. Perhaps most critical is the topographic data over which the flow will be simulated. Hydro2de requires a uniform rectangular grid to be discretised over the area of interest, in this case the Restored-Planform reach. This was produced using a Digital Elevation Model (DEM) constructed from topographic data collected using an Electronic Total Station and was processed using the ArcInfo™ 8.3 GIS package. The raw point data was initially converted into a Triangulation Interpolation Network (TIN) before being converted to a raster DEM and exported in an ASCII grid file format. The topographic survey consisted of 15,000 points at a spatial resolution of approximately $0.25m^2$. This resolution was considered sufficient to pick out the micro-topography that has been observed on natural floodplains (Nicholas and Walling, 1998) especially on forested floodplains (Jefferies *et al.*, 2003).

As the reach was semi-natural, there were no hydraulic control structures within the reach. There were a number of tree stumps upon the floodplain surface and these were represented within the topography. Within the reach, there was a large wood accumulation that acted as an overflow accumulation. The representation of large wood accumulations within hydrodynamic models is a difficult issue for which there is currently no method (Pasternack *et al.*, 2004). A review was undertaken as to the best method of representing the large wood accumulation and this is presented later.

At an inflow boundary, Hydro2de is able to specify the flow variables at a grid point using the uniform flow approximation. Using the flow discharge and the energy slope, the flow is distributed between specified boundary cells based on the uniform flow relationship taking into account bed topography and the relevant friction values. The discharge was specified accordingly for the calibration and validation events at the same inflow location. The discharge was measured within the field for each observed events using a Valeport Electro-Magnetic Current Meter (EMCM) The depth-averaged velocity at 8 points within the inflow cross-section was measured and used with the area of each section to create an inflow discharge. Velocity measurements were averaged over a 30-second period to take into account any turbulent fluctuations present within the river channel.

At the outflow boundary, the user can specify the flow depth, the water level or the energy slope. In the case of the Highland Water, the water surface slope was surveyed during the observed events and this value was specified as for each event.

A key component of hydrodynamic models is the representation of sub-grid scale topography through the use of a roughness parameter. Reliable results of inundation simulations rely on an accurate estimate of the resistance coefficient (Wu *et al.*, 1999). There are various methods for obtaining this including field estimates from a guide such as Chow (1959) or Barnes (1967) (see Gee *et al.*, 1990; Bates *et al.*, 1992; Siggers *et al.*, 1999; Pasternack *et al.*, 2004), calibration using water surface elevations and flood extents (see Nicholas and Walling, 1998; Connell *et al.*, 2001), and estimation from grain size distributions (Nicholas and McClelland, 1999, Lane *et al.*, 2000). For the purpose of this research, the Manning's *n* roughness parameter was calibrated for a number of events. Calibration was achieved using observed water levels, inundation extents and velocity measurements. Observed water levels and inundation extents were collected in the field using a Geodimeter total station during the flood event. Observed extents were then plotted using ArcInfo 8.3 and the area of inundation measured for comparison with the simulated data. Other modelling studies have used just inundation extents or stage to calibrate hydrodynamic models (eg. Nicholas and Walling, 1997; Nicholas and Walling, 1998; Stewart *et al.*, 1999; Connell *et al.*, 2001; Nicholas and Mitchell, 2003). As stage is closely related to inundation extent for the bankfull event it was unnecessary to separately calibrate for stage. However, where data is available, and particularly for in-channel flows, it is possible to calibrate for observed velocity measurements (Bradbrook *et al.*, 1998; Hodskinson and Ferguson, 1998) although these are usually studies using three-dimensional CFD models. Velocity data for calibration of the two-dimensional hydrodynamic model was collected using an EMCM for two of the observed events ($0.16 m^3 s^{-1}$ collected on 20/05/05 and $0.37 m^3 s^{-1}$ collected on 11/01/05). The EMCM was used to measure velocity at a number of cross-sections along the reach. Within the cross section, at least five measurements were taken at regular intervals across the channel width and the velocity measurement was taken at 60% of the flow depth where the depth-averaged velocity is reported to occur in uniform flow (Leopold *et al.*, 1964).

For the largest observed inundation event on the 20th October 2004 (Discharge=$0.45m^3s^{-1}$) an experimental approach to the acquisition of velocity measurements was taken. Due to the highly responsive nature of the study catchment to rainfall, the flood peak was often very short and thus an event could last for as little as two hours. This meant it was extremely difficult to capture the amount of data and resolution that would have been preferred to allow a rigorous calibration and validation of the hydrodynamic model. In order to overcome this, an experimental approach was taken which involved the use of large particles to track the surface velocity within the channel. This technique is commonly referred to as Large Scale Particle Image Velocimetry (LSPIV) and the approach is described below.

## *8.4. Large Scale Particle Image Velocimetry*

LSPIV is a relatively new application of a technique that has been commonly used within the flume environment (Creutin *et al.*, 2003). The technique involves the measuring of a flow velocity field though the seeding of visible particles into the flow field and recording a series of images from which the velocity of the particles can be obtained. It differs from conventional Particle Image Velocimetry (PIV) used in flume environments in that the LSPIV covers much larger fields of views and uses natural light and video equipment to record video digital images of the flow surface (Meselhe *et al.*, 2004). The benefits of this method are that it can allow a large number of flow measurements to be made synoptically with little external intrusion of the flow in a relatively short period of time. This is critical in terms of the Highland Water where the rapid rise and fall of a flood event can mean it is impractical to obtain sufficient flow data.

In the Highland Water, the large particles (conventional wine corks and table tennis balls) were seeded at an upstream location and a fixed video camera was used to film their progress over a small section of the river (~10-15m). Included in each recording, was a number of fixed points that were surveyed using a total station. These fixed points were then used to georeference individual video frames using the ArcMap 8.3 Spatial adjustment extension.

Two preliminary experiments were conducted prior to data collection to assess the accuracy of the approach taken. The first was used to determine accuracy of the georeferencing technique. A video camera was attached to an extendable pole (shown in Figure 8.4.1) and was used to take images of a range of numbered table tennis balls. The location of the particles and a number of targets were surveyed using the electronic total station. The video camera was then remotely operated to take some images from which a number of still pictures were taken similar to figure 8.4.2. These were shown to have a field of view of approximately 9m by 8m.

**Figure 8.4.1: The Extendable Pole used for the Large Scale Particle Image Velocimetry.**

The locations of black and white targets were also surveyed to allow the georeferencing of the image based on the co-ordinates of these control points. A third order transformation was chosen in ArcMap, which aligned the image to the surveyed locations on the ground. This resulted in an image shown in figure 8.4.3.

**Figure 8.4.2: Sample Image of the Highland Water from the Elevated Camera**

**Figure 8.4.3: Georeferenced Image of the Highland Water (same scene as figure 8.4.2).**

From the georeferenced image, it was possible to zoom in and identify the particles in the channel and on the floodplain and then it was possible to obtain the co-ordinates of the particles within the image. An average of 65.4% of the particles were identified within the two images that were sampled with a root mean squared error between image derived co-ordinates and surveyed co-ordinates of 5.1cm in the x-axis and 5.6cm in the y axis. Figure 8.4.4 shows the plot of surveyed co-ordinates versus image-derived co-ordinates for the X co-ordinates and Y co-ordinates. As can be seen the scatter of data points for both X and Y co-ordinates are well clustered around the line that shows the residual between surveyed and image derived co-ordinates.

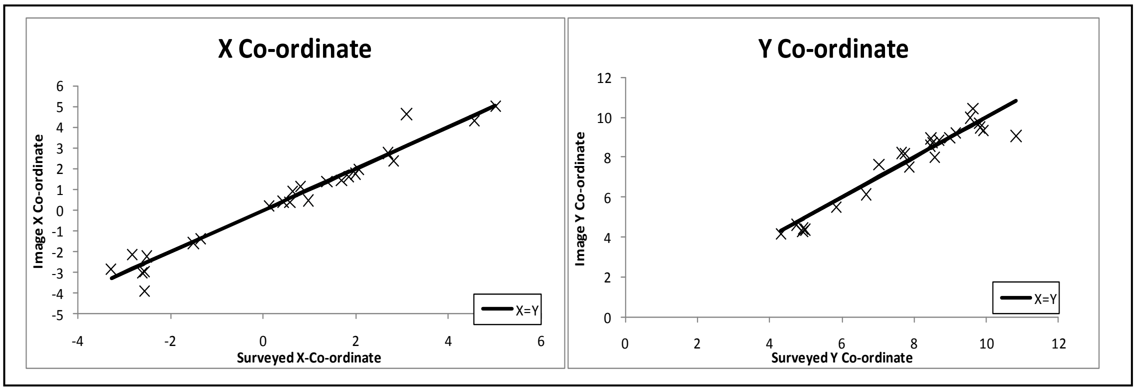



**Figure 8.4.4: The surveyed Co-ordinates plotted against the Co-ordinates obtained from the georeferenced image.**

A summary of the residuals between the two test images are shown in table 8.4.1.

| **Image** | **Average X-Residual (cm)** | **Average Y-Residual (cm)** | **X RMS (cm)** | **Y RMS (cm)** | **Total RMS (cm)** |
|---|---|---|---|---|---|
| 6_20 | 7.6 | 13 | 3.1 | 5.7 | 4.6 |
| 6_22 | 3.5 | 11 | 5.1 | 5.6 | 5.3 |
| **Average** | **5.55** | **12** | **4.1** | **5.65** | **4.95** |

**Table 8.4.1: Residuals between the surveyed co-ordinates and the co-ordinates obtained from the georeferenced image.**

The root mean squared errors are relatively small with an average of 4.95cm. The method for obtaining velocity vectors and magnitude is to take two images and identify the same particle in each image. The difference in the particle location between the two images is the distance that the particle has travelled and by using the difference in time between the two image frames, it is possible to convert this to a velocity magnitude in the typical flow direction.

Further tests involved taking velocity measurements in a number of vertical profiles to assess whether the near-surface velocity could be used to estimate the depth-averaged velocity. Twenty-two vertical profiles were sampled and the near surface velocity compared with the depth-averaged velocity. The results showed a surprisingly good fit with an $r^2$ value of 0.987. The gradient of the trend line suggests that the depth-average velocity is 85 percent of the surface velocity.

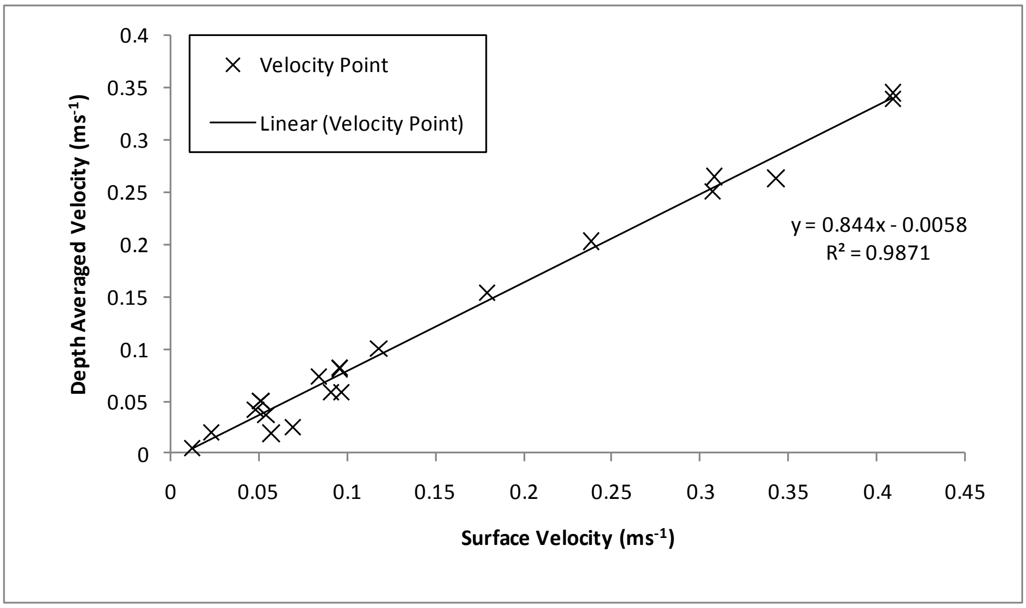



**Figure 8.4.5: Relationship from Experimental Data of Surface Velocity versus Depth-Averaged Velocity.**

On the strength of the relationship, it was decided that the surface velocities obtained from the LSPIV could be scaled by 0.85 to provide estimates of the depth-average velocity for comparison with the modelled simulated depth-averaged velocities. This enables the LSPIV data to be used to help validate the event that occurred on the 20th October 2004. Due to practical reasons in employing the LSPIV equipment, the LSPIV was not carried out for the other calibration and validation events on the 20th May 2005 and 11th January 2005.

## *8.5. Grid Independency*

With the model geometry setup and the calibration and validation data collected it is first necessary to assess the effect of the grid resolution on the model results and to achieve grid independency whereby an increase in the grid resolution does not produce a significant increase in model results. For a large number of numerical modelling applications the problem of specifying an optimum mesh resolution remains unbounded. Grid cell size or cell resolution have been shown to lead to variations between simulated model results with the general trend pointing to an increase in model predictive capability as a result of increased grid resolution (Bates *et al.*, 1996; Hardy *et al.*, 1999). Hardy *et al.* (1999) suggested three possible explanations for this hypothesis. These being:-

- Improvements in model simulation stability as the grid spacing tends towards the true continuum level,
- The ability of higher resolution models to enable more complex and therefore more realistic parameterization,
- A closer correspondence between field measurement and model scales.

There is often a desire to simulate over a grid, sufficiently high enough in resolution, that it provides a large amount of information about the flow domain. However, there comes a point whereby increasing the grid resolution does not yield significant improvements in model output accuracy (Bates *et al.*, 1996; Hardy *et al.*, 1999). Coupled with this is the computational power required to run ever increasing spatial resolutions. An increased grid resolution greatly increases the number of calculations required thus increasing the computing time for a simulation. Therefore, there is often a compromise between the level of detail represented and the computational time taken.

To assess how the grid resolution affects model output it is necessary to run a number of simulations with different grid sizes. Obviously, the smaller the grid cell sizes, the more cells are required to discretise the flow domain, and with an increased number of cells, there is an associated increase in the time taken to compute the equations over the flow domain. Table 8.5.1 shows the grid sizes that were used for the Restored-Planform reach model and the number of grid cells, which give an indication of the computational effort required for each simulation.

| Grid Size (m) | Number of cells in the Restored-Planform Model |
|---|---|
| 0.2 | 281,000 |
| 0.3 | 125,584 |
| 0.4 | 70,782 |
| 0.5 | 45,426 |
| 0.6 | 31,396 |
| 0.8 | 17,766 |
| 1 | 11,413 |
| 1.5 | 5092 |

**Table 8.5.1: Number of Grid Cells for the Model Domain for each Grid Cell Size**

Hardy *et al.* (1999), by investigating the importance of grid resolution upon floodplain models, found that spatial resolution was of more importance than the most commonly calibrated parameter, the friction parameter. However, they suggest that friction parameter values should not be transferred between models. Friction values in hydrodynamic models are used in order to represent sub-grid topographic variability (Nicholas and Mitchell, 2003) and therefore the resistance factor is likely to be a function of the grid resolution. For this reason, the calibration of the roughness parameter is performed in conjunction with grid cell resolution.

## 8.6. Calibration of Manning's n

Hydrodynamic models have a number of parameters that can be varied in order to change certain characteristics of the flow domain. This is because, despite the fact that the hydraulics of well-defined systems are well understood, floodplain inundation is a problem that does not have well defined boundary conditions, or well defined parameterizations of the energy losses associated with such complex flows (Romanowicz *et al.*, 1996). One of the most fundamental parameter is the

Manning's *n* roughness coefficient. The roughness value is a composite term embracing all the frictional or retarding influences causing energy loss in the motion of flow (Richards, 1982). Where a single value is chosen, it is often calibrated in order to allow a 'best fit' between modelled and observed flood events (e.g. Bates *et al.*, 1998; Nicholas and Mitchell, 2003; Hall *et al.*, 2005).

The problem of calibrating hydrodynamic models of river flooding, for example by varying Manning roughness coefficients for channel and floodplain, is widely recognized (Romanowicz *et al.* 1996; Aronica *et al.* 1998), as it has been argued that such calibration destroys a model's predictive capability and severely hampers physically-based and site-independent modelling (Cunge, 1998; Cobby *et al.*, 2003; Pasternack *et al.*, 2004). However, it is a technique that is required in order to reduce some of the uncertainties involved in flow modelling and to fine tune simulations. A two-stage approach was taken to the model calibration, firstly a largely in-bank event (Date 20/05/05 Discharge=0.16$m^3s^{-1}$) was used to calibrate the channel roughness coefficient and once this had been specified then a larger flood event (Date=11/01/05 Discharge=0.35$m^3s^{-1}$) was simulated with the chosen channel coefficient in order to calibrate the floodplain roughness coefficient. This was done with the full range of grid sizes to ensure grid independency was reached. In order to assess the sensitivity of Hydro2de to the spatial resolution of the input raster, a number of raster resolutions were simulated (0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.5).

To calibrate the Manning's roughness coefficient *n*, the model was run with a number of different values for Manning's *n* from 0.01 to 0.2 and then compared with the observed inundation extents and flow velocities. Simulations were carried out on an eight processor IBM x440 with 16GB of memory through eight separate 1.9Ghz Intel Xeon MP processors running a Linux operating system. However, this was a multi-access facility so simulations did vary depending on the time of day and the number of users. Typically, a 1.5m grid simulation took a number of minutes whereas a 0.2m grid took 7-8 hours.

The simulations were run as steady state runs and were run for a 2 hours, which was sufficient time to achieve equilibrium between inflows and outflows. The results were exported using Hydro2de's own POst Processor (POP) unit before being processed into grids using ArcMap.

The chosen Manning's *n* was used over the whole flow domain for the $0.16m^3s^{-1}$ flood event as this was the smallest event with the least amount of out-of-bank flow and so accurate parameterisation of the floodplain Manning's *n* was not necessary for the $0.16m^3s^{-1}$ simulation. As the Restored-Planform reach was newly restored and considered a semi-natural channel, the channel shape was non-uniform especially the margins between the channel and the floodplain. There were small depressions where the channel bankfull discharge started to inundate lower parts of the floodplain close to the channel (in particular one recirculation zone at the top end of the reach and upstream of a large wood accumulation. As a result, some slight inundation of the floodplain close to the channel margins was observed and therefore an approach using inundation extents can be used. However, in addition to the stage data, velocity measurements were also used to assist model calibration and help determine the value of Manning's roughness parameter.

Figure 8.6.1 shows the simulated inundation area plotted against Manning's *n* for a range of grid size resolutions (0.2m-1.5m). It can be seen that as the cell resolution increases, the area of inundation decreases, this trend is consistent with that observed by Hardy *et al.* (1999). Hardy *et al.* (1999) suggest that this is linked to the loss of topographic information at higher grid cell sizes due to mesh filtering by which a courser grid will average out the topographic variability.

Channel Manning's *n* values were tested over a wide range (0.01-0.2) and found to have little impact upon the simulated inundation extent for the smaller grid sizes (see Figure 8.6.1). From the simulated inundation extents, a Manning's *n* of around 0.1 most closely represented the observed inundation extent.

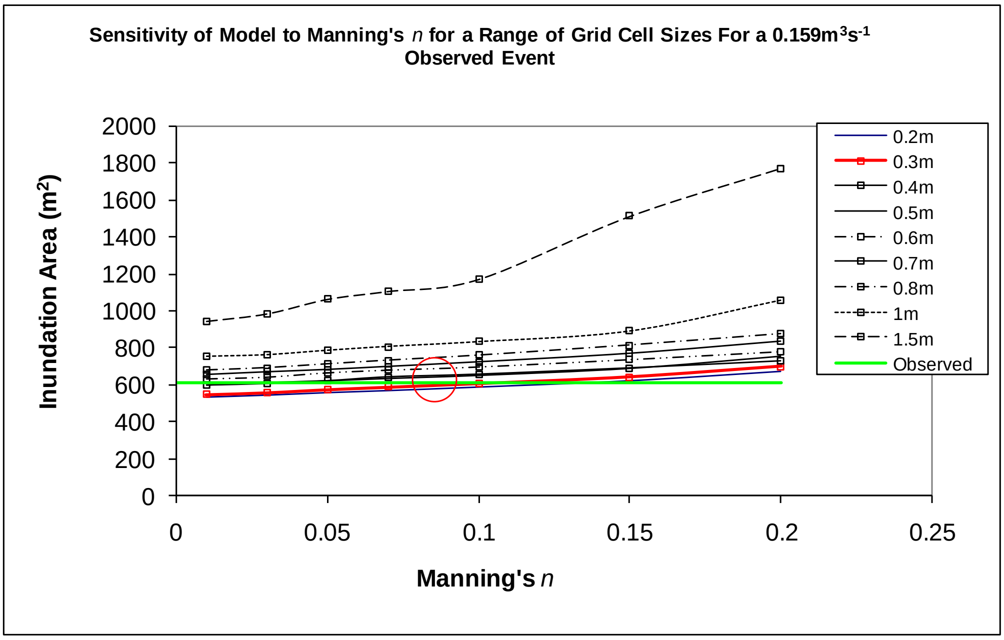



**Figure 8.6.1: Simulated Inundation Area for a number of Manning's *n* for a range of grid sizes for the 0.16m$^3$s$^{-1}$ calibration event.**

Figure 8.6.2 shows the simulated velocity versus the observed velocity for the 0.16m$^3$s$^{-1}$ event. As can be seen, generally there is a good correspondence between the simulated and observed although there is a slight systematic error with over-prediction of low velocities and under-prediction of the higher velocities.

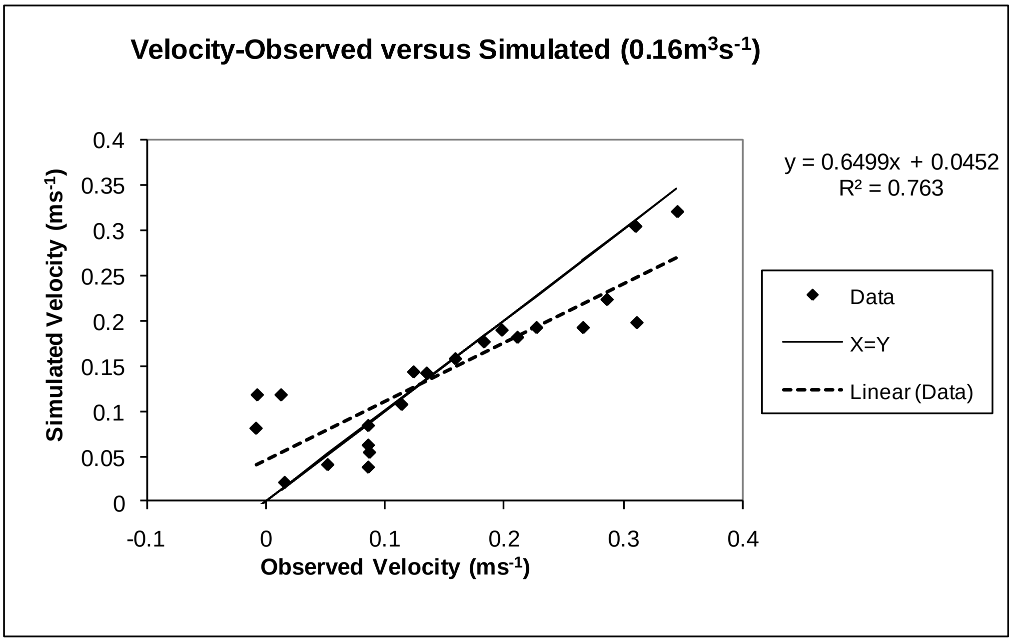



**Figure 8.6.2: Simulated Velocity versus Measured Velocity for the 0.16m$^3$s$^{-1}$ event.**

A Manning's *n* of 0.1 was chosen as this was the parameter that gave the simulated extent that most closely represented the inundation extent and this compares with those used in other studies carried out using hydrodynamic models. It is, however, somewhat larger than the value of 0.01 used by Nicholas and Mitchell, 2003 using the same hydrodynamic code on a reach of the River Culm, Devon, UK. Both simulated channels are gravel-bed rivers and therefore sediment size is not likely to be vastly different between the two modelled locations. Nicholas and Mitchell (2003) found that a large proportion of the channel roughness can be attributed to the model grid and therefore the model results are relatively insensitive to the exact value of n within the range of 0.005 and 0.02. The calibration graph (Figure 8.6.1) shows rather similar results with little variation in inundation extents for a single grid cell size. The average range between a 0.01 Manning's *n* and 0.2 value is 25% of the inundation extent as predicted by the largest grid cell but decreases for smaller grid sizes. Table 8.6.1 shows the absolute and relative differences for each grid cell when the Manning's *n* is subject to a 20-fold increase.

| Grid Size | 0.01 | 0.2 | Absolute Difference ($m^2$) | Percentage Difference |
|---|---|---|---|---|
| **0.2** | 535.06 | 671.04 | 135.98 | 20.2 |
| **0.3** | 547.2 | 696.78 | 149.58 | 21.4 |
| **0.4** | 598.56 | 731.2 | 132.64 | 18.1 |
| **0.5** | 601.5 | 758 | 156.5 | 20.6 |
| **0.6** | 634.68 | 778.32 | 143.64 | 18.4 |
| **0.7** | 654.15 | 838.39 | 184.24 | 21.9 |
| **0.8** | 677.76 | 874.88 | 197.12 | 22.5 |
| **1** | 753 | 1059 | 306 | 28.9 |
| **1.5** | 942.75 | 1773 | 830.25 | 47 |

**Table 8.6.1: Sensitivity of Inundation Area to the specification of two extreme Manning's *n* values for the Restored-Planform Reach.**

The difference for the grid size of 1.5m can largely be explained by loss of topographic information through grid filtering (Hardy *et al.*, 1999). The range is much smaller for the smaller grid resolutions with a relative difference of typically 20% for those grid resolutions $0.7m^2$ and less. This decrease in model sensitivity to Manning's *n* is something that has been observed previously and is due to the increasing accuracy in the representation of the bed topography. This is because roughness is scale-dependent. As the spatial resolution is increased, the description of roughness changes to encompass topographic effects not explicitly covered by the classic fluvial dynamics description of roughness (i.e. where the topographical surface protrudes through the viscous sub-layer) (Lane, 2005). By increasing the spatial resolution, it is necessary to change the amount of topography that must be parameterised as roughness. Therefore, the smaller the grid resolution, the more accurate the representation of the topography and the less uncertainty involved in determining exactly what the roughness coefficient represents. A more accurate representation of bed topography means that there is no requirement for the roughness coefficient to represent meso-scale bed forms. In two-dimensional hydrodynamic modelling, a roughness coefficient is primarily used to represent sub-grid scale topography and the smaller the grid resolution the smaller the sub-grid scale topography. As a result the model becomes less sensitive to the specified roughness; in this case Manning's *n*. Therefore, the value of 0.1 used for the channel roughness is only appropriate for a grid resolution of 0.3m.

## *8.7. Representation of Large Wood Accumulation within a Hydrodynamic Model*

When compared to the observed inundation extents the $0.16m^3s^{-1}$ simulated extent did not portray the same type of flow paths that were observed. Figure 8.7.1 shows the initial simulated inundation extent for the $0.16m^3s^{-1}$ event together with the surveyed observed flow extent.

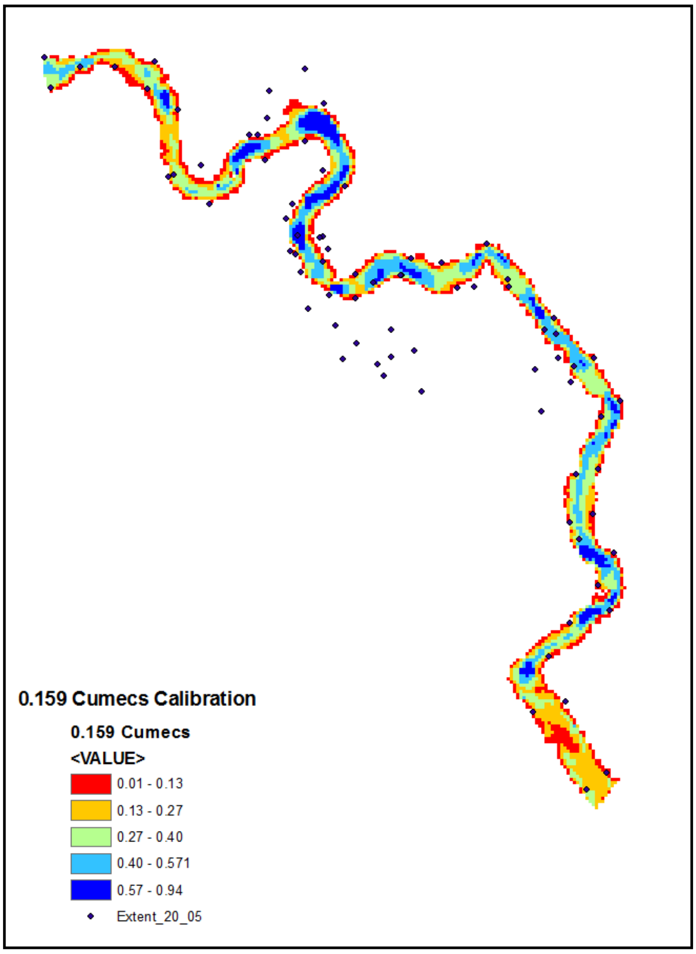



**Figure 8.7.1: Simulated $0.16m^3s^{-1}$ (Coloured by depth in metres) versus the observed extent (dots)**

A flow route was observed upstream of the large wood accumulation where the large wood accumulation had a backwater effect. A lower bank level on the right bank meant that flow began to inundate the floodplain flowing along distributary channels upon the floodplain. This is similar to the mapped channels observed elsewhere in the Highland Water catchment by Millington (2007) whereby shallow channels are formed upon the floodplain upstream of large wood accumulations which route flow over the floodplain (see Figure 8.7.2) in an anastomosing flow pattern. The dynamics of these systems seem to be controlled by the formation and development of large wood accumulations which route flow onto the floodplain. Over time, the presence of large wood and the inundation of the floodplain will further distinguish these floodplain channels which eventually will deepen and can form an anastomosed channel pattern rather than a single meandering thread (Brown *et al.*, 1995; Sear, 2010). This supports the findings of Walter and Merritts (2008) who suggested that large wood accumulations blocked channels and led to the formation of side channels and floodplain sloughs which produce anabranching channels and conditions preferable for the development of wet woodland. This is a significant finding as it suggests that large wood can be used to re-establish the anastomosing flow patterns which many argue is the pre-settlement condition of many European rivers (Brown, 2002; Francis *et al.*, 2008) and North American rivers (Sedell and Frogatt, 1984; Walter and Merritts, 2008; Montgomery, 2008). The multi-channel pattern also has potential to retain more large wood (Millington and Sear, 2007; Sear *et al.*, 2010) which means that large wood is less likely to be transferred to downstream sites where it may become more of a flood risk (for example in urban areas). The presence of multi-channel anastomosed channel pattern and the related large wood is likely to further attenuate the flood peak. The flood peaks monitored in chapter 6 were predominantly in-bank events and therefore attenuated by in-channel large wood. As a result, the attenuation effect appeared to converge at a discharge of $1m^3s^{-1}$ as the in-channel large wood roughness was drowned out. The development of an anastomosed channel pattern and the development of wet woodland with large volumes of large wood could retard the passage of much larger flood events (>1-

$100m^3s^{-1}$) and could potentially attenuate much larger flood events than the ones that have been observed within this research.

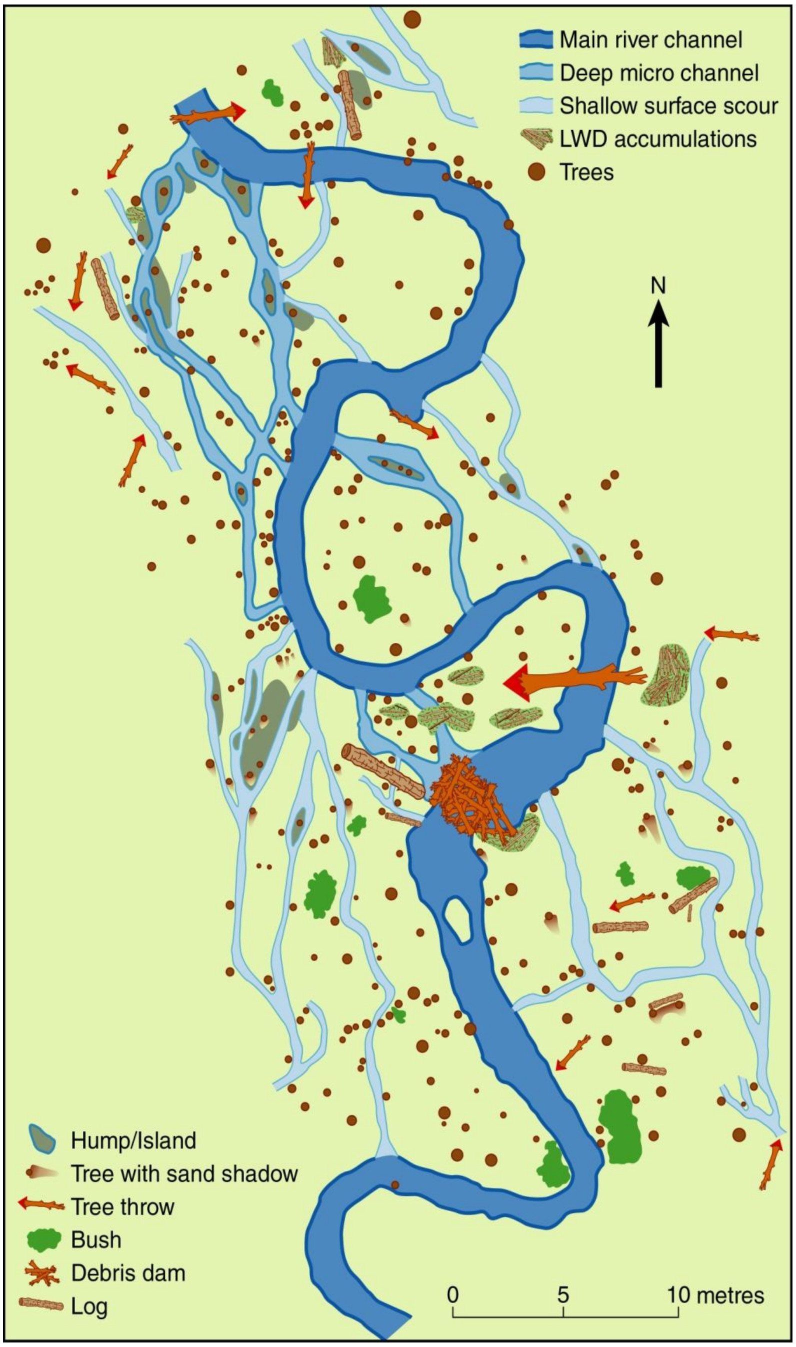



**Figure 8.7.2: Floodplain Distributary Channels (classified here between deep micro channels and shallow scour channels) from Millington (2007).**

The presence of large wood in forested environments is significant in creating anastomosed flow channels. As such, it is necessary to represent large wood accumulations within the hydrodynamic model to ensure the flow patterns are accurately represented.

The representation of vegetation in hydraulic and hydrodynamic models is a topic that is often visited by hydraulic modellers and large wood is no exception (Pasternack *et al.*, 2004). Most often, the effect of vegetation is lumped into a roughness approach as essentially the vegetation is a sub grid topographic element. The vegetative resistance can be calibrated in the same way that channel bed resistance may be calibrated (Cobby *et al.*, 2003). Alternatively, the roughness can be chosen from tables such as those of Chow (1959) and Arcement and Schneider (1987), however neither explicitly contain large wood accumulations in their guidance. Another method is to use empirical equations using vegetal properties to roughness for example those developed by Kouwen and Unny (1975) and Kouwen and Li (1980) for short vegetation, and Fathi-Moghadem and Kouwen (1997) and Kouwen and Fathi-Moghadem (2000) for tall vegetation. Therefore, one method tested as part of this hydrodynamic modelling was to apply the measures of large wood resistance developed in the previous chapter. As the large wood accumulation present within the reach was an overflow accumulation, the average Manning's $n$ of 1.4 derived in the previous chapter of this thesis was used within the hydrodynamic model. Using polygon commands in Hydro2de an area of differing roughness could be represented within the hydrodynamic model.

Other work has treated vegetation as discrete topographic entities represented within the ground model. Fischer-Antze *et al.* (2001) used vertical cylinders to represent aquatic vegetation. Although considered preferable as it gives a representation of the vegetation throughout the flow depth, the study of Fischer-Antze *et al.* (2001) was implemented within a three-dimensional hydrodynamic model. However, it is still possible to represent vegetation as a topographic element in a lower dimension model such as often used when representing bridge piers, buildings and other obstructions.

The limitation of using topography to represent vegetation is that the topographic element is non-porous. However, in the case of large wood accumulations the presence of fine wood and leaf litter means that this assumption is not entirely inappropriate. During the topographic survey the large wood accumulation in the middle of the reach was surveyed and added to the topographic DEM and was subsequently represented within the hydrodynamic model. The model was run with the two different setups using a discharge of $0.16 m^3 s^{-1}$ and the results are shown in figure 8.7.3 where they are plotted against the surveyed flood extents. It is clear that representing the large wood using a topographic entity leads to a much more anabranching than was observed. The representation of the large wood using the Manning’s *n* approach produced a much better match with the observed extents.

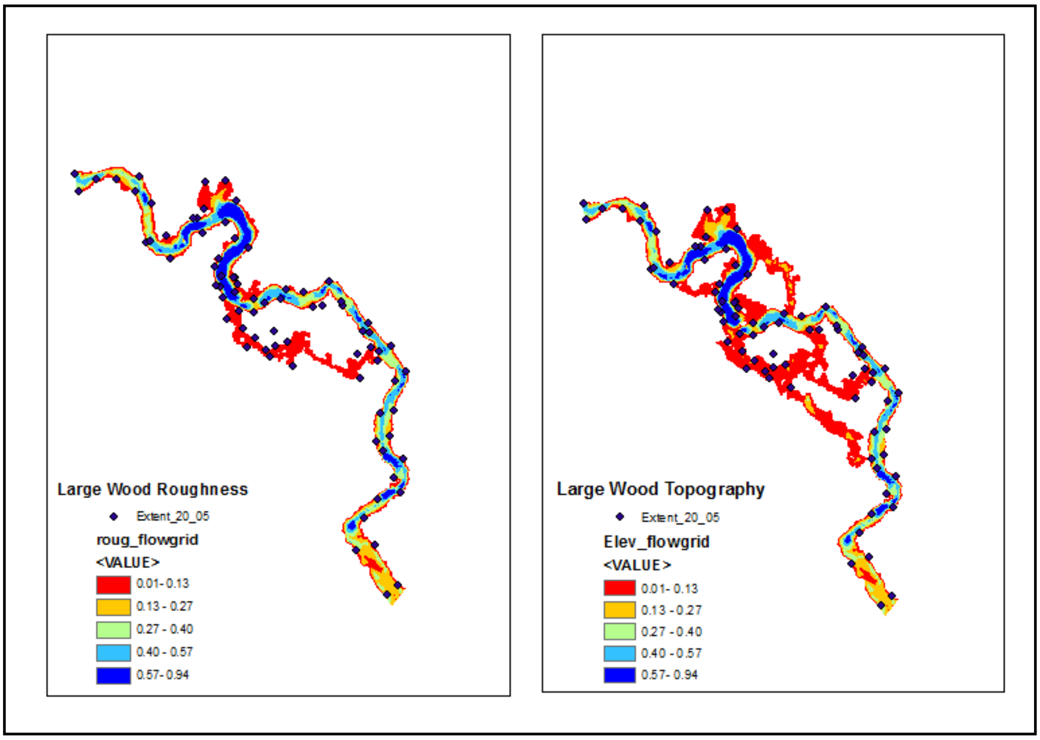



**Figure 8.7.3: The Sensitivity of the Flow Depth Output to the method of representing the Large Wood Accumulation.**

The increased anabranched flow area is a function of the topographic representation, which does not allow any flow to pass through the large wood accumulation. The non-porous topographic representation leads to a higher level of backwater, increasing upstream stage and consequently increased flow on the floodplain. Although this represents the mechanism whereby an overflow accumulation initiates floodplain inundation the topographic approach to representing the large wood accumulation over-predicts the amount of floodplain inundation.

To further test the two methods of representing large wood accumulations in a hydrodynamic model the sensitivity of the flow velocities downstream of the large wood accumulation was assessed. Table 8.7.1 shows the velocity for a number of random points downstream of the simulated large wood accumulation. The large wood-elevation scenario consistently has lower velocities than the large wood-roughness scenario. This suggests that the Manning's *n* approach allows some flow through the simulated large wood accumulation although it is significantly retarded by the high Manning's *n* value. The large wood-elevation approach does not allow any flow through the simulated large wood accumulation and thus flow velocities are lower. This indicates that the Manning's *n* is better at conserving the momentum of flow through the large wood accumulation.

| | **Velocity ($ms^{-1}$)** | |
|---|---|---|
| **Point No.** | **Large Wood-Roughness** | **Large Wood-Elevation** |
| 1 | 0.23 | 0.18 |
| 2 | 0.12 | 0.09 |
| 3 | 0.18 | 0.04 |
| 4 | 0.18 | 0.04 |
| 5 | 0.16 | 0.03 |
| 6 | 0.10 | 0.07 |
| 7 | 0.14 | 0.04 |
| 8 | 0.16 | 0.08 |
| 9 | 0.20 | 0.19 |
| 10 | 0.19 | 0.11 |

**Table 8.7.1: The sensitivity of velocity to the representation of the large wood accumulation. The velocity locations were taken downstream of the simulated large wood accumulation.**

The Manning's *n* approach also produces a much better match with observed flow extents and is therefore considered better suited to the representation of the processes that occur at large wood accumulations within the Restored-Planform reach in this study. Therefore, the roughness approach will be used for the representation of large wood accumulations for the subsequent simulations.

The final, calibrated $0.16m^3s^{-1}$ extent, coloured by flood depth, is shown in figure 8.7.4 together with the observed outline. As can be seen the flow is mainly contained within the channel with some flow beginning to exit the channel at a recirculation zone and also upstream of a large wood accumulation where water flows begins to anabranch.

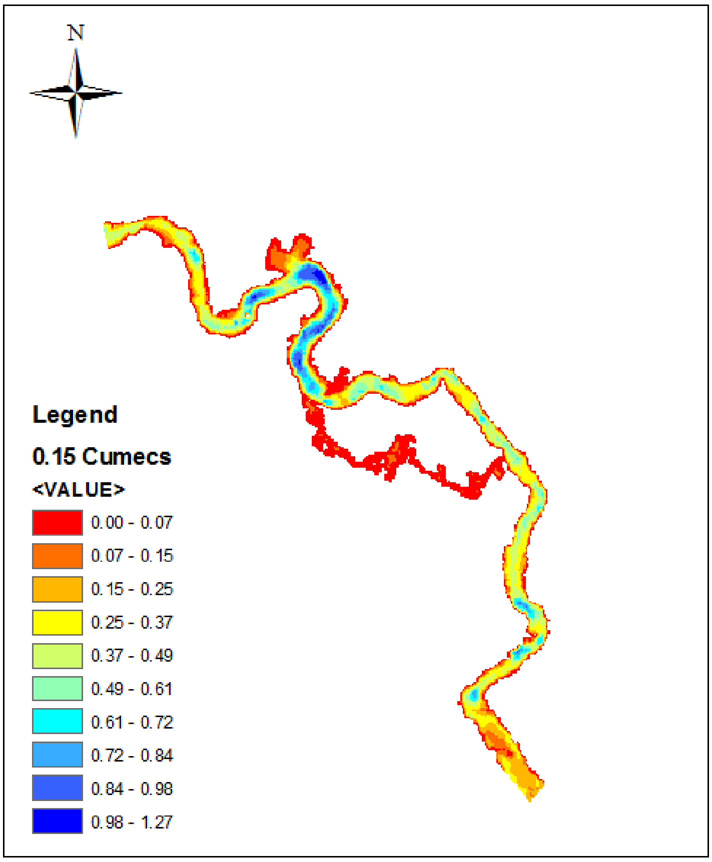



**Figure 8.7.4: The Calibrated $0.16m^3s^{-1}$ flood event mapped flow depth.**

Once the large wood accumulation was represented, then it was possible to begin to calibrate the floodplain roughness coefficient, which has been shown to have a far greater effect on model results than channel roughness (Hardy, 1997).

## *8.8. Floodplain Roughness Coefficient*

A similar roughness parameter sensitivity analysis was carried out to calibrate the floodplain roughness coefficient using an observed event of $0.37m^3s^{-1}$ measured on the 11th January 2005. Again, velocity inflow measurements were taken so that the inflow discharge could be calculated using the velocity-area method. Inundation extents and water surface elevations were surveyed relative to a standard datum and velocity measurements were taken at two cross-sections within the reach. Figure 8.8.1 shows the inundation extent for a range of Manning's *n* values as it varies with grid cell size. As would be expected there is a decrease in inundation extent when Manning's *n* is reduced as there is less resistance to the flow flowing across the floodplain.

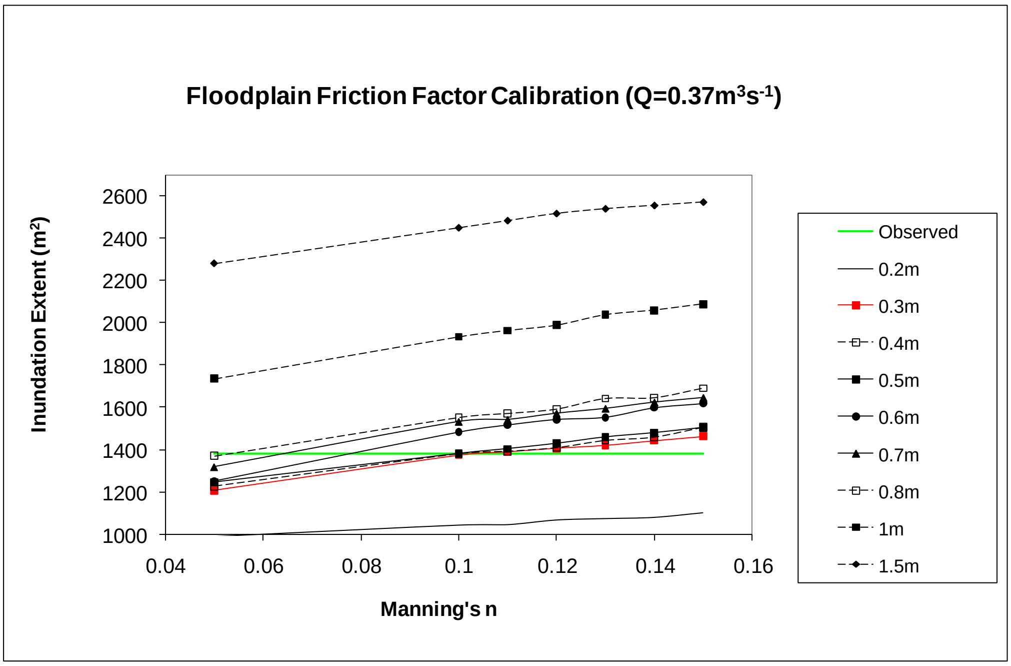



**Figure 8.8.1: Simulated Inundation Area for a number of Manning's n for a range of grid sizes for the $0.37m^3s^{-1}$ calibration event.**

The floodplain friction factor is generally more sensitive than that for the channel friction factor and contributes to larger variations in simulated inundation extents. This is consistent with the findings of Hardy (1999) and is likely to be due to the interaction of the shallow flow with the floodplain friction components compared with the deeper flow depths associated with the channel, which drown out any skin friction effects. As can be seen from the figure, the Manning's *n* which provides simulation results most akin with those observed was *n*=0.11. As a result, this was chosen for subsequent simulations. This compares favourably with the values for floodplain roughness used by Nicholas and Mitchell (2003, *n*=0.06 for rough pasture) and Connell *et al.* (1998) (shown in table 8.8.1 for various land use types) in previous applications of Hydro2de.

| **Description** | **Manning's *n*** |
|---|---|
| General pastoral farm land (grass and fences) | 0.05 |
| Areas of trees | 0.125 |
| Hedges | 0.125 |
| Crops | 0.07 |
| Roads | 0.03 |

**Table 8.8.1: Recommended Floodplain Friction Values used by Connell *et al.* (1998).**

A Manning's *n* value of 0.11 also compares well with those observed values of Arcement and Schneider (1989) that had values between 0.1 and 0.2 for forested floodplains. Their description for those sites with a Manning's *n* of 0.15 is as follows:-

"*Computed roughness coefficient: Manning's n=0.15*
*Date of flood: December 7, 1971*
*Date of photograph: April12, 1979*
*Depth of flow on floodplain: 4.1 ft*
*Description of floodplain: The vegetation of the food (sic) plain is large and small trees, including oak, gum and ironwood. The base is firm soil and has minor surface irregularities caused by rises and depressions. Obstructions are*

*negligible (some exposed roots). Ground cover is negligible, and undergrowth is minimal.*" (Arcement and Schneider, 1989 Figure 17 p 24.)

This description is similar to that of the floodplain of the current study. The main tree species that is present upon the floodplain are Alder (*Alnus glutinosa*) which is present along the stream margins. The base is a firm soil although the floodplain surface does have surface irregularities such as sand shadows, topographic lows and hummock features. There is no major ground cover and undergrowth is limited. There are some obstructions in the form of logs, tree stumps and debris, which can disturb the flow pattern.

The $0.37m^3s^{-1}$ calibration event was also checked for the correspondence between measured and simulated velocity values. It was not deemed appropriate to calibrate the Manning's *n* for the $0.37m^3s^{-1}$ model using velocity measurements because observed velocity measurements were limited to points within the channel. The low flow depths present upon the floodplain make it difficult to obtain flow velocity measurements using conventional EMCM instruments where the sensor can only measure velocity in flow depths greater than 0.08m.

The measured and simulated velocity shows a good fit with the simulated velocity (as shown in Figure 8.8.2) with an average difference of $0.02ms^{-1}$ and a Root Mean Squared Error of $0.1ms^{-1}$. Therefore, the channel roughness coefficient was set to 0.1 and the floodplain roughness coefficient was set to 0.11 for the remainder of the numerical experiments.

Figure 8.8.3 shows the calibrated $0.37m^3s^{-1}$ inundation extent together with the surveyed points taken at the edge of the inundated area. The simulated extent had an area of $1404m^2$, which is slightly larger than the observed flow area of $1382m^2$, but it is still considered a good fit.

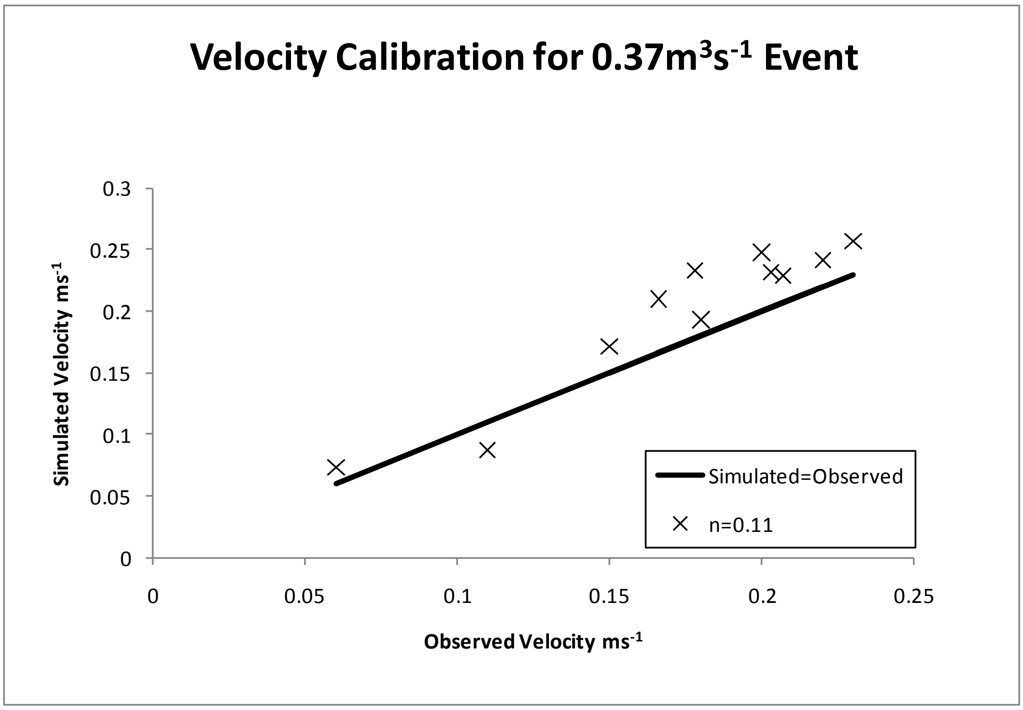



**Figure 8.8.2: Simulated versus Observed Velocity for the 0.37m$^3$s$^{-1}$ event.**

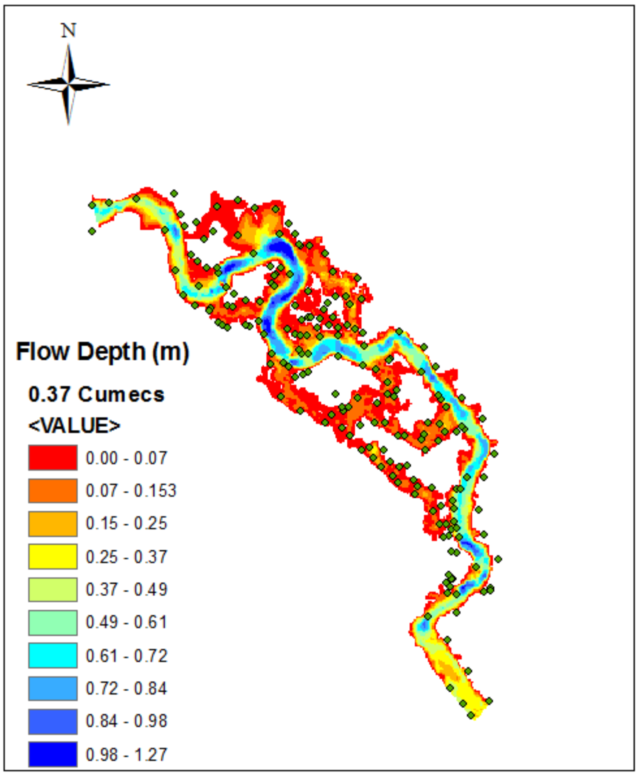



**Figure 8.8.3: Calibrated 0.37m$^3$s$^{-1}$ Result (Coloured by flow depth in metres) versus the observed extent (dots)**

Now that the grid size and Manning's *n* parameters have been specified it is possible to assess the sensitivity of the turbulence parameters.

## 8.9. Model Sensitivity to Turbulence Parameters

Turbulence is a fundamental component of all non-laminar flows and therefore there is a necessity to represent it within a hydrodynamic model as it can affect both the velocity and momentum transfer present within the flow domain (Nelson *et al.*, 2003). Hydro2de uses the Boussinesq approximation to model turbulent stresses with the eddy viscosity determined using a zero-equation model. The default method is where the eddy coefficient ($v_i$) is estimated using the following default equation.

$$v_t = 0.07 u_* h \tag{8.7}$$

Where $u_*$ is the friction velocity and $h$ is the flow depth. The value of 0.07 is the default value for the eddy coefficient, which can be varied by the user. It has been argued the eddy viscosity concept has a poor physical basis and the viscosity is difficult to measure in the field (Lane, 1998)

However, there is also a mixing length method that can be used in Hydro2de based on Prandtl's (1925) equation. The Hydro2de mixing length equation is below:-

$$n = lm^2 * \left( \frac{du}{dy} + \frac{dv}{dx} \right) \tag{8.8}$$

Where $lm$ is the mixing length, $u$ and $v$ are components of the flow velocity and $x$ and $y$ are distance values. This is thought to have a better physical basis and is preferred. However, for the purposes of this work a sensitivity analysis was conducted on both parameters to assess their significance.

A sensitivity analysis was undertaken by varying the eddy coefficient between 0.01 and 0.2. For eleven locations where velocity was measured, the average standard deviation was 0.0007, which is deemed insignificant (see Table 8.9.1). As the variation in simulated velocity was small, it can be considered that the Restored-Planform model is relatively insensitive to the specification of the eddy coefficient.

The mixing length model was also subject to a sensitivity analysis with the mixing length value altered between 0.01 and 0.25. Again, the variation in simulated velocity was insignificant with the average standard deviation being 0.002 (see Table 8.9.2).

| **Eddy Coefficient** | **0.01** | **0.02** | **0.05** | **0.07** | **0.1** | **0.15** | **0.2** | **Standard Deviation** |
|---|---|---|---|---|---|---|---|---|
| **Point** | | | | | | | | |
| Cross-Section 1 Point 1 | 0.212 | 0.212 | 0.212 | 0.211 | 0.211 | 0.21 | 0.208 | 0.001 |
| Cross-Section 1 Point 2 | 0.232 | 0.232 | 0.232 | 0.231 | 0.231 | 0.231 | 0.23 | 0.001 |
| Cross-Section 1 Point 3 | 0.243 | 0.243 | 0.242 | 0.242 | 0.241 | 0.241 | 0.241 | 0.001 |
| Cross-Section 1 Point 4 | 0.229 | 0.229 | 0.228 | 0.228 | 0.229 | 0.229 | 0.229 | 0.000 |
| Cross-Section 1 Point 5 | 0.191 | 0.191 | 0.191 | 0.192 | 0.192 | 0.192 | 0.193 | 0.001 |
| Cross-Section 1 Point 6 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 | 0.056 | 0.000 |
| Cross-Section 2 Point 1 | 0.102 | 0.102 | 0.102 | 0.102 | 0.102 | 0.102 | 0.101 | 0.000 |
| Cross-Section 2 Point 2 | 0.336 | 0.336 | 0.336 | 0.336 | 0.337 | 0.337 | 0.337 | 0.001 |
| Cross-Section 2 Point 3 | 0.254 | 0.254 | 0.255 | 0.255 | 0.255 | 0.254 | 0.253 | 0.001 |
| Cross-Section 2 Point 4 | 0.239 | 0.239 | 0.238 | 0.238 | 0.238 | 0.237 | 0.237 | 0.001 |
| Cross-Section 2 Point 5 | 0.175 | 0.174 | 0.174 | 0.175 | 0.174 | 0.174 | 0.174 | 0.000 |
| | | | | | | | **Total** | 0.001 |

**Table 8.9.1: Sensitivity of Velocity ($ms^{-1}$) to the specification of the Eddy Coefficient.**

| Mixing Length<br>Point | 0.01 | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 | Standard Deviation |
|---|---|---|---|---|---|---|---|
| Cross-Section 1 Point 1 | 0.211 | 0.212 | 0.21 | 0.21 | 0.209 | 0.208 | 0.001 |
| Cross-Section 1 Point 2 | 0.234 | 0.232 | 0.233 | 0.232 | 0.232 | 0.231 | 0.001 |
| Cross-Section 1 Point 3 | 0.243 | 0.243 | 0.236 | 0.236 | 0.235 | 0.234 | 0.004 |
| Cross-Section 1 Point 4 | 0.233 | 0.229 | 0.229 | 0.229 | 0.229 | 0.228 | 0.002 |
| Cross-Section 1 Point 5 | 0.193 | 0.191 | 0.193 | 0.193 | 0.193 | 0.193 | 0.001 |
| Cross-Section 1 Point 6 | 0.07 | 0.06 | 0.073 | 0.07 | 0.07 | 0.073 | 0.005 |
| Cross-Section 2 Point 1 | 0.086 | 0.087 | 0.087 | 0.087 | 0.087 | 0.086 | 0.001 |
| Cross-Section 2 Point 2 | 0.258 | 0.252 | 0.26 | 0.26 | 0.26 | 0.261 | 0.003 |
| Cross-Section 2 Point 3 | 0.255 | 0.256 | 0.255 | 0.254 | 0.254 | 0.253 | 0.001 |
| Cross-Section 2 Point 4 | 0.24 | 0.239 | 0.24 | 0.239 | 0.238 | 0.238 | 0.001 |
| Cross-Section 2 Point 5 | 0.171 | 0.175 | 0.171 | 0.172 | 0.173 | 0.171 | 0.002 |
| | | | | | | **Total** | 0.002 |

**Table 8.9.2: Velocity ($ms^{-1}$) Sensitivity to Specification of the Mixing Length.**

This is not entirely unexpected as the main limitation with zero-equation models is that they implicitly assume that the turbulence is dissipated where it is generated (Rodi, 1980). Zero-equation models do not account for the movement of turbulent structures in the mean flow and for situations where turbulence at a point is significantly influenced by turbulence generation in other areas of the flow domain (Lane, 1998). This is a problem for all zero-equation models and is often overcome through the use of one- or two-equation models that solve additional differential equations (Lane, 1998). However, there is currently no option to solve these in Hydro2de. It is likely that the locations where velocity measurements were made were in areas where turbulence generation was low and flow interference by outside agents was minimal. However, the turbulence structures rarely have a significant effect upon inundation extents which is the prime interest in this study given that the model is insensitive it was appropriate to use the default values. As the mixing length model is considered to be physically based this was used with the default setting of 0.1, which was used for the remainder of the modelling study.

## 8.10. Model Validation

In order to assess the validity of the model calibration it is necessary to use the calibrated model to simulate a situation for which there is further observed data without any further calibration of the model. For the purposes of this study, two events were used to ensure accurate model calibration and a further larger event was used to validate the model. This larger event on 20th October 2004 was the largest observed with a discharge of $0.45m^3s^{-1}$.

In order to conduct the validation the model was run with an inflow of $0.45m^3s^{-1}$ and run to provide results. The simulated flow extent was $1660m^2$, which compares to an observed extent of $1620m^2$, which is a good fit, and results can be considered valid in terms of inundation extent.

Figure 8.10.1 shows the simulated inundation extent for the $0.45m^3s^{-1}$ event together with the surveyed points of inundation extent. There is generally a very good fit between the observed and simulated extents with minor differences likely to be caused by the complex micro-topography that is present on natural floodplains (Nicholas and Walling, 1998) which is averaged out when represented using a 0.3m grid cell.

Validation was also undertaken for the velocity values as obtained by LSPIV method. Table 8.10.1 shows the velocity values obtained from the acquired images of flooding on the 20th October 2004. As the velocity values were surface flow velocities acquired from geo-referenced images, the values were scaled by 0.85. This value of 0.85 was found in trials to be an appropriate value to scale between surface flow velocity and depth average flow velocity.

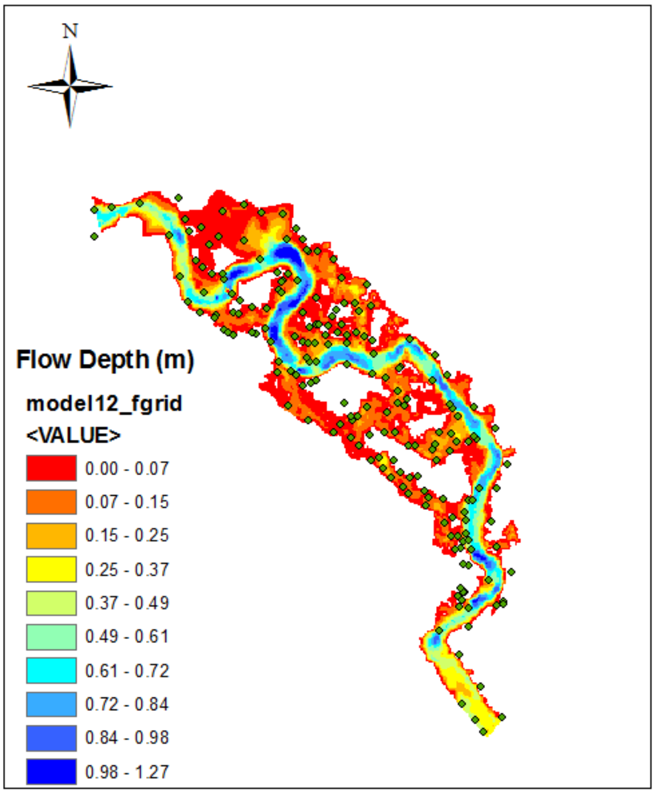



**Figure 8.10.1: The Validated $0.45m^3s^{-1}$ Simulated Inundation Extent with the Surveyed Inundation Extents.**

Figure 8.10.2 shows the plot of the observed flow velocity versus the simulated flow velocity. Graphically it can be seen that the simulated velocity consistently over-predicts the observed velocity. However, the average difference is $0.05ms^{-1}$, which is considered to be well within the uncertainties associated with the LSPIV method given the data collection methods, georeferencing residuals and the subsequent analysis. However, this must be considered when reviewing the outputted results of the model.

| Image Number | Easting | Northing | Surface Flow Velocity ($ms^{-1}$) | Depth Averaged Flow Velocity ($ms^{-1}$) | Simulated Flow Velocity ($ms^{-1}$) |
|---|---|---|---|---|---|
| **Image 1** | 7.62 | 40.36 | 0.16 | 0.13 | 0.24 |
| | 8.07 | 39.85 | 0.25 | 0.22 | 0.226 |
| | 8.68 | 39.75 | 0.20 | 0.17 | 0.238 |
| | 9.76 | 39.58 | 0.15 | 0.13 | 0.197 |
| | 8.44 | 40.51 | 0.14 | 0.12 | 0.241 |
| | 9.09 | 40.14 | 0.23 | 0.19 | 0.259 |
| | 9.8 | 40.56 | 0.25 | 0.21 | 0.279 |
| | 10.56 | 40.75 | 0.30 | 0.26 | 0.28 |
| | 9.64 | 41.16 | 0.11 | 0.09 | 0.235 |
| | 8.85 | 41.31 | 0.24 | 0.20 | 0.215 |
| **Image 2** | 27.79 | 24.3 | 0.16 | 0.13 | 0.175 |
| | 28.65 | 24.3 | 0.14 | 0.12 | 0.166 |
| | 27.83 | 23.73 | 0.16 | 0.13 | 0.2 |
| | 28.77 | 23.44 | 0.25 | 0.21 | 0.23 |
| | 29.48 | 23.37 | 0.24 | 0.20 | 0.24 |
| | 29.99 | 23.05 | 0.23 | 0.20 | 0.255 |
| | 27.19 | 23.12 | 0.2 | 0.18 | 0.189 |
| | 27.98 | 22.65 | 0.17 | 0.14 | 0.178 |
| | 28.98 | 22.44 | 0.13 | 0.10 | 0.189 |
| | 29.45 | 21.4 | 0.13 | 0.11 | 0.121 |
| **Image 3** | 48.1 | -10.53 | 0.31 | 0.26 | 0.262 |
| | 48.7 | -10.95 | 0.29 | 0.25 | 0.257 |
| | 49.31 | -11.53 | 0.30 | 0.26 | 0.297 |
| | 48.61 | -11.86 | 0.15 | 0.13 | 0.202 |
| | 49.29 | -12.28 | 0.24 | 0.20 | 0.246 |
| | 51.46 | -13.26 | 0.28 | 0.24 | 0.231 |
| | 49.87 | -13.17 | 0.20 | 0.17 | 0.179 |
| | 49.5 | -13.19 | 0.19 | 0.16 | 0.178 |
| | 49.78 | -13.89 | 0.15 | 0.12 | 0.198 |
| | 50.62 | -13.71 | 0.20 | 0.17 | 0.204 |

**Table 8.10.1: The Velocity Values obtained from three LSPIV images for validation of the Restored-Planform model for the 0.45$m^3s^{-1}$ event.**

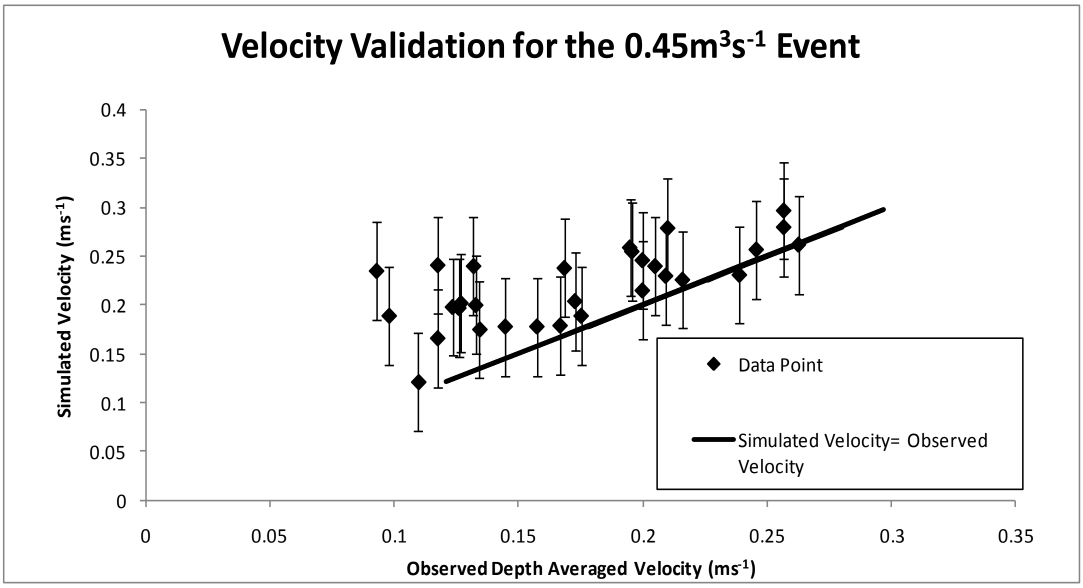



**Figure 8.10.2: Observed Velocity versus Simulated Velocity for the 0.45m$^3$s$^{-1}$ event. Plotted with 0.05m error bars on the observed velocity values obtained from the LSPIV approach.**

The model validation has shown that the Hydro2de model of the Restored-Planform reach can successfully recreate the inundation patterns that have been observed in three separate events of differing magnitude. The Hydro2de model is also suitable for use as a tool to simulate flow velocities within the reach. However, it should be noted that for both the 0.37m$^3$s$^{-1}$ and 0.45m$^3$s$^{-1}$ events the flow velocity is over-predicted with average errors of 0.03ms$^{-1}$ and 0.05ms$^{-1}$ respectively. However, this is considered an acceptable error given the uncertainties associated with the hydrodynamic model, the model setup and the measurement error.

One of the key outputs from hydrodynamic modelling is maps of flood depth and flow velocity from which it can ascertain inundation extents and patterns. Figure 8.10.3 shows the maps of flow depth for three simulated events of 0.16m$^3$s$^{-1}$, 0.37m$^3$s$^{-1}$ and 0.45m$^3$s$^{-1}$. From these datasets, it is possible to derive inundation area as well as flow depth distributions, which can be used to calculate metrics to determine the effect of different variables. Therefore, the Restored-Planform hydrodynamic model can be used to assess flow patterns within semi-natural anastomosed channels in the presence of large wood as well as for undertaking numerical experiments that forms the basis for the rest of this chapter.

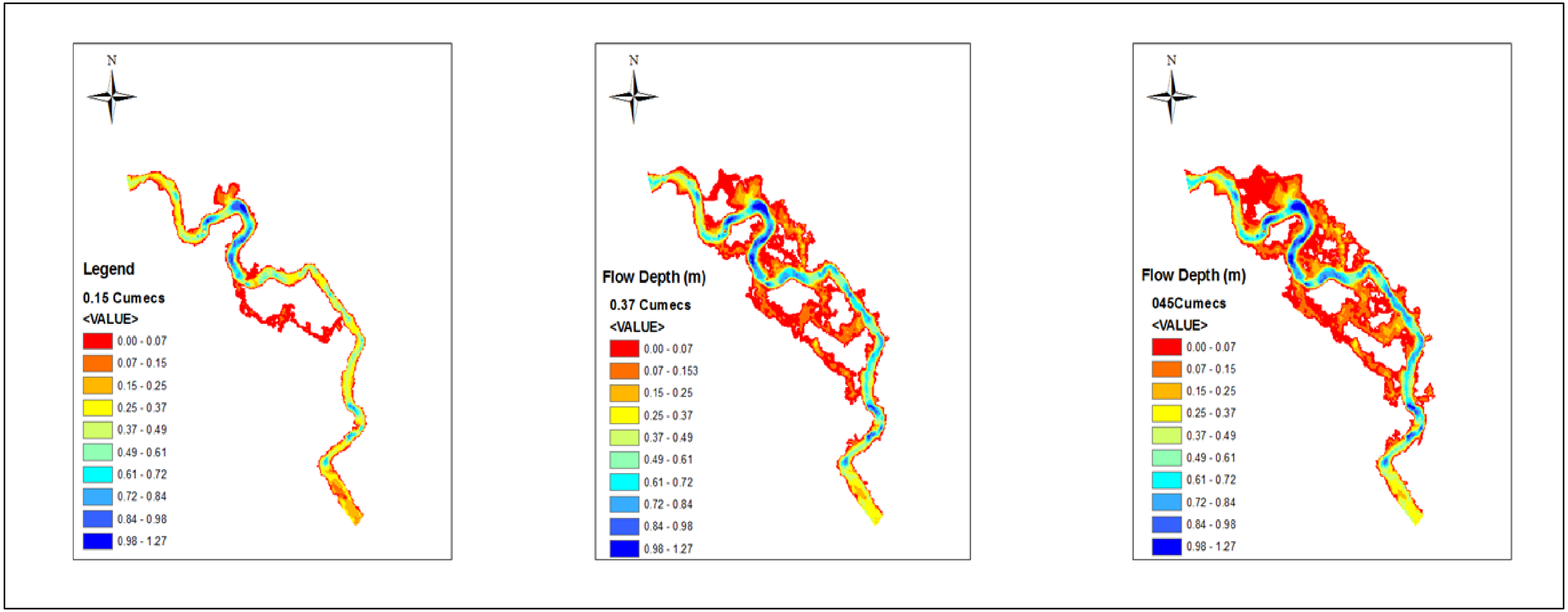



**Figure 8.10.3: The Simulated Inundation extents for the 0.16m$^3$s$^{-1}$, 0.37m$^3$s$^{-1}$ and 0.45m$^3$s$^{-1}$ flood events.**

## *8.11. The Effect of Large Wood Accumulations on Floodplain Inundation*

Large wood accumulations have been shown to be important in retarding and ponding flow leading to the backwatering of flow (Gippel *et al.*, 1992; Gippel *et al.*, 1996). If the blockage ratio of the wood area to the channel cross-section is sufficient then there may be conditions favourable for the initiation of anastomosing flow to occur. The role that different large wood accumulations play in influencing anabranching is not currently known. It is hypothesised that the more hydraulically active accumulations identified in the previous chapter such as the overflow accumulations are likely to result in increased anabranching with more diverse anastomosing patterns. The calibrated and validated Hydro2de model was used to undertake a number of numerical experiments into the role of large wood accumulations for the three observed discharges ($0.16m^3s^{-1}$, $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$). The model was not used to simulate any larger events as this would extrapolate outside of the validated range (up to $0.45m^3s^{-1}$) of the model. In these experiments, the type and number of large wood accumulations were varied to assess the impact upon inundation extent and pattern. Simulations were conducted for the following large wood scenarios for each discharge:-

- No Large Wood present,
- 1 * Underflow Accumulation,
- 1* Deflector Accumulation,
- 1* Overflow Accumulation,
- 3 * Underflow Accumulations,
- 3 * Deflector Accumulations,
- 3 * Overflow Accumulations.

The different large wood accumulations were represented through the parameterisation of the Manning's *n* parameter. The values obtained in the previous chapter were used and these are summarised in table 8.11.1.

| Type | Manning's *n* Value |
|---|---|
| None | 0 |
| Underflow Accumulation | 0.27 |
| Deflector Accumulation | 0.32 |
| Overflow Accumulation | 1.42 |

**Table 8.11.1: The average Manning's n values for various large wood accumulation types as derived in chapter 7. These were applied to the area where the large wood accumulation was positioned within the simulation.**

The number of accumulations was also varied to simulate different management scenarios. A management scenario, which involves the clearance of large wood accumulations, consistent with past management practices (Gurnell and Sweet, 1998), from the reach was simulated by not representing any large wood accumulations within the model. The presence of one large wood accumulation represents the current restored situation as observed on the ground today whereas three accumulations represents the average number of large wood accumulations per 100m (average value 2.69 per 100m) for the Highland Water as a whole. This latter scenario is considered to be an unmanaged scenario where large wood is not cleared and is allowed to accumulate naturally within the channel. The unmanaged scenario is one that current management practices seem to be moving towards (Collins and Montgomery, 2002). With limited management and interference, large wood can be continuously supplied through the erosion of river banks, transport from upstream or through windblown large wood (Gurnell, 1997) and thus this estimate of unmanaged wood loading is conservative.

Within the Hydro2de model, the large wood was located according to where it was observed and also at known jam points observed within the reach. The single large wood accumulation was represented in the middle of the reach (Point A), this is the same location as the observed overflow accumulation and as represented in the calibrated model. In the three large wood accumulations scenario the accumulations were represented at known jam points within the reach where large wood collected. These points are shown schematically in figure 8.11.1. Point B was a jam point at the exit point of a meander bend and Point C was a jam point at a narrow section of the reach where a poplar tree sits on the edge of the bank and often catches large wood. It is thought that the ability of large wood accumulations to trap large wood and self-perpetuate is influenced by type (Piégay and Gurnell, 1997; Gurnell and Sweet, 1998) but this was not represented within the modelling framework.

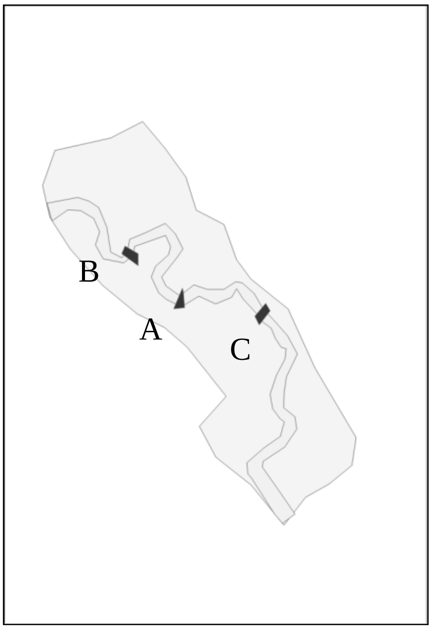



**Figure 8.11.1: Location of simulated Large Wood Accumulations within the Restored-Planform reach.**

Figures 8.11.2, 8.11.3 and 8.11.4 plots each flow extent against the large wood accumulation type for the three discharges. The large wood accumulations are plotted in order of increased hydraulically activity. The results from the numerical experiments show that the type of large wood accumulation influences the amount of anabranching and the flow area. As can be seen, as the large wood accumulation becomes more hydraulically active the flow extent also increases and this is also shown in Figure 8.11.5 which summarises the flow area for each model scenario. The increased resistance offered by the overflow accumulations can increase flow extent by up to 46% for a single large wood accumulation and up to 67% for three overflow accumulations within a reach for the $0.37 m^3 s^{-1}$ scenario.

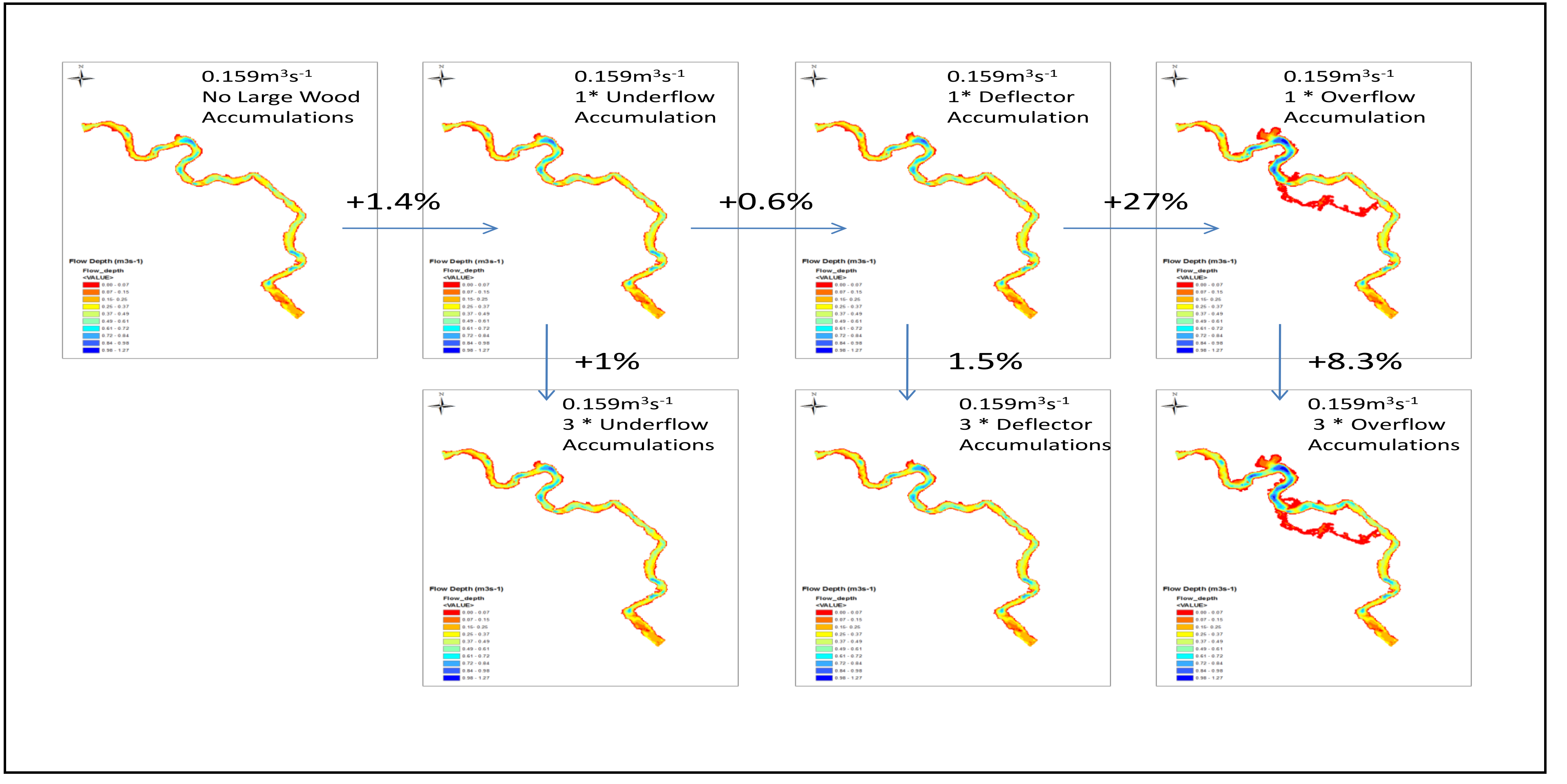



**Figure 8.11.2: Simulated Flow Extent for the 0.16m$^3$s$^{-1}$ Large Wood Accumulation Scenarios showing the percentage change in Flow area.**

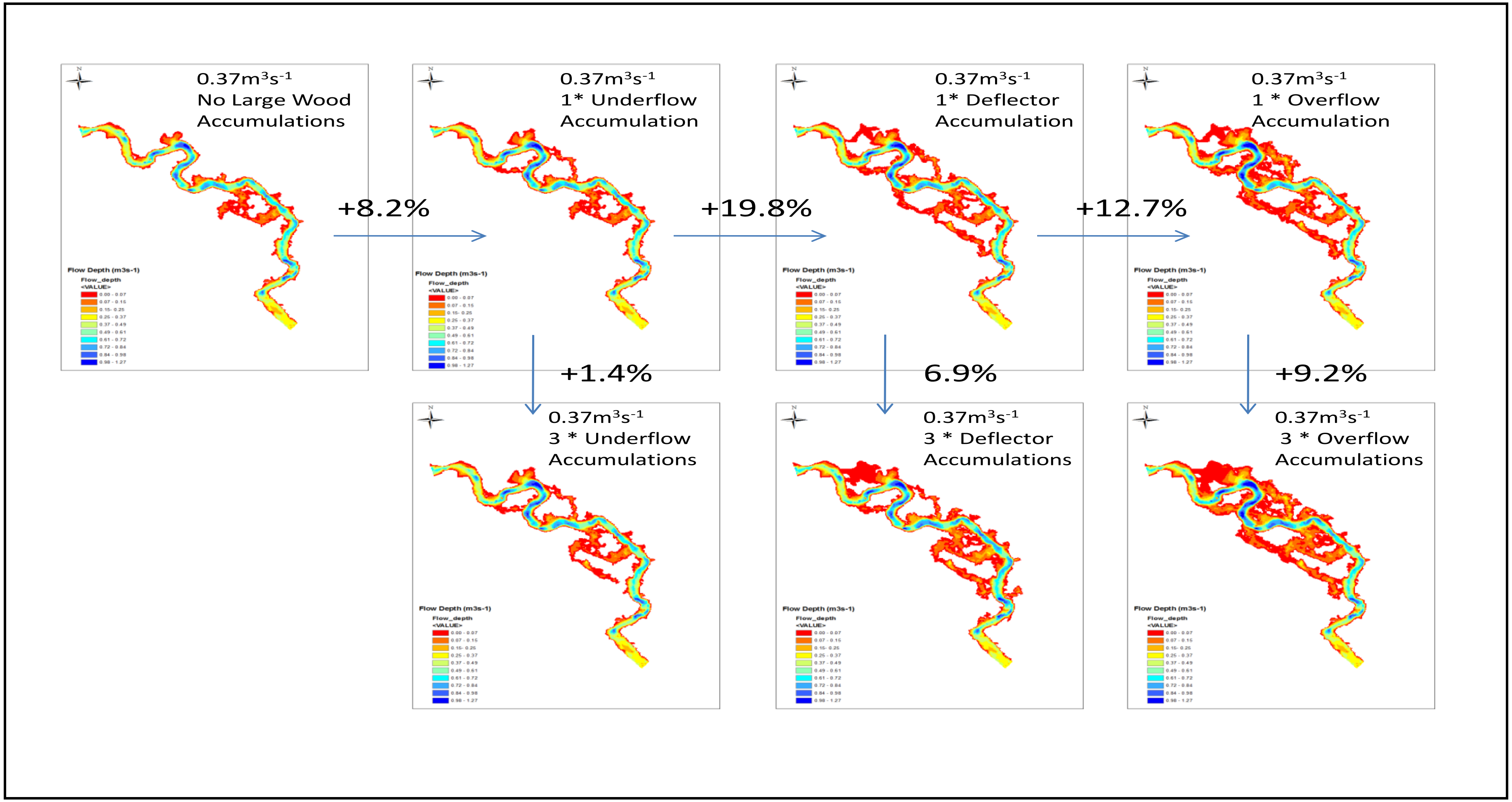



**Figure 8.11.3: Simulated Flow Extent for the $0.37m^3s^{-1}$ Large Wood Accumulation Scenarios showing the percentage change in flow area.**

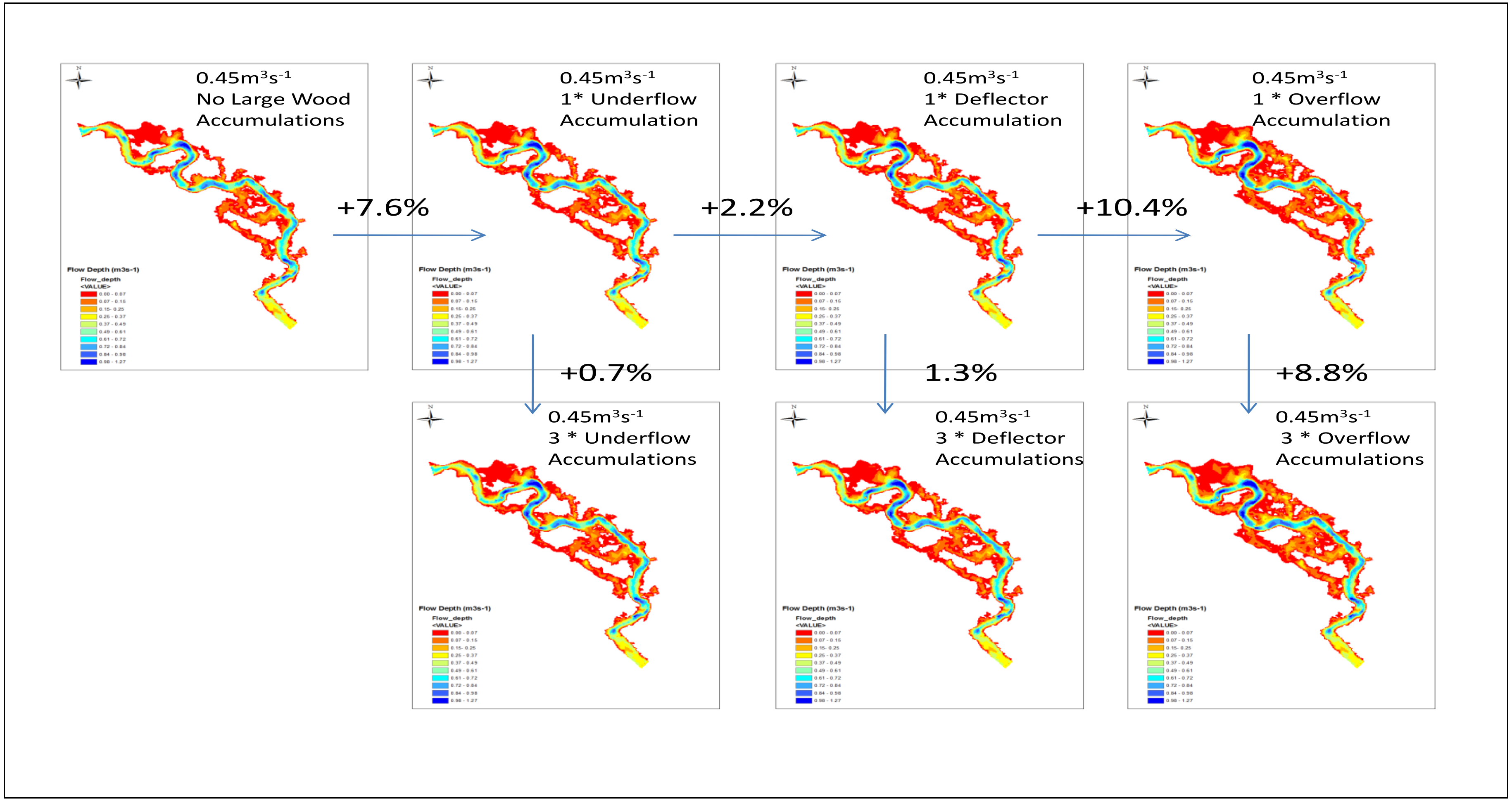



**Figure 8.11.4: Simulated flow Extent for the 0.45m$^3$s$^{-1}$ Large Wood Accumulation Scenarios showing the percentage change in flow area.**

A single underflow large wood accumulation, which has the lowest hydraulic efficiency, can be responsible for up to an 8.2% increase in flow area where the discharge is sufficient to initiate inundation (ie at the $0.37m^3s^{-1}$ discharge). Table 8.11.2 summarises the impact upon the inundation area for the four management scenarios and the three discharge scenarios.

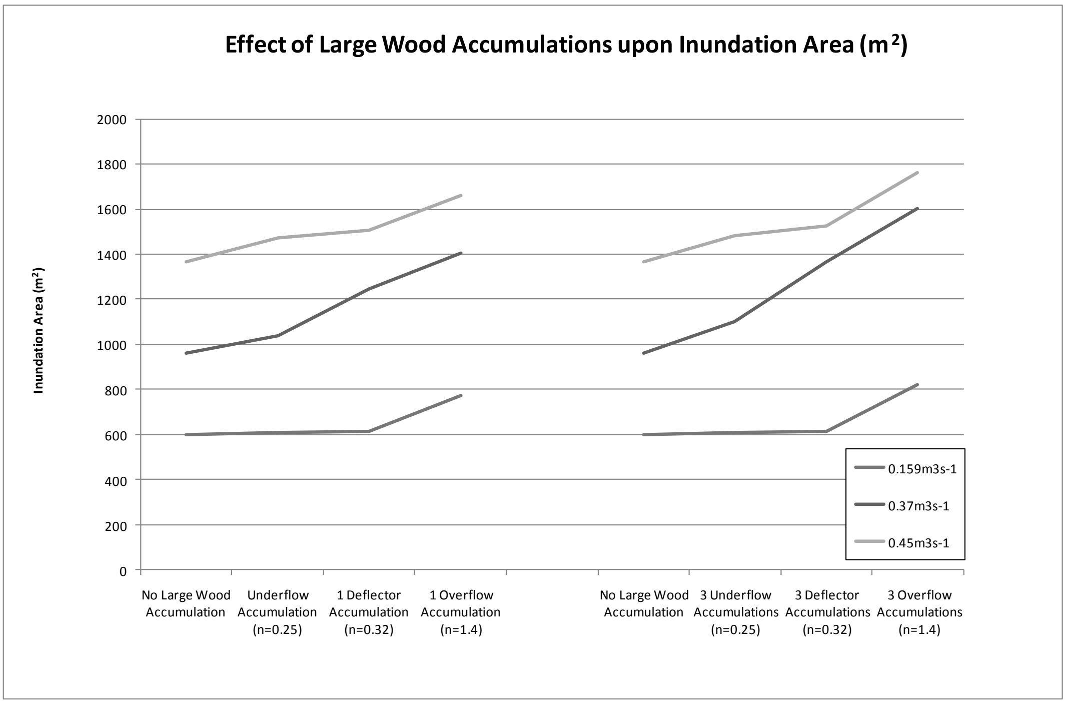



**Figure 8.11.5: The influence of different types of large wood accumulation upon inundation extent ($m^2$) for a range of discharges ($0.16m^3s^{-1}$, $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$).**

| **Large Wood Accumulation Type** | **Discharge ($m^3s^{-1}$)** | **Large Wood Clearance Scenario ($m^2$)** | **Present Large Wood Loading Scenario ($m^2$)** | **% Increase in Inundation Area** | **Unmanaged Scenario ($m^2$)** | **% Increase in Inundation Area** |
|---|---|---|---|---|---|---|
| Underflow Accumulation | 0.16 | 600.03 | 608.40 | 1 | 610.38 | 2 |
| | 0.37 | 961.83 | 1040.31 | 8 | 1101.78 | 15 |
| | 0.45 | 1367.46 | 1471.32 | 8 | 1481.67 | 8 |
| Deflector Accumulation | 0.16 | 600.03 | 612.18 | 2 | 615.15 | 3 |
| | 0.37 | 961.83 | 1246.41 | 30 | 1367.46 | 42 |
| | 0.45 | 1367.46 | 1504.17 | 10 | 1523.79 | 11 |
| Overflow Accumulation | 0.16 | 600.03 | 775.17 | 29 | 822.15 | 37 |
| | 0.37 | 961.83 | 1404.81 | 46 | 1603.71 | 67 |
| | 0.45 | 1367.46 | 1660.14 | 21 | 1762.11 | 29 |

**Table 8.11.2: Influence of Management Strategy and Large Wood Accumulation Type upon Inundation Area ($m^2$).**

As expected the more hydraulically active overflow large wood accumulation has the biggest impact upon inundation extent with an average increase of 32% for the current large wood loading scenario. However, it is the middle discharge of $0.37m^3s^{-1}$ which is most influenced by the presence of large wood. At this discharge, the large wood acts to create a tipping point beyond which inundation becomes more widespread. Taking a sequence of inundation maps for the single overflow accumulation for three different discharge scenarios, it is clear that for the discharge of $0.16m^3s^{-1}$ the flow is largely contained to the channel margins and the low depressions on the bank. Without any large wood accumulations, the $0.37m^3s^{-1}$ is also constrained to the channel margins and it is only with the presence of large wood that the $0.37m^3s^{-1}$ event starts to inundate the floodplain.

This finding contrasts with the findings of Young (1991) who concluded that large wood would only have a small impact upon inundation with large wood causing negligible increases in stage with an 80% blockage required for a significant increase in inundation. This work suggests that for a single deflector accumulation with a blockage ratio of between 25% and 75% the increase in inundation area is 42% for a $0.37m^3s^{-1}$ discharge. The effect of one large wood accumulation appears to have a similar effect to that of three large wood accumulations suggesting that it is not necessary to install a large number of large wood accumulations to get a significant effect upon floodplain inundation. Some have argued that the effect of large wood is often localised with Jeffries *et al.* (2003) suggesting that one overflow accumulation creates overbank inundation on only 5% of the floodplain area. Results from this study suggest that the presence of an overflow accumulation will lead to an increase in inundation of up to 46% for a discharge of $0.37m^3s^{-1}$, which is equivalent to 15% of the floodplain area. This reduces to 10% of the floodplain when the discharge rises to $0.45m^3s^{-1}$. Furthermore, the increase in inundation extent can be further than 50 metres from the location of the large wood accumulation. The presence of large wood accumulations helps to initiate anabranching flow leading to a multi-channel anastomosing river pattern which leads to a range of flow types. The interaction of the floodplain, riverine woodland and overbank flow can have a number of benefits with one of the main ones being potential flood relief downstream (Brown, 1997). The presence of water on the floodplain leads to the storage of flow upon the floodplain. Figure 8.11.6 shows the volume of the inundation (summarised in table 8.11.3) and a similar pattern to inundation area is observed with inundation storage increasing with flow discharge, with increasing number of large wood accumulations, and with the hydraulic impact of large wood accumulations.

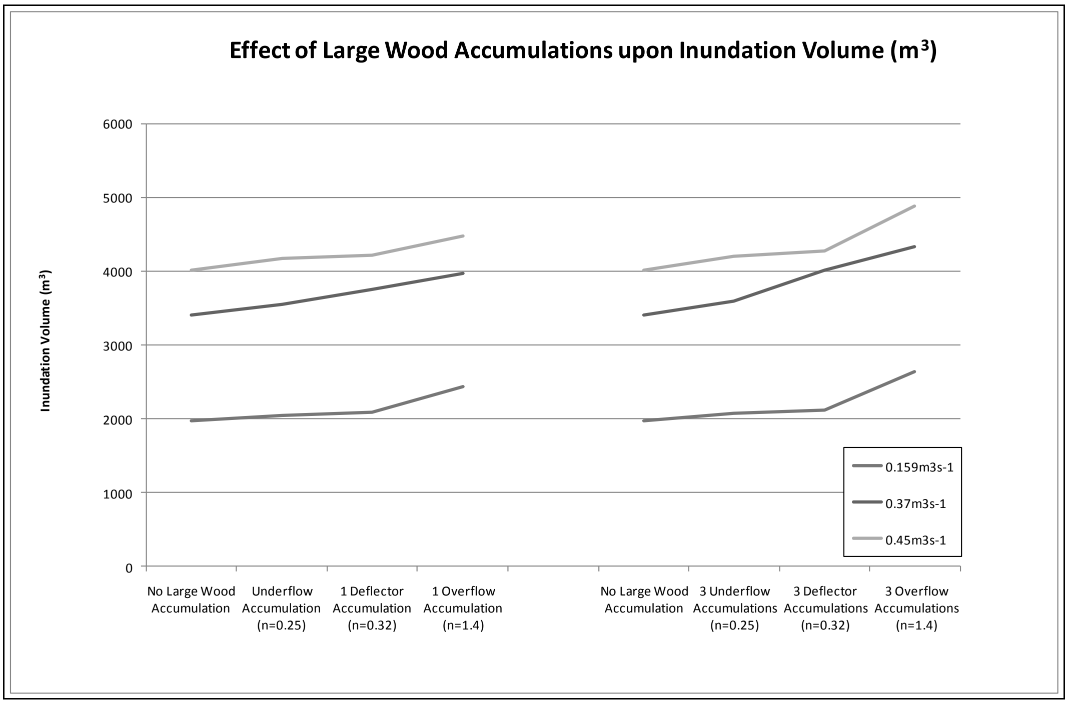


**Figure 8.11.6: Effect of Large Wood Accumulations upon Inundation Volume.**

The current study also suggest that once an inundation threshold is overcome that the effect of large wood is drowned out at higher flows. This is shown by the increased control of large wood at the $0.37m^3s^{-1}$ event compared to the $0.45m^3s^{-1}$ event. This has implications for flood risk management and supports the findings of Gregory *et al.* (1985) that large wood can reduce low probability floods (1-10 year floods).

| Large Wood Accumulation Type | Discharge ($m^3s^{-1}$) | Large Wood Clearance Scenario ($m^3$) | Present Large Wood Loading Scenario ($m^3$) | % Increase in Inundation Volume | Unmanaged Scenario ($m^3$) | % Increase in Inundation Volume |
|---|---|---|---|---|---|---|
| Underflow Accumulation | 0.16 | 1973.43 | 2048.28 | 3.79% | 2068.51 | 4.82% |
| | 0.37 | 3398.47 | 3548.61 | 4.42% | 3599.15 | 5.91% |
| | 0.45 | 4011.22 | 4168.74 | 3.93% | 4198.07 | 4.66% |
| Deflector Accumulation | 0.16 | 1973.43 | 2081.41 | 5.47% | 2112.02 | 7.02% |
| | 0.37 | 3398.47 | 3753.08 | 10.43% | 4011.22 | 18.03% |
| | 0.45 | 4011.22 | 4211.68 | 5.00% | 4266.61 | 6.37% |
| Overflow Accumulation | 0.16 | 1973.43 | 2428.87 | 23.08% | 2630.88 | 33.31% |
| | 0.37 | 3398.47 | 3964.69 | 16.66% | 4330.02 | 27.41% |
| | 0.45 | 4011.22 | 4482.38 | 11.75% | 4875.17 | 21.54% |

**Table 8.11.3: Influence of large wood accumulations upon inundation volume ($m^3$)**

However, data from figures 6.9.4 and 6.9.9 suggests that any attenuation effect linked to the volume of flow upon the floodplain converges around a $1m^3s^{-1}$ discharge which suggests that larger flood events may not be attenuated by large wood and its ability to route flow onto the floodplain. Also, the Highland Water is a small catchment with a catchment area of $25km^2$ and therefore the influence of large wood however is unlikely to scale up to larger rivers and their floodplains as large wood accumulations are less prevalent in larger rivers due to the reduction in large wood length to channel width which means blockages are rarer and therefore large wood is less hydraulically active in initiating inundation.

## *8.12. Inundation Diversity*

Observed inundation patterns and those outputted from hydrodynamic models are currently expressed qualitatively (for example see Lewin and Hughes, 1980; Nicholas and Walling, 1997, Nicholas and Mitchell, 2003). Often inundation patterns are referred to as 'complex', 'linear' or 'multi-directional' with little attempt made to classify inundation or quantify the inundation complexity (Brown *et al.*, 1995; Nicholas and Mitchell, 2003). Emery *et al.* (2003) used a statistical classification procedure (Hierarchal Clustering Algorithm or HCA) to determine statistically significant clusters of velocity representing different flow habitats.

However, although coherent flow structures were identified, the diversity was not quantified. One of the key perceived benefits of the use of large wood and the restoration of forested floodplains and anastomosed river patterns is the improvement of relative flow habitat diversity present upon the floodplain (Tockner *et al.*, 2000; Tockner and Stanford, 2002). The range of hydro-morphological processes present upon the floodplain can support the formation of diverse ecological habitats (Schropp and Bakker, 1998, Simons *et al.*, 2001) which can support high species diversity for both flora and fauna (Sterba *et al.*, 1997, Peterken and Hughes, 1998, Hughes *et al.*, 2001).

Gurnell (1997) suggests that:-

"*riverine woodlands develop though interactions between the vegetation and the physical processes that are active.*" (p 222).

That is the distribution of plant species and communities within floodplain zones reflects the sensitivity of the vegetation species to the physical processes occurring such as the magnitude, energy and frequency of floodplain inundation. There is strong evidence that physical habitat plays a key role in providing biodiversity in river environments (Ward and Tockner, 2001). The concept of the '*flood pulse*', in which the variation in river level controls the recruitment of riparian species, is seen as a key qualitative model of the spatial variation of habitats in fluvial system (Petts, 1998; Richards *et al.*, 2002). Without the variation in flow regime, there is a shift to terrestrial species. Currently this relative flow habitat diversity has not been quantified. This thesis seeks to provide an approach to quantifying the complexity of the floodplain flow depth and flow velocities by using a spatial pattern analysis often used in ecological studies. Fragstats (McGarigal *et al.*, 2002) is a spatial pattern analysis software, which was originally developed to quantify habitat diversity and land cover change. It has the ability to analyse classified raster images and to analyse them to calculate a wide range of diversity indices that represent the spatial composition of the domain of interest.

In order to utilise Fragstats to analyse the outputted flood depth and flood velocity results from Hydro2de it was necessary to convert them to classified raster images. This was done within the ArcMap GIS package and a simple classification was used for all the simulation scenarios. The $0.45m^3s^{-1}$ with three overflow accumulations had the largest inundation area and therefore was used to create a generic classification that was applied to all the other scenarios. This was done separately for flow depth and flow velocity, which were both analysed within Fragstats. ArcMap has a number of ways to specify classes to a raster datasets. These can be classified manually using assigned values, defined intervals, quantiles and standard deviations. They can also be defined automatically using Jenks Natural Breaks, which are naturally occurring groupings inherent within the dataset. To reduce user bias, this automatic classification was used to classify the Hydro2de results. In the Jenks Natural Breaks Method, ArcMap chooses the thresholds between different groups by picking the class breaks that group similar values and maximises the differences between classes. The classification is based upon a user-defined number of classes, in this case 10. The Jenks Natural Breaks algorithm (Jenks and Caspall, 1971) assigns the values into classes by iteratively comparing the sums of the squared differences between each value and the class mean. The Jenks Natural Breaks algorithm settles upon the classes that minimises the sum of the squared differences. The Jenks Natural Breaks classification for the $0.45m^3s^{-1}$ with three overflow accumulations flow depth and velocity is shown in table 8.12.1 and was applied to all other model scenario to ensure consistency and simplicity. Figure 8.12.1 shows the classified flow depth and flow velocities for the current scenario (one overflow accumulation) for the three simulated discharges ($0.16m^3s^{-1}$, $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$).

| **Flow Depth Class** | **Flow Depth (m)** | **Flow Velocity Class** | **Flow Velocity ($ms^{-1}$)** |
|---|---|---|---|
| 1 | 0-0.07 | 1 | 0-0.07 |
| 2 | 0.07-0.15 | 2 | 0.07-0.16 |
| 3 | 0.15-0.25 | 3 | 0.16-0.27 |
| 4 | 0.25-0.37 | 4 | 0.27-0.40 |
| 5 | 0.37-0.50 | 5 | 0.40-0.51 |
| 6 | 0.50-0.61 | 6 | 0.51-0.62 |
| 7 | 0.61-0.72 | 7 | 0.62-0.72 |
| 8 | 0.72-0.84 | 8 | 0.72-0.83 |
| 9 | 0.84-0.98 | 9 | 0.83-0.97 |
| 10 | 0.98-1.27 | 10 | 0.97-1.25 |

**Table 8.12.1: Classification of Flow Depth and Flow Velocity together with Class ID.**

Once classified, the rasters could be imported into Fragstats for analysis. Composition statistics, derived from Fragstats, can give an indication of the characteristics associated with the variety and abundance of different patch units within a domain through indices such as diversity (Gustafson, 1998) where the patch units would be flow depth or flow velocity classes for this analysis. Two of the most common diversity measures used in ecological spatial analysis are the Shannon's Diversity measure and Simpson's diversity measure (McGarigal, *et al.*, 2002). Shannon's diversity measure is defined as:-

$$SHDI = \sum_{i=1}^{m} \left(P_i \ln P_i\right) \qquad \textbf{(8.9)}$$

Where $P_i$ is the proportion of landscape occupied by each patch type. A value of zero indicates that there is one homogenous patch. The value of Shannon's diversity index increases as the number of different patch types increase and the proportional distribution of area amongst patch types becomes more even.

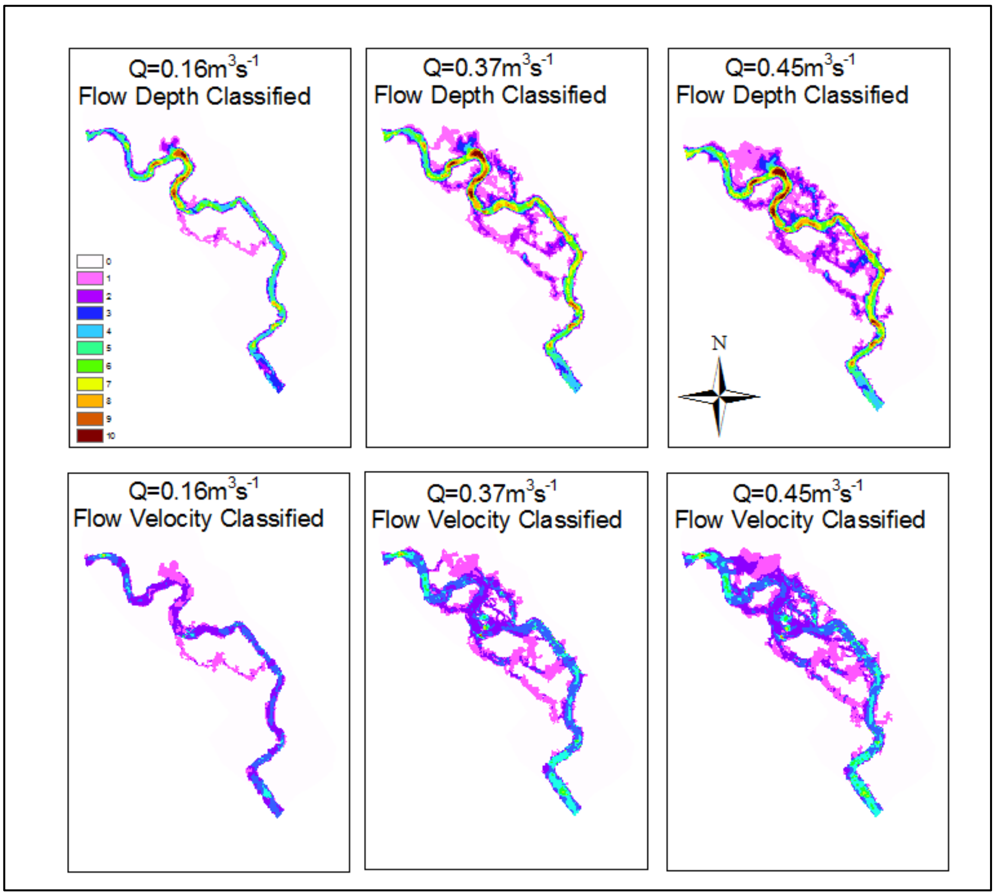



**Figure 8.12.1: The classified flow depth and flow velocity patches for the 3 simulated discharges ($0.16m^3s^{-1}$, $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$) for the current scenario (one Overflow accumulation). See table 8.12.1 for the classifications.**

One limitation of Shannon's diversity index is that it is somewhat sensitive to the presence of rare patch types (i.e. where proportion of the landscape covered is low) and therefore is more sensitive to the number of patches rather than the evenness of the distribution of area (McGarigal *et al.*, 2002).

The Simpson's Diversity Index is defined as:-

$$SIDI = 1 - \sum_{i=1}^{m} P_i^2 \qquad \textbf{(8.10)}$$

The Simpson's diversity index is less sensitive to rare patch types and places more weight upon common patch types (McGarigal *et al.*, 2002). It has a more intuitive meaning than the Shannon's Diversity Index and represents the probability that any two cells picked at random would be different patch types. A value of zero represents a homogenous landscape whereas an increase in the number of different patch types leads to an increase in the Simpson's diversity index, approaching a value of one, where the proportional area of each patch type becomes equal.

Figure 8.12.2 shows the Shannon's Diversity index for the simulated flow depth for three different discharges whilst Figure 8.12.3 shows the Simpson's Diversity Index as well as summarised in table 8.12.2. Table 8.12.2 also shows the number of distinct flow depth patches present within the model domain, the density of patches and the edge density. The patch density is the total number of patches divided by the model domain area and the edge density is the total length of patch edges divided by the model domain area. Figures 8.12.2 and Figure 8.12.3 both display similar trends with floodplain flow-depth diversity increasing with discharge, the hydraulic efficiency of the large wood accumulation type and the number of large wood accumulations. The increase in flood depth diversity with an increasing discharge is not surprising as flow depth is a function of discharge and the complex floodplain topography including any morphological features (Gippel, 1995).

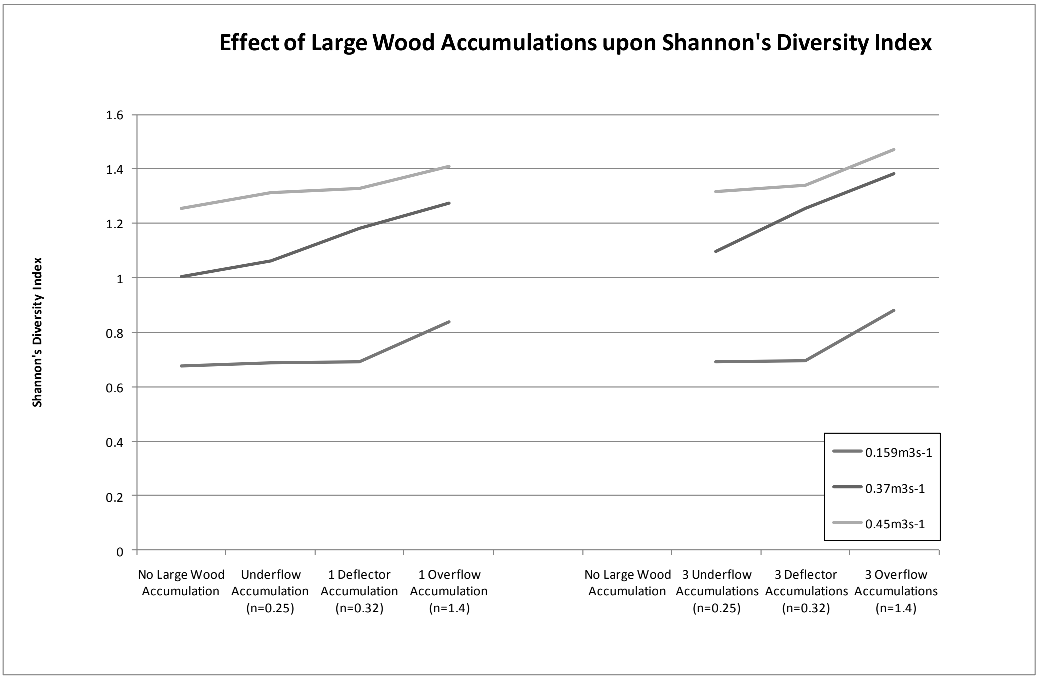



**Figure 8.12.2: Effect of Large Wood Accumulations upon the Shannon's Diversity Index for Flow Depth (m).**

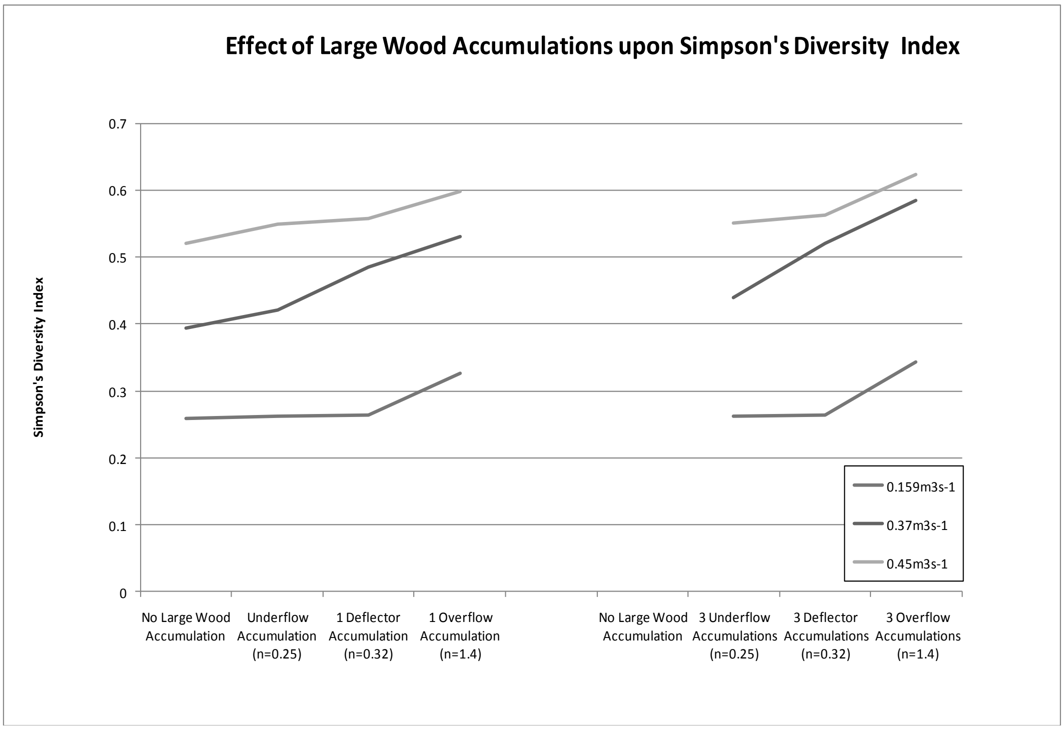



**Figure 8.12.3: Effect of Large Wood Accumulations upon the Simpson's Diversity Index for Flow Depth (m).**

| Discharge | Large Wood | Number of Patches | Patch Density | Edge Density | Shannon's Diversity Index | Simpson's Diversity Index |
|---|---|---|---|---|---|---|
| $0.16m^3s^{-1}$ | No Large Wood Accumulation | 973 | 92345.0 | 2231.4 | 0.676 | 0.26 |
| $0.16m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 987 (1.4%) | 93673.8 (1.4%) | 2263.8 (1.5%) | 0.689 (1.9%) | 0.26 (1.4%) |
| $0.16m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 1007 (3.5%) | 95571.9 (3.5%) | 2275.8 (2.0%) | 0.693 (2.5%) | 0.26 (1.9%) |
| $0.16m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 1067 (9.7%) | 101266.4 (9.7%) | 2655.3 (19.0%) | 0.838(24.0%) | 0.33 (26.1%) |
| $0.16m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 995 (2.3%) | 94433.0 (2.3%) | 2277.5 (2.1%) | 0.691 (2.2%) | 0.26 (1.7%) |
| $0.16m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 1021 (4.9%) | 96900.6 (4.9%) | 2287.5 (2.5%) | 0.697 (3.1%) | 0.26 (2.5%) |
| $0.16m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 1087 (11.7%) | 103164.5 (11.7%) | 2767.5 (24.0%) | 0.881 (30.3%) | 0.34 (32.8%) |
| $0.37m^3s^{-1}$ | No Large Wood Accumulation | 1214 | 115217.8 | 3202.8 | 1.003 | 0.39 |
| $0.37m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 1223 (0.7%) | 116166.8(0.8%) | 3411.3 (6.5%) | 1.061 (5.8%) | 0.42 (6.9%) |
| $0.37m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 1301 (7.2%) | 123474.7 (7.2%) | 3823.5 (19.4%) | 1.183 (17.9%) | 0.48 (23.2%) |
| $0.37m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 1296 (6.8%) | 123000.2 (6.8%) | 3997.5 (24.8%) | 1.273 (26.8%) | 0.53 (35.0%) |
| $0.37m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 1239 (2.1%) | 117590.5 (2.1%) | 3549.9 (10.8%) | 1.098 (9.5%) | 0.44 (11.9%) |
| $0.37m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 1287 (6.0%) | 122146.0 (6.0%) | 3927.8 (22.6%) | 1.256 (25.1%) | 0.52 (32.3%) |
| $0.37m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 1318 (8.6%) | 125088.2 (8.6%) | 4222.7 (31.8%) | 1.381 (37.7%) | 0.58 (48.5%) |
| $0.45m^3s^{-1}$ | No Large Wood Accumulation | 1287 | 122146.0 | 3927.8 | 1.256 | 0.52 |
| $0.45m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 1325 (3.0%) | 125752.5 (3.0%) | 4096.9 (4.3%) | 1.311 (4.4%) | 0.55 (5.5%) |
| $0.45m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 1308 (1.6%) | 124139.1 (1.6%) | 4139.3 (5.4%) | 1.329 (5.8%) | 0.56 (7.2%) |
| $0.45m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 1313 (2.0%) | 124613.6 (2.0%) | 4321.0 (10.0%) | 1.411 (12.3%) | 0.60 (15.0%) |
| $0.45m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 1305 (1.4%) | 123854.4 (1.4%) | 4107.1 (4.6%) | 1.318 (5.0%) | 0.55 (6.1%) |
| $0.45m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 1295 (0.6%) | 122905.3 (0.6%) | 4155.0 (5.8%) | 1.341 (6.8%) | 0.56 (8.2%) |
| $0.45m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 1324 (2.9%) | 125657.6 (2.9%) | 4440.8 (13.1%) | 1.473 (17.3%) | 0.62 (20.0%) |

**Table 8.12.2: Flow Depth Classification and Diversity Metrics with % difference from No Large Wood Accumulation scenario for each discharge.**

For the largely in-channel event ($Q=0.16m^3s^{-1}$) the flow depth is relatively uniform with minor variations depending on bed-forms such as pools and riffles. The presence of a single deflector or underflow accumulations has little impact upon this (increases Simpson's diversity metric by 1.4% and 1.9% respectively) but an overflow accumulation increases the flow depth diversity by 26.1% by retarding flow upstream and initiating floodplain inundation. The initial inundation of the floodplain leads to a number of low depth flow areas that add to the flow type diversity. An increasing discharge leads to an increased floodplain stage, which increases the amount of deep flow patches. Higher elevated parts of the floodplain are inundated and thus the low flow depth patches are maintained. The complex topography present on forested floodplains exacerbates this effect as the presence of islands leads to low flow depth areas and distributary channels lead to higher flow depth areas which produce an anastomosed channel pattern. Although the presence of large wood can help the initiation of out-of-bank flow, it is the floodplain topography which controls the flow diversity. Large wood can help to increase the flood stage and allow larger areas of the floodplain to be inundated, for example, the presence of large wood at higher discharges ($0.37m^3s^{-1}$, $0.45m^3s^{-1}$) helps to add to the diversity of flow depth as shown in the increase in Simpson's diversity metric by 32.4% and 15% for a single overflow accumulation for the $0.37m^3s^{-1}$ and $0.45m^3s^{-1}$ scenarios respectively.

Large wood has an impact upon flow depth diversity as it controls the amount of inundation and routes flows to different areas of the floodplain. The overflow accumulation has the biggest impact as can be seen from the $0.16m^3s^{-1}$ discharge. For the underflow and deflector accumulations, the flow depth diversity is relatively low as flow is confined to the channel. For the overflow accumulation, the flow begins to inundate the floodplain and the number of flow patches increases. At higher discharges, the diversity increases with the presence of large wood accumulations by 2.95%, 1.58% and 1.99% for a single underflow, deflector and overflow accumulation respectively. The distribution of varying flow depth patches adds to the relative habitat diversity present upon the floodplain.

A similar general trend is also observed with velocity with an increasing velocity diversity (for both Diversity indices shown in Figures 8.12.4 and 8.12.5 and summarised in table 8.12.3) with discharge, and large wood accumulation type and quantity. This similar trend suggests that there is a relationship between the flow depth diversity and flow velocity diversity.

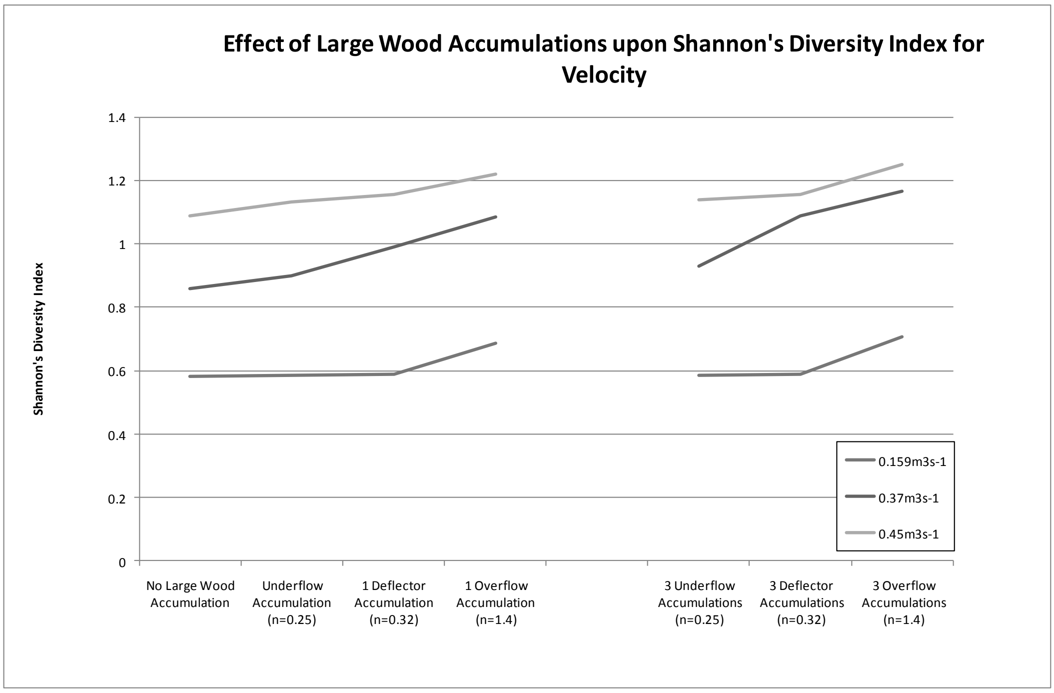



**Figure 8.12.4: Effect of Large Wood Accumulations upon the Shannon's Diversity Index for Flow Velocity ($ms^{-1}$).**

Figure 8.12.6 shows the Simpson's diversity measure for both of flow depth and flow velocity with a trend line that accounts for 85% of the variation in the data. A similar pattern is also observed for the Shannon's diversity measure.

The trend of increasing velocity diversity with discharge shown in the present study for forested floodplains has previously been identified for in-channel flow by Emery *et al.* (2003). The diversity of flow velocity is smallest for the lowest discharges (e.g. 0.16m$^3$s$^{-1}$) with 973 flow velocity patches representing the diversity in the pools and riffles present within the channel.

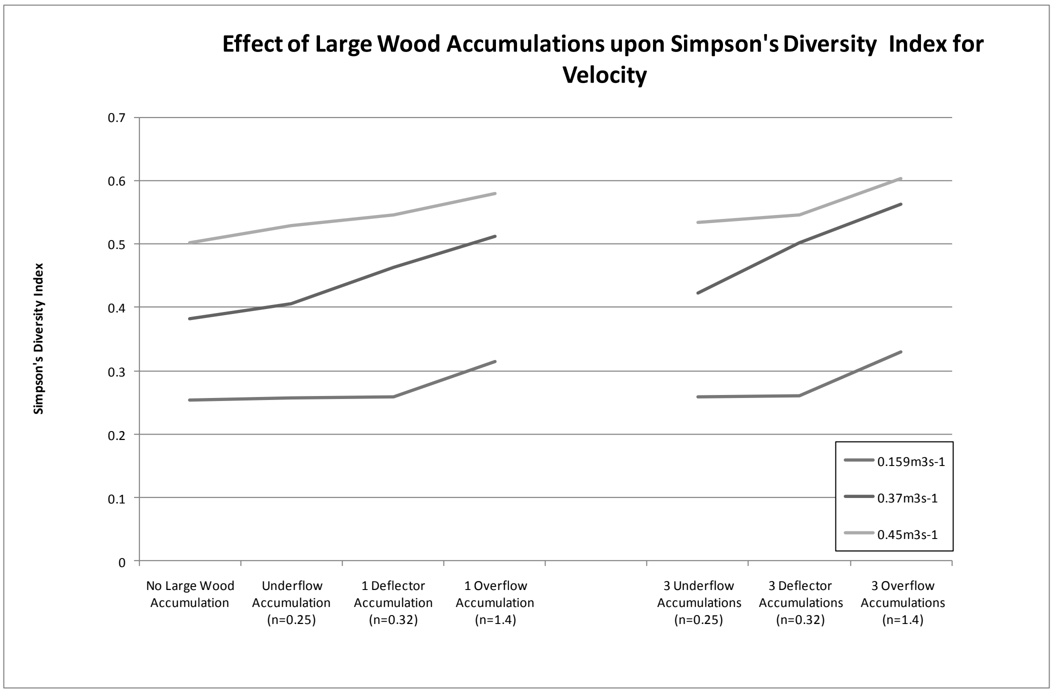



**Figure 8.12.5: Effect of Large Wood Accumulations upon the Simpson's Diversity Index for Flow Velocity (ms$^{-1}$).**

The presence of large wood accumulations leads to a small reduction in the number of flow velocity patches for the low discharges (0.16m$^3$s$^{-1}$ and 0.37m$^3$s$^{-1}$) which is due to the deflection of flow within the channel which is known to locally reduce channel flow velocity (Shields *et al.*, 2001; Shields *et al.*, 2004). The initial inundation of the floodplain leads to a number of low velocity areas as the low flow depth is retarded by the high relative roughness of the floodplain vegetation. An increasing discharge leads to an increased floodplain flow velocity as the flow depth increases relative to the roughness height of the floodplain vegetation.

Complex topography present on forested floodplains leads to low velocity areas in deeper parts of the floodplain surface such as recirculation zones or ponds whilst also having high velocity areas such as distributary channels, which distribute flow across the floodplain.

| Discharge | Large Wood | Number of Patches | Patch Density | Edge Density | Shannon's Diversity Index | Simpson's Diversity Index |
|---|---|---|---|---|---|---|
| $0.16 m^3s^{-1}$ | No Large Wood Accumulation | 545 | 51724.61 | 1472.30 | 0.58 | 0.25 |
| $0.16 m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 522 (-4.2%) | 49541.74 (-4.2%) | 1433.86 (-2.6%) | 0.58 (0.6%) | 0.26 (1.3%) |
| $0.16 m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 516 (-5.3%) | 48972.29 (-5.3%) | 1423.33 (-3.3%) | 0.59 (1.1%) | 0.26 (1.9%) |
| $0.16 m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 551 (1.1%) | 52294.06 (1.1%) | 1694.10 (15.1%) | 0.69 (18.3%) | 0.31 (23.7%) |
| $0.16 m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 506 (-7.2%) | 48023.22 (-7.2%) | 1425.89 (-3.2%) | 0.59 (0.8%) | 0.26 (1.7%) |
| $0.16 m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 498 (-8.6%) | 47263.96 (-8.6%) | 1421.90 (-3.4%) | 0.59 (1.3%) | 0.26 (2.3%) |
| $0.16 m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 495 (-9.2%) | 46979.24 (-9.2%) | 1690.68 (14.8%) | 0.71 (21.9%) | 0.33 (29.8%) |
| $0.37m^3s\text{-}^1$ | No Large Wood Accumulation | 693 | 65770.93 | 2077.91 | 0.86 | 0.38 |
| $0.37 m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 692 (-0.1%) | 65676.02 (-0.1%) | 2229.38 (7.3%) | 0.90 (4.9%) | 0.41 (6.5%) |
| $0.37 m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 628 (-9.4%) | 59601.94 (-9.4%) | 2495.31 (20.1%) | 0.99 (15.5%) | 0.46 (21.4%) |
| $0.37 m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 775 (11.8%) | 73553.35 (11.8%) | 2907.02 (39.9%) | 1.08 (26.5%) | 0.51 (34.2%) |
| $0.37 m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 727 (4.9%) | 68997.79 (4.9%) | 2344.98 (12.9%) | 0.93 (8.4%) | 0.42 (11.0%) |
| $0.37 m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 731 (5.5) | 69377.42 (5.5%) | 2793.98 (34.5%) | 1.09 (26.8%) | 0.50 (31.7%) |
| $0.37 m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 819 (18.2%) | 77729.28 (18.2%) | 3165.55 (53.3%) | 1.16 (35.8%) | 0.56 (47.8%) |
| $0.45 m^3s^{-1}$ | No Large Wood Accumulation | 731 | 69377.42 | 2793.98 | 1.09 | 0.50 |
| $0.45 m^3s^{-1}$ | 1 Underflow Accumulation (n=0.25) | 759 (3.8%) | 72034.83 (3.8%) | 2969.66 (6.3%) | 1.13 (4.1%) | 0.53 (5.5%) |
| $0.45 m^3s^{-1}$ | 1 Deflector Accumulation (n=0.32) | 776 (6.2%) | 73648.26 (6.2%) | 3037.71 (8.7%) | 1.16 (6.4%) | 0.55 (8.6%) |
| $0.45 m^3s^{-1}$ | 1 Overflow Accumulation (n=1.4) | 839 (14.8%) | 79627.43 (14.8%) | 3285.13 (17.6%) | 1.22 (12.2%) | 0.58 (15.6%) |
| $0.45 m^3s^{-1}$ | 3 Underflow Accumulations (n=0.25) | 761 (4.1%) | 72224.64 (4.1%) | 2987.31 (6.9%) | 1.14 (4.7%) | 0.53 (6.3%) |
| $0.45 m^3s^{-1}$ | 3 Deflector Accumulations (n=0.32) | 776 (6.2%) | 73648.26 (6.2%) | 3037.71 (8.7%) | 1.16 (6.4%) | 0.55 (8.6%) |
| $0.45 m^3s^{-1}$ | 3 Overflow Accumulations (n=1.4) | 786 (7.5%) | 74597.33 (7.5%) | 3354.32 (20.0%) | 1.25 (15.0%) | 0.60 (20.2%) |

**Table 8.12.3: Flow Velocity Classification and Diversity Metrics**

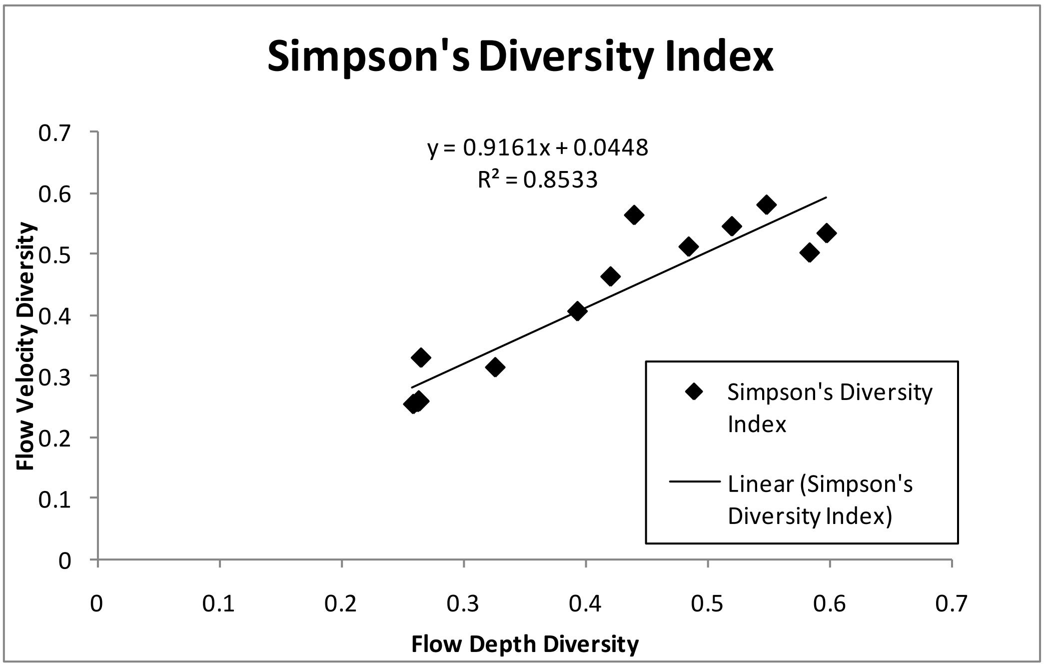



**Figure 8.12.6: The relationship between the Flow Depth Simpson's Diversity index and the Flow Depth Simpson's Diversity index for the modelled reach.**

For a discharge of $0.45m^3s^{-1}$ with no large wood accumulation there are 731 flow velocity patches whereas the addition of a single large wood accumulation increases the number of patches to 759, 776 and 839 for the underflow, deflector and overflow accumulation respectively (increase of 3.8%, 6.2% and 14.8% respectively). This results in an increase in the Simpson's diversity value of 5.5%, 8.6% and 15.6% for the underflow, deflector and overflow accumulation respectively.

The flow velocity diversity and a number of flow velocity patches within the river channel and floodplain has important implications for fish and other invertebrates as they rely on different flow types for different parts of their life cycle (Amoros and Bornette, 2002). Results shown here suggest that large wood can be beneficial for this by increasing flow diversity, which highlights the potential of large wood in providing fish habitat as well as the provision of organic particulates (Lehane *et al.*, 1998).

## 8.13. Inundation Patterns in Riverine Woodland with Large Wood

As can be seen from the various flow depth maps the simulated floodplain flow is not distributed linearly across the floodplain, as is often the case with morphologically uniform floodplain surfaces. Topographic variability and the presence of biotic matter upon the floodplain surface create a complex multi-directional flow field, which has been observed in the field (Brown *et al.*, 1995; Nicholas and Walling, 1998; Nicholas and Mitchell, 2003). It is this complex pattern of inundation coupled with the routing of flows into preferential flow paths that leads to the complex island dominated topography that can be seen in most riverine woodlands (Gurnell *et al.*, 2002).

The routed flow of relatively high velocity, scours into the floodplain surface creating a network of floodplain distributary channels, which assist in inundating parts of the floodplain that are far removed from the channel margins. The routing of flow creates anastomosed flow pattern with multiple channels conveying flow. The complex pattern of flow also leads to a plethora of flow habitat types with ponded areas, recirculation zones and areas of high velocity which are features of floodplains with complex topography (Nicholas and Walling, 1998; Nicholas and McLelland, 1999) especially riverine woodland (Jeffries *et al.*, 2003). This is in direct contrast with the conventional model of floodplain inundation where those areas on the channel margin are inundated first with a linear relationship between distance from the channel and inundation (Hughes, 1980; Lewin and Hughes, 1980; Kiely, 1990) and subsequent lateral patterns of floodplain sedimentation (eg. James, 1985; Pizzuto, 1987).

The general flow direction follows the downstream direction with flow structures following the floodplain topography as suggested by Kiely (1990) although the presence of vegetation, raised islands and distributary channels play a key role in partitioning flow, and resulting in diverse overbank velocities and multi-directional velocities (Harwood and Brown, 1993; Brown *et al.*, 1995; Piégay, 1997; Nicholas and McLelland, 1999). The partitioning of flow also causes shear layers, which are known to strongly influence deposition mechanisms and control the spatial variation of floodplain sedimentation (Jeffries *et al.*, 2003). Observations showed that inundation created a range of depositional features including sand and silt shadows both at channel margins and on the downstream side of trees and large wood. These occur due to the rapid drops in velocity (Li and Shen, 1973; Brayshaw *et al.*, 1983; Tsujimoto, 1999) and are often aligned in the direction of flow (Zwolinski, 1992; Jefferies *et al.*, 2003; Sear *et al.*, 2010). There are also a number of erosional features observed on the floodplain including areas of scour, floodplain channels and depressions caused by recirculation zones. Erosion is also observed where high velocity threads of flow are formed by topographic variations and also the distribution of rigid woody vegetation on the floodplain (Brown and Brookes, 1997). This results in a complex network of floodplain channels and depressions upon the floodplain. Erosion and sedimentation can occur at particular locations in different events (Hughes, 1997) which can significantly influence floodplain geomorphology (O'Connor *et al.*, 2003).

Figure 8.13.1 shows a vegetation map from the Ain River in France, which shows the detail and complexity of the evolving habitat in a meandering river system.


**Figure 8.13.1: Vegetation Mosaic of the Lower Ain River, France (from Amoros *et al.*, 1987).**

Although this complex vegetative pattern is the product of a dynamic meandering system, it can be argued that the diverse nature of inundation patterns in the presence of large wood can provide heterogeneous habitat for vegetation to develop in a similar pattern.

Brown (1997) claims that the multi-channel state may be the natural character for the floodplains of North-West Europe before they were subject to deforestation and channelisation and this is also supported in North America by Walter and Merritts (2008)_and Montgomery (2008). This can be further modified by the presence of large wood, as it is often transient in nature (Braudrick and Grant, 2000) and can locally affect flow hydraulics and subsequently erosion and depositional processes. The temporary residence of large wood and the formation of temporary, semi-permanent and permanent accumulations can create a dynamic floodplain where different magnitude flows with differing frequencies create a diverse floodplain with a range of different ecosystems (Brown, 1997). The results presented show that for a given discharge, the presence of large wood can increase flow depth diversity by up to 49% and flow velocity by 48%. The presence of large wood also increases the frequency and duration of floodplain inundation meaning that the flow depth and flood velocity patches are present upon the floodplain more regularly and for longer time periods than for reaches without the presence of large wood. This suggests that large wood can, through the restoration of the 'flood pulse', increase the relative flow diversity, providing habitat for vegetation, fish and invertebrate species.

The flood pulse is also linked to the dynamics of floodplain geomorphology as the constant erosion and deposition of the floodplain surface creates and renews habitat patches for colonisation and regeneration. Sear *et al.* (2010) suggest that large wood accumulations are a fundamental control over the development of floodplain geomorphology and hypothesise that more complex networks of floodplain channels are associated with hydraulically active large wood accumulations. Sedell and Frogatt (1984) summarise the effect of large wood removal upon morphological diversity:-

*The pristine river was a series of multiple channels, sloughs and backwater areas. Historically, the floodplain and valley had extensive marshes. Numerous downed trees helped to create and maintain shoals, multiple channels, oxbow lakes and complex aquatic habitats at the outside of bends on the river. After 80 years of snag removal and riparian forest deforestation, there now exists one main channel, few downed trees, relatively simple and homogenous habitat for aquatic vertebrates and over a four-fold decrease in river shoreline*" (Sedell and Frogatt, 1984. P1833).

The complex floodplain inundation patterns and geomorphology in riverine woodland have been well documented (Brown *et al.*, 1997, Jeffries *et al.*, 2003) and Richards *et al.* (2002) suggest that the restoration of smaller-scale geomorphological and sedimentological processes can encourage vegetation regeneration creating heterogeneous fluvial environments such as that in figure 8.13.1. Results presented in this chapter suggest large wood can be used for this purpose.

## *8.14. Summary*

A hydrodynamic model was constructed of the Restored-Planform reach to simulate the effect of large wood upon floodplain inundation dynamics with a view of determining whether the use of large wood can recreate multi-directional flow conditions that are present within riverine woodland. The hydrodynamic model, constructed using the two-dimensional Hydro2de code, was calibrated and validated using observed inundation extents and velocity measurements. As part of the calibration procedure, the best method for representing large wood accumulations was found to be through the parameterisation of the Manning's *n* parameter, which gave better fit with observed inundation patterns, and better representation of flow processes through the large wood accumulation. The validated model provided evidence that the processes occurring in the presence of large wood were similar to those observed in riverine woodland environments with complex flow patterns, which did not follow conventional floodplain inundation patterns.

Once the best method for representing large wood accumulations was established, the hydrodynamic model was used experimentally to determine the effect of large wood accumulations upon floodplain inundation. The number (0, 1 and 3) and type of large wood accumulation (underflow, deflector and overflow) was varied for three discharges ($0.15m^3s^{-1}$, $0.35m^3s^{-1}$ and $0.45m^3s^{-1}$) to establish its influence. The number and type of large wood accumulation were found to influence both inundation extent and the diversity of flow types both in terms of depth and flow velocity. This has a number of implications for both geomorphology and ecology.

# 9. Conclusions

## *9.1. Thesis Findings*

This thesis has sought to develop the understanding the role of large wood accumulations upon the reach-scale flow resistance hydraulics, floodplain hydrology and catchment flood hydrology. It has used a number of techniques to assess the role of large wood at a number of spatial scales. To summarise the findings of this thesis it is useful to assess the key questions the thesis aimed to address. The key questions set out in chapter two of this thesis are as follows:-

- Are current methods for assessing flow resistance offered by large wood accumulations appropriate for use for different types of large wood accumulations?

  What is the effect of large wood accumulations upon the reach-scale floodplain inundation frequency?
- Can the presence of large wood accumulations initiate diverse anastomosing flow patterns?

- How do large wood accumulations affect the attenuation of flood peaks in a small-scale wooded catchment?

### Are current methods for assessing flow resistance offered by large wood accumulations appropriate for use for different types of large wood accumulations?

The classification of Wallerstein *et al*. (1997) was used to classify large wood accumulations based on their hydraulic influence. Field measurements were added to flume data and other data from Shields and Gippel (1995) and Curran and Wohl (2003). The main findings were that overflow accumulations had the biggest impact upon local in-channel hydraulics and, subsequently, floodplain hydrology. Average Manning's *n* values of 1.4 ±0.82 were derived from field measurements for overflow accumulations. The bulk of this resistance was contributed by the local acceleration and deceleration of flow otherwise known as spill resistance (Leopold *et al.*, 1964) with form drag providing little of the total reach-scale resistance (<1% for overflow accumulations). The proportion of resistance offered by form drag for deflector (10.6%) and underflow accumulations (11%) was larger but this study shows that the approach taken by Shields and Gippel (1995) to predict large wood flow resistance is not suitable for higher gradient rivers where large wood blockages ratios are high. This supports the findings of Curran and Wohl (2003) who found large residuals in a high-gradient step-pool channel. A new approach is required which seeks to predict the resistance provided by spill resistance within those environments where large wood accumulations initiate high-gradient water surface slopes. Preliminary data from this study suggests that some of the spill resistance can be accounted for by the Froude number.

## What is the effect of large wood accumulations upon the reach-scale floodplain inundation frequency?

The presence of large wood within the river channel can reduce local channel conveyance capacity and reduce the amount of flow required for the inundation of the floodplain. Data from this thesis shows that the inundation discharge can be reduced by up to 63% in river sections upstream of large wood accumulations. This reduction in inundation discharge increased the frequency of floodplain inundation (by up to 175%) and the inundation duration (by up to 156%) when compared to other river sections within the same reach. This localised effect can result in an anastomosed channel form which can facilitate development of rich heterogeneous riverine woodland habitat (Bayley, 1991). A multi-channel anastomosing channel form through riverine woodland will lead to an increase in the amount of large wood present within the reach. The anastomosed pattern and high sinuosity will lead to the retention of large wood both within channels and upon the floodplain (Millington and Sear, 2007; Sear *et al.*, 2010).

## Can the presence of large wood accumulations initiate diverse anastomosing flow patterns?

Increased floodplain-channel connectivity coupled to the complex floodplain topography on forested floodplains results in increased fluvial habitat diversity (Gurnell, 1998). Large wood accumulations can be responsible for increasing inundation extent by up to 67%. Different large wood accumulations can provide different inundation extents for the same inflow discharge with a single overflow accumulation providing 1660m$^2$ of inundation, a single deflector accumulation 1504m$^2$ and underflow accumulations 1471m$^2$ for a 0.45m$^3$s$^{-1}$ inflow, which compares to an inundation area of 1367.5m$^2$ in the absence of a large wood accumulation. The increase in inundation area also has a subsequent effect upon the storage of flow upon the floodplain with an overflow accumulation accounting for up to a 23% increase in stored water for a 0.16m$^3$s$^{-1}$ discharge event (equivalent to a 1.5 year return period event). Data from figures 6.9.4 and 6.9.9 suggests that the attenuation affect of large wood can be drowned out at high flows (around 1m$^3$s$^{-1}$) which suggests that the role of the floodplain goes from one which stores flow to one that conveys flow.

Large Wood can also aid the ecological health of the river system, as floodplain inundation leads to the re-activation of shallow floodplain channels which create an anastomosing flow pattern. This multi-channel anastomosing flow pattern is characterised by multi-directional flow patterns with high velocity threads of flow together with re-circulation zones that create heterogeneous flow conditions which could be a mechanism for the formation of multiple channel patterns. This heterogeneity is demonstrated by increases in Shannon’s and Simpson’s Diversity Measures of up to 49% and 48% for flow depth and flow velocity respectively. The simulated and observed multi-channel anastomosing flow patterns suggest that the goal of the EU Life 3 project should not have been the restoration of a single-thread meandering channel but should have been a diverse anastomosing channel pattern which is subject to regular overbank inundation events. Inundation frequency in the reaches where large wood is present was in the order of 8-10 inundation events a year which contrasts with the typical bankfull condition of a 2 year flood (Wolman and Miller, 1960). The presence of large wood can produce dynamic floodplain processes such as floodplain accretion and the formation of floodplain channels, which suggests large wood could be key in the formation of multi-channel anabranching river systems which could be analogous to pre-settlement river systems (Walter and Merritts, 2008).

## How do large wood accumulations affect the attenuation of flood peaks in a small-scale wooded catchment?

The influence of large wood accumulations in reducing the channel conveyance and increasing the frequency, duration and storage of floodplain inundation has had a net impact upon the downstream flood hydrology within the Highland Water catchment. Large wood densities have been shown to significantly alter the timing of the passage of the flood peak by up to 33% for small magnitude flood events. The data only includes results up to the 2.2 year return period flood event; further monitoring is required to assess the impact of large wood accumulations on the timing of larger flood events. The associated flood risk in the Highland Water for the 2.2 year return period flood is not significant with a few properties and few structures at risk as a consequence of the flooding. Typical river channels are known to commonly achieve bankfull condition around the 2 year flood return period (Wolman and Miller, 1960) and therefore significant flood risk is associated with return periods which run into the 10's and 100's of years where large scale inundation is present. The flood peaks monitored in this study were predominantly in-bank events for the majority of the monitoring reach and therefore attenuated by in-channel large wood. As a result, the attenuation effect appeared to converge at a discharge of $1 m^3 s^{-1}$ as the in-channel large wood roughness was drowned out. The development of an anastomosed channel pattern and the development of wet woodland with large volumes of large wood could retard the passage of much larger flood events ($>1-100 m^3 s^{-1}$) and could potentially attenuate much larger flood events than the ones that have been observed within this research.

Furthermore, the flood risks associated with large-magnitude events within the Highland Water are negligible in comparison with larger river catchments where inundation is much more intensive and often of a longer duration. The results presented within this thesis relate to a catchment with an area of 12.5km$^2$ and therefore can only be reasonably applied to other small-scale catchments with an area of less than 100km$^2$. There was no statistically significant attenuation effect of large wood on the flow peak magnitude and further data is required before large wood can be determined to have a beneficial effect upon downstream flood risk. In particular, there is difficulty in isolating the effects of large wood accumulations from other catchment variations so one approach may be through the use of one-dimensional catchment flood models.

## *9.2. Implications for Riverine Woodland Restoration*

Riverine woodlands and floodplain forests are highly dynamic ecosystems that depend on flood regimes for their functioning (Fetherston *et al.*, 1995; Hughes *et al.*, 2003; Hughes and Rood, 2003). Riverine woodlands require a wide variety of river and flood flows to maintain biodiversity that is present upon the floodplain and the integrated restoration of the channel-floodplain connectivity is one way to allow the development of floodplain ecosystems (Richards *et al.*, 2002). Large wood and large wood accumulations have been shown to be useful tools in re-creating the connectivity between the river channel and the floodplain especially at low to medium flows with an increase in inundation frequency, duration, extent and volume, which can affect vegetation patterns (Hupp and Osterkamp, 1996). At these levels, inundation could replenish floodplain water tables, which allow the growth of established rigid vegetation (Hughes *et al.*, 2003). Petts (1998) describes the flooding pulse not as a disturbance but as a resource in the ecological integrity of floodplain rivers with it providing the mechanisms for the exchange of materials and organisms that promote a mosaic of river floodplain habitats. In this manner, large wood accumulations will allow the periodic high flows, which create dynamic channel and floodplain erosional and depositional processes that provide potential regeneration sites for seeds and seedlings (Hughes *et al.*, 2003).

Any meaningful sense of channel recovery is based on increasing the channel resistance (Brooks and Brierly, 2004). Large wood accumulations provide significant levels of flow resistance (up to a Manning's *n* of 1.4) with different resistance offered by different types of large wood accumulations. The presence of large wood in the river channel and its hydraulic resistance can locally slow river flow creating low-flow refugia and habitat diversity, which is often a goal of river restoration (Bisson *et al.*, 1987; Smock *et al.*, 1989; Brookes and Shields, 1996). As different large wood accumulations influence channel hydraulics in a number of ways their use can quickly create a number of different flow types and habitats both within the channel for fish (Bisson *et al.*, 1987; Lehane *et al.*, 2002) and invertebrates (Smock *et al.*, 1989). Flow patterns on wooded floodplains show a diverse multi-channel anastomosed pattern which improves the diversity of floodplain inundation depth and velocity as shown in this study providing similar habitats which can be useful during the lifecycles of some species (Gippel, 1995). The hydraulic diversity around large wood accumulations is not purely a function of the large wood accumulations but also morphological features that are associated with large wood accumulations such as scour pools and bars (Gippel, 1995).

The use of large wood for the restoration of riverine habitat goes against management practices that seek to remove large wood from rivers in order to improve conveyance and reduce local flood risk (Gippel *et al.*, 1992; Abbe and Montgomery, 1996)). Low wood volumes can result in channel incision, disconnected floodplains and simplification of the channel planform (Sear *et al.*, 2010). However, the use of large wood, the reconnection of the channel within its floodplain and the potential for the development of an anastomosing channel pattern can also alter downstream flood hydrology. The initiation of multi-channel anastomosing channel patterns through vegetated floodplains can also assist in the attenuation of flood waters through the increased hydraulic roughness with forested margins efficiently slowing water flow (Piégay, 1997). They can also lead to an increase in the presence of large wood and also help retain it (Sear *et al.*, 2010). The retention of further large wood will further slow water flow and increase any attenuation affects thatmay be present. Furthermore, the presence of forested floodplains can also have a direct impact on the catchment hydrological processes through the interception of rainfall, potential evapo-transpiration and also through the uptake of water through flood events (Calder and Aylward, 2006).

The use of large wood significantly affects channel processes across a range of spatial scales (Montgomery and Piégay, 2003). This study suggests that large wood accumulations have a significant influence on flow hydraulics and floodplain hydrology at the reach scale. Richards *et al*. (2002) suggest that the reach scale is that at which the most mutual association occurs between the channel and the floodplain vegetation dynamics although the connectivity of the river means that reach scale changes can impact throughout the catchment (Clarke *et al.*, 2003). Such an approach keeps restoration project construction costs to a minimum and strives towards a sustainable approach to the restoration of natural functioning (Holmes, 1998; Petts, 1998). For example, the installation of large wood accumulations creates localised inundation that can create those conditions favourable for riverine woodland. The presence of rigid standing vegetation of the floodplain gives a source of further large wood, which during inundation events, finds its way from the floodplain to the river channel whereby it accumulates replacing large wood that has been transported from the reach (Millington and Sear, 2007).

Large wood is highly seasonal in temperate river systems with the highest concentrations following the autumnal leaf fall (Smock *et al.*, 1989). This suggests that the hydraulic effect of large wood is seasonal with porosity varying depending on the time of year. With a lower porosity during the winter months, large wood accumulations are likely to create more of a blockage to flow than during the summer months when river flows and levels are lower.

There is some concern about the use of large wood especially in urban areas where structures such as bridges and culverts are prevalent (Gippel *et al.*, 1992). Therefore large wood is likely to be more acceptable for use in river headwaters in undeveloped areas where it is possible to store flood waters with little flood hazard. However, with forested floodplains being a significant source of large wood (Abbe and Montgomery, 1996), an increase in inundation could increase the amount of wood being transferred from the forested floodplain to the river channel and also downstream in the system. One option, suggested by Thomas and Nisbet (2007) would be to have a series of patches of riverine woodlands throughout the river catchment with the aim of locally initiating inundation and storage of floodwaters, with those closest to sensitive urban areas managed to increase the retention of large wood and reduce its downstream effects on developed urban areas and human populations. The management of large wood and its accumulations is therefore critical to maximise environmental and flood risk benefits whilst also minimising associated risks. The use of large wood and its accumulations requires management to ensure there are no adverse impacts upon fish, fauna, bank erosion and channel avulsion. The use of large wood as a restoration tool requires the costs of undertaking the work, the provision of in-flow habitat and potential attenuation of flood peaks for small flood events to be balanced against the loss of floodplain land which may be of value as agricultural or forestry land, potential erosion risks and the potential loss of the river channel as a recreational amenity. Restoration is likely to take place on a reach-scale basis where the addition of large wood does not pose a significant local flood risk and loss of the use of the floodplain for agricultural or forestry purposes is acceptable for the purpose of habitat creation and the potential to reduce downstream flood probability for small magnitude flood events.

The management of large wood and its accumulations is therefore critical to maximise environmental and flood risk benefits whilst also minimising associated risks. Restoration is likely to take place on a reach scale basis where local inundation does not pose a significant flood risk although this can subsequently impact upon the wider scale flood hydrology.

## *9.3. Future Work on the Highland Water site*

To further understand the role of large wood accumulations especially in terms of the hydraulic and hydrologic influence it is recommended that further high discharge flood events are monitored and observed so that the attenuation effect of large wood accumulations can be assessed for medium to extreme flood events (25-200 year flood return periods). It is also possible to do this using a one-dimensional catchment model to further investigate the effect of large wood on the catchment scale hydrology including the effect of large wood accumulation dynamics whilst removing the effect of the changes to planform. A catchment flood model can also be used to probabilistically determine the impact upon the downstream flood peak including the potential impact of the synchronisation of the flood peaks from the Highland Water and the River Blackwater. More intense storms and/or longer duration rainfall events should be simulated to assess the impact of large wood upon the attenuation of both flood peak magnitude and timing. Multiple flood events should also be simulated to assess the impact of the restoration upon the flood risk associated with such events. Although the restoration seeks to increase the frequency of the use of the floodplain to store flow this could, in the case of two successive flood events, mean that the flood risk is exacerbated as flow from the first events may not have sufficiently drained away upon commencement of the latter flood event. The use of a coupled one-dimensional: two-dimensional hydrodynamic model such as ISIS-TUFLOW or Infoworks RS can be used to assess the influence of large wood and in particular the inundation of floodplains and the impact of inundation upon flood hydrographs. Such software approaches allow the simulation of large reaches on river channel within the one-dimensional aspect of the software whilst also allowing the detail of the floodplain flow mechanisms to be represented within the two-dimensional software.

Furthermore, it is recommended that repeat topographic surveys are undertaken of the Restored-Planform reach to assess how the floodplain topography and anastomosing channel pattern develops under flood flows and the influence of large wood and other floodplain vegetation. Further surveys of the locations of large wood to supplement existing datasets presented within this thesis to further the understanding of the temporal dynamics of large wood within the Highland Water. It is suggested that these surveys are extended to include the floodplain especially in reaches where multi-channel and anastomosed channel patterns are developing.

## *9.4. Recommendations for further research*

Although this thesis has aimed to provide a thorough assessment of the hydraulic and hydrologic role of large wood accumulations there are a number of questions that have arisen from the work in this thesis that need addressing through future research.

The first is the development of a large wood accumulation resistance model which provides a much better comparison between observed and predicted resistance especially in high gradient channels and where large wood is abundant and blockage ratios are high such as those described both within this thesis and by Curran and Wohl (2003). It may be necessary to look at the resistance offered by step-pool channels and draw analogies to those large wood accumulations that cause a step in the water surface profile. Wilcox *et al.*, (2006) undertook a number of flume experiments which assessed the presence of simplified large wood elements within a scaled step-pool environment. A similar range of flume experiments using more complex large wood elements, a range of large wood accumulation types could be utilised in a scaled physical models of other river environments such as the Highland Water, studied within this thesis, and the low-gradient channels of Shields and Gippel (1996) could be undertaken to further assess the contribution of large wood resistance to the total flow resistance using a flow partitioning approach. It is possible that a single large wood flow resistance model which is applicable to all river environments does not exist and in this case, it may be necessary to develop a methodology to estimate the spill resistance in high-gradient channels with high blockage ratios whilst retaining the form-drag approach in the low-gradient river channels where it has been used with more success (Shields and Gippel, 1996).

To assess the hydraulic interactions of large wood accumulations, a Froude-scaled flume study looking at the local flow velocity fields around different large wood accumulations could highlight the different hydraulic processes operating and allow an understanding of the local accelerations and decelerations around the accumulations. The use of three-dimensional acoustic Doppler velocimeters and Acoustic Doppler Current Profilers could be used to determine the three dimensional hydraulics around large wood accumulations. This will provide an improved understanding of the deflection of flow in the presence of large wood and can be used to determine the potential effects upon bank erosion. Three-dimensional hydraulic data will also assist in the understanding of the contribution of spill resistance to the reach scale resistance and could assist in the development of a large wood accumulation resistance model.

To assess the role of large wood accumulations on catchment flood hydrology and to isolate the effect of large wood accumulations from other catchment dynamics a coupled one-dimensional: two-dimensional hydraulic modelling approach should be adopted, simulating the cumulative effect of a number of large wood accumulations over larger areas. Recent advances in hydraulic and hydrodynamic models have seen the development of coupled one-dimensional:two-dimensional models, such as ISIS-TUFLOW and Infoworks RS, and these could be useful to fully assess the catchment role of in-channel large wood accumulations in simultaneously retarding in-channel flow and routing flow onto the floodplain. A modelling approach would enable the simulation of a number of design flood events to determine the attenuation performance of large wood accumulations on a range of flows. The use of coupled one-dimensional: two-dimensional hydrodynamic models or other reduced complexity models like two-dimensional cellular kinematic-wave hydraulic models such as LISFLOOD and JFLOW can be used to explore the uncertainty involved in the understanding of large wood within larger reaches, larger catchments, larger flood events and for multiple flood events. Currently, the role of large wood in influencing catchment flood hydrology is limited to small catchments such as the Highland Water, with a catchment area of 12.5km$^2$, and further work is needed to assess whether the findings of this thesis upscale to larger river systems and determine whether large wood restoration has the potential to be used within larger river catchments and for larger magnitude flood events where flood risk is likely to be more significant than that of the Highland Water. It is the larger flood events such as the 25 year, 100 year and 200 year which are of more interest to flood risk management. The uncertainties involved in influencing the timing of flood peaks and synchronising flood peaks from different tributaries needs to be investigated. Using a reduced-complexity model such as one-dimensional or two-dimensional hydraulic models, which can be simulated quickly and for multiple flood event types in a probabilistic manner such as a Monte-Carlo analysis, can assist in the understadning of flood peak synchronisation and the subsequent impact upon downstream flood risk.

Investigations into the optimum large wood accumulation frequency for the purposes of habitat restoration and for potential flood risk benefits should be undertaken to enable clear management guidelines to be developed. This will help determine whether there is a role for large wood and restoration within flood risk management practices.

The presence of large wood has initiated flow patterns which portray characteristics of multi-channel anastomosing channel form suggesting that large wood accumulations play a key role in controlling the development in such systems. The long term role of large wood accumulations in controlling floodplain processes and channel evolution over long time-scales (eg. over the Holocene) merits further research. Such research should assess the prevalence of large wood and the subsequent formation of multi-channel planform over time using the stratigraphic record from the floodplain. This will assist in determining whether the true pre-disturbance state of river systems such as the Highland Water where large wood is prevalent, is a multi-channel anastomosing pattern. Results from such investigations will have significant implications for applied restoration as well as provide management guidelines for dealing with large wood within river systems.

Within this thesis, a quantitative method of describing simulated flow patterns using flow depth and flow velocity diversity measures. Further extension of this method is merited to help move away from the qualitative methods of describing flow patterns that are currently used by hydraulic modellers. The methodology could be extended to patch, edge and connectivity measures as well as combining multiple variables (flow depth, three-dimensional flow velocity) to quantify flow diversity. A flow diversity classification could then be developed to allow description of flow patterns whilst also allowing further research as to the ecological potential of such flow diversity classes. This could involve the analysis of ecological, landcover and topographical diversity to fully understand the diversity present within rivers and their floodplains. An analysis of the flora and fauna associated with the different flow type areas will help assist river restoration practitioners to tailor restoration techniques for particular outcomes.

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