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School of Geography

A geomorphological framework for providing ecosystem services in lowland rivers

by

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ABSTRACT
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The publication of the Millennium Ecosystem Assessment (MA, 2005) has generated widespread scientific debate regarding the importance of linkages between ecosystems and human well-being. An ecosystem services approach has presented many challenges during its early stages of development; fundamentally the ability to classify and value an ecosystem and its services. By its complex nature, ecosystem service research requires an interdisciplinary approach.

The thesis focuses on the role of 'geomorphology' as a means to providing a framework for delivering ecosystem services in lowland rivers. The framework introduces a reach-scale analysis of how geomorphological functions (GF) help provide a platform for bio-physical interactions that deliver multiple ecosystem services in lowland rivers. The analysis will assess the influence of geomorphological functions (GF) in providing ecosystem services.

Understanding the links between 'ecosystem services' and the functioning of ecosystems to human welfare is critical for a wide range of decision-making contexts (Fisher *et al.*, 2008). River restoration provides a useful and practical technique for placing monetary costs to the functions that characterise geomorphologically diverse rivers, whilst allowing for a spatial understanding on how physical characteristics impact the delivery of multiple ecosystem services. Case studies help reveal other direct and indirect benefits associated with riverine environments.

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DECLARATION OF AUTHORSHIP

I, Simon Hunter

declare that the thesis entitled

A geomorphological framework for providing ecosystem service in lowland rivers

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;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
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1.0. Introduction

Ecosystem services have become a key model for connecting the functioning of ecosystems to human welfare (Fisher *et al.,* 2009). The principle aim of this thesis is to highlight the role of geomorphology as an influencing factor towards the delivery of multiple lowland riverine ecosystem services. There will be focus on existing approaches to riverine ecosystem management including river restoration and how habitat restoration can impact the delivery of other ecosystem services. Firstly, ecosystem services needs to be defined. This thesis has approved and applied the ecosystem service definition used by Fisher *et al.* (2009):

Ecosystem services:	The aspects of ecosystems utilized (actively or passively) to produce human well-being (Fisher *et al.*, 2009).

Ecosystem service characteristics (Fisher and Turner, 2008):

- Ecosystem services are not ‘benefits’
- Ecosystem services are ecological in nature
- Ecosystem services do not have to be utilised directly

However, ecosystem services have been defined differently from one publication to another, causing academic debate within the literature (Daily, 1997; MA, 2005; Boyd and Banzhaf, 2007; Wallace, 2007; Fisher and Turner, 2008). The various definitions used within existing research of ‘ecosystem services’ are explored within chapter one when discussing existing ecosystem classification approaches. Sections 1.3. and 1.4. outline the history and background of sustainable development and environmental management whilst section 1.5. introduces the concept of an ‘ecosystem services’ approach.

An interdisciplinary approach where all aspects of the environment are considered could help strengthen the application of the ‘ecosystem service’ concept. A stronger interrelationship between biophysical, economical and social sciences is required to help strengthen the understanding of environmental interactions and their connections with people at various scales (Mace *et al.,* In Press). Ostrom *et al.* (2002) provide evidence that sustained interdisciplinary effort can yield sound science and practical guidance. Therefore, the wider knowledge we obtain regarding the science of ecosystems, the better the quality of decision making and policy formulation. This thesis will explore the contribution of 'geomorphology' in providing and influencing the delivery of a range of ecosystem services in riverine environments.

Over the past decade, ecosystem service valuation has been promoted by many to help make conservation and protection of ecosystems mainstream (Daily *et al.*, 2009). Pioneering research has led many to form frameworks which aim to 'classify' and 'value' ecosystem services (Daily, 1997; MA, 2005; NRC, 2005; Boyd and Banzhaf, 2007; Wallace, 2007; Fisher and Turner, 2008; Fisher *et al.*, 2009) but quantifying the levels and values of these services has proven difficult (Nelson *et al.*, 2009).

Valuation methods to help aid decision-making have been explored in chapter two through the application of a 'geomorphological framework' for providing ecosystem services for lowland rivers. The 'benefits' humans gain from ecosystems are derived as a result of ecosystem services and often require other forms of capital (Fisher *et al.*, 2009). Therefore, there is a clear difference between 'ecosystem services' and 'benefits'. This concept will be discussed in further detail during chapter one of the thesis.

Sections 1.1. and 1.2. introduces the characteristics of river ecosystems whilst describing how ecosystem degradation has impacted naturally-functioning geomorphology and highlighting the need for an ecosystems approach in river management.

1.1. Lowland river ecosystems

This thesis studies the role of geomorphology in delivering ecosystem services in lowland river ecosystems. River systems in their natural condition are recognised as interconnected dynamic ecosystems incorporating an interdependence of physical and biological processes (Sear *et al.,* 2009). A high level of spatio-temporal heterogeneity makes riverine floodplains among the most species-rich environments known (Ward *et al*., 1999). Lowland river corridors comprise a diverse array of landscape elements such as riparian systems which include alluvial forests, marshes and meadows, geomorphic features such as bars and islands, levees, deltas, fans and wood debris deposits. The formation of diverse landscape elements is largely influenced by energy, water, sediment, nutrients, organic matter and chemicals which move through upstream tributaries and across floodplains at varying rates and concentrations. River form and fluvial processes evolve simultaneously and operate through mutual adjustments towards self-stabilisation (Rosgen, 1994).

'Geomorphology' is the movement and storage of sediment within riverine landscapes. 'Morphology' refers to the description of the features within the channel and floodplain that are formed as a result of geomorphological processes (Sear *et al*., 2010). A morphological description alone is not enough to accurately provide information on the processes that alter sediment transfer and channel adjustment. Brookes and Shields (1996) explain that the morphology of a river is the product of erosion and deposition generated by fluvial processes to produce scour and fill locally. It is the interrelationship between erosion and depositional processes that explains how morphological features are formed. These interrelationships act upon various scales along a river channel, both in longitudinal directions (entire longitudinal profile or reach scale) and in cross-sections (entire width of valley for the total width of a floodplain, or a cross-section of a channel itself only) (Alekseevskiy *et al.,* 2008). This suggests that lateral and longitudinal connectivity is crucially important for sustaining natural river ecosystems.

1.2. Riverine ecosystem degradation

This section highlights some of the major problematic outcomes of previous riverine ecosystem management, illustrating how modifications to river systems have impacted geomorphology and ecosystems. In this project, the key terms are defined as follows:

'Sustainable river management' is the proclaimed aim of many agencies and institutions, but bringing the level of politics to the practical level of river management has proven challenging (Clark, 2002).

The term 'sustainability' is defined as the "...development that meets the needs of the present without compromising the needs of future generations to meet their own needs" (Brundtland, 1987).

'Sustainable development' has broad appeal and little specificity (Parris & Kates, 2003). Despite the persistent definitional ambiguities associated with sustainable development, this thesis defines 'Sustainable development' as "...development that conserves the natural capital, limits population and total resource demand in scale, maintains the integrity of ecosystems and diversity of species, remedies social inequities and environmental damage, while maintaining a sound economic base, fulfils basic health and educational needs, and is based on participatory democracy" (Harris, 2003).

1.2.1. An overview of the human role in changing channels:

The human role in changing river channels has been exercised for more than 4000 years. However, only since 1956 has this subject been addressed in widespread explicit scientific investigations (Gregory, 2006). Channel stability problems associated with conventional engineering and channelisation have been explored in detail over many years (Bilby, 1984; Brookes and Shields, 1996; Brookes, 1990; Griggs and Paris, 1982; Harvey and Watson, 1986; Hey, 1994; Shields and Hoover, 1991; Neil and Yaremko, 1988; Shields and Abt, 1989.)

Catchment surface, floodplain and channel structure along with hydrology and climate have been degraded as a result of anthropogenic change (Brookes, 1988; Petts & Amoros, 1996;

Sear *et al.,* 2000). The majority of channel networks in the UK have undergone modification either directly through modifications to morphology or indirectly through regulation of the flow regime or sediment regime (Raven *et al.,* 1998; Sear *et al.,* 2000). Alterations to land use within riverine environments have resulted in a wide array of complex morphological problems relating to sediment supply and erosive processes (Lufafa *et al.,* 2003; Costa *et al*., 2003; Rakovan & Renwick, 2011) which have degraded the health of rivers (Naiman & Décamps, 1997) including terrestrial and aquatic habitats and the diverse assemblage of organisms which thrive under natural river conditions.

This section aims to provide an overview for a number of potential human impacts to riverine environments. The core focus for this section is geomorphological processes and morphological form that operate within river environments, which over time will affect the generation of many ecosystem services.

1.2.2. Morphological impacts

It is imperative to recognise that a natural stream is a conveyor of sediment as well as water and that they are both inherently dynamic (Brookes and Shields, 1996). Natural rivers alter their geometry to convey the discharge that is accountable for the largest amounts of sediment transport, or the one that does the most work on the channel (Brookes & Shields, 1996). Complex processes interact creating an output over time of the catchment sediment. River morphology is the product of the sediment system within river channels which interacts with biological and geochemical systems to create an array of physical and biological habitats (Sear *et al.,* 2010).

The human role in changing channels has induced high levels of adjustment to river systems resulting in adverse effects to channel morphology. The majority of UK rivers have undergone some form of modification, causing alterations to the sediment regime, regulation of the flow regime, or direct modifications of channel morphology (Raven *et al.,* 1998; Sear *et al.,* 2000). Centuries of management mean that the processes and form seen today are unrelated to the natural processes before modifications. This helps explain why there is a lack of natural adjustment and very few natural re-recreations of past morphological features (Dury, 1984; Sear *et al.,* 1999). The term hydromorphology was introduced by the EC Water Framework Directive (European Commission, 2000) which can be used to explain:

- The extent of modification to the flow regime
- The extent to which water flow, sediment transport and the migration of biota are impacted by artificial barriers
- The extent to which the morphology of the river channel has been modified, including constraints to the free movement of a river across its floodplain.

The impact of man and in particular the impact of channelisation has prevented rivers from having freedom to meander and adjust within their floodplain. The purpose of channelisation is to reduce the flood level in a reach by increasing flow velocity, and to widen and deepen the channel to constrain the flow in the channel and lower the water table to improve agricultural efficiency (Brookes, 1988; Rhoads & Herricks, 1996). Channel-floodplain interactions in many cases have been degraded or largely modified as a result of changes in land-use, over-widened or straightened channels. The loss of channel-floodplain interactions can result in more rapid sediment transfer through the river network, as channel and floodplain morphology help regulate the storage and transfer of sediment (Sear *et al.*, 2010). Flood regimes of rivers have been altered as a result of straightening or over widening channels causing changes in the way alluvial soils develop (Allen, 2005). Changes to the flood regime hold the potential to cause wetland degradation as wet floodplain soils dehydrate and 'dry up' encouraging more sensitive woodland species to encroach such as beech (Allen, 2005).

Morphological forms that are distinctive of lowland natural river channels such as riffle-pool sequences and point bars (depending on geological context) are lost or removed from the system due to channel modifications such as straightening (Brookes, 1988). The removal of these naturally forming features from a river system can have a severe impact on the ecosystem occupying the stream bed, reducing the niche potential and habitat diversity within a reach (Brookes, 1988). The pattern of sediment transport and deposition will alter, causing knock-on effects downstream of channelised reaches. For example, a decrease in sediment supply during a time when peak stream flows have increased can result in an imbalance between sediment supply and sediment transporting power in the stream system (Rakovan & Renwick, 2011) causing channel instability at a catchment scale because autogenic change is restricted. Although the problems associated with channelisation have been described in terms of morphology, significant ecological impacts are caused as a result of removing natural processes and natural habitat structures. For example, the impact of chanelisation on fish habitats is a major problem.

Ecosystem services generated by fish populations are also at risk, with consequences for ecosystem functioning, biodiversity, and human welfare (Holmlund & Hammer, 1999). Salmon require gravel bed rivers to spawn as the female salmon deposits her eggs in redds which are fertilized and then covered with a layer of gravel. The gravel must be large enough to allow a passage of water through to the eggs to deliver oxygen and to allow the dispersal of by-products. Continual salmon spawning at the same location over many years can modify the bed contours, creating dune heights of over a metre (DeVries, 1997). These structures provide suitable habitats for juvenile salmonids and also enhance the survival of salmon embryos from rapid stream current (Montgomery *et al.,* 1996). Salmonids cause bioturbation in streams whilst spawning removes aquatic macrophytes and organic matter as well as displacing invertebrates from the bottom of the water column making them available to other river fish (Bilby *et al.,* 1998). However, conventional engineering such as channelisation (e.g. dredging, straightening) has removed many of the natural stream structures such as bed substrate which is vital for spawning. In doing so, knock-on effects to other fish species are likely as bioturbation associated with foraging or burrowing can no longer occur. Thus by removing a fish species with key ecological characteristics from the ecosystem, a loss of resilience is likely to occur causing the ecosystem to adjust from one equilibrium state to another (Holling, 1986). This type of river management is not sustainable as the environment is being degraded, biodiversity is declining and fish stocks are being reduced. This can also impact recreational benefits such as angling.

Another example of conventional river management is the removal of in-channel vegetation cover which causes a decline in macro-invertebrates and fish species, whilst the construction of large steep banks or levees can cause further knock-on effects to other species by removing wetland breeding grounds (Brooker, 1985). It has been established that in-stream vegetation decreases near-bank flow velocity and soil particle entrainment by protecting soil particles from raindrops, trapping and retaining sediment, increasing infiltration rate, and reducing erosion potential via runoff (Abernethy & Rutherfurd, 1998; Millar, 2000; Rey *et al.,* 2004; Lau *et al,*. 2006).

The continuing degradation of ecosystems and loss of biodiversity are widespread. River restoration is now largely recognised by governmental agencies and stakeholders as an approach which complements conservation and natural resource management by providing a "guiding image" (Palmer *et al.,* 2005) of a restored ecosystem. However, although many river restoration projects have distinct goals, the actual pathways to achieve those goals are rarely considered (Lake *et al.,* 2007). Determining such pathways can play a large part towards the success of a restoration project because they link ecological goals to the ground strategies used to achieve them (Mika *et al.,* 2010). An interdisciplinary understanding of biophysical form-function interactions which link geomorphology, hydrology and ecology can help establish these pathways (Fisher *et al.,* 2007).

1.2.3. Water quality impacts

The 'European Centre for River Restoration' (ECRR) states that intensive floodplain agricultural practices combined with channelisation and the construction of dams, embankments and straightened river channels, have also caused an increase in the load of organic matter, nutrients and other contaminants which have detrimentally affected most European rivers (ECRR, undated). Incision processes caused by channelisation increase sediment turbidity, concentration and phosphorus content (Shields *et al.,* 2010). This impact is often combined with land-use practices such as fertilisation methods, crop type, and artificial drainage systems which influence the peak runoff rates, sediment and nutrient loads (Skaggs *et al.,* 1994). The ECRR (undated) explains that water treatment has significantly reduced the concentration of contaminants such as nitrogen, phosphorus and organic matter, but many European rivers still contain high levels through eutrophication.

1.2.4. The impact of land-use change

Figure 1a) illustrates the manner to which temporal land-use changes and urbanisation relate to channel condition (Wolman, 1967). Figure 1b) displays the concept of river metamorphosis and thresholds (Schuum, 1969); and the application of a rate law (Graf, 1977) which involves reaction and relaxation-times as part of the response time from changing equilibrium conditions. Figure 1c) highlights the various types of equilibrium. For example, if land use change causes a river system to fall into disequilibrium, it is apparent to recognise that disequilibrium between the flow transporting capacity and sediment flux can alter the balance between interacting processes causing transformations of the longitudinal profile of a river. Channel planform will also shift causing channel morphology (pattern) to adjust (Alekseevskiy *et al.*, 2008).

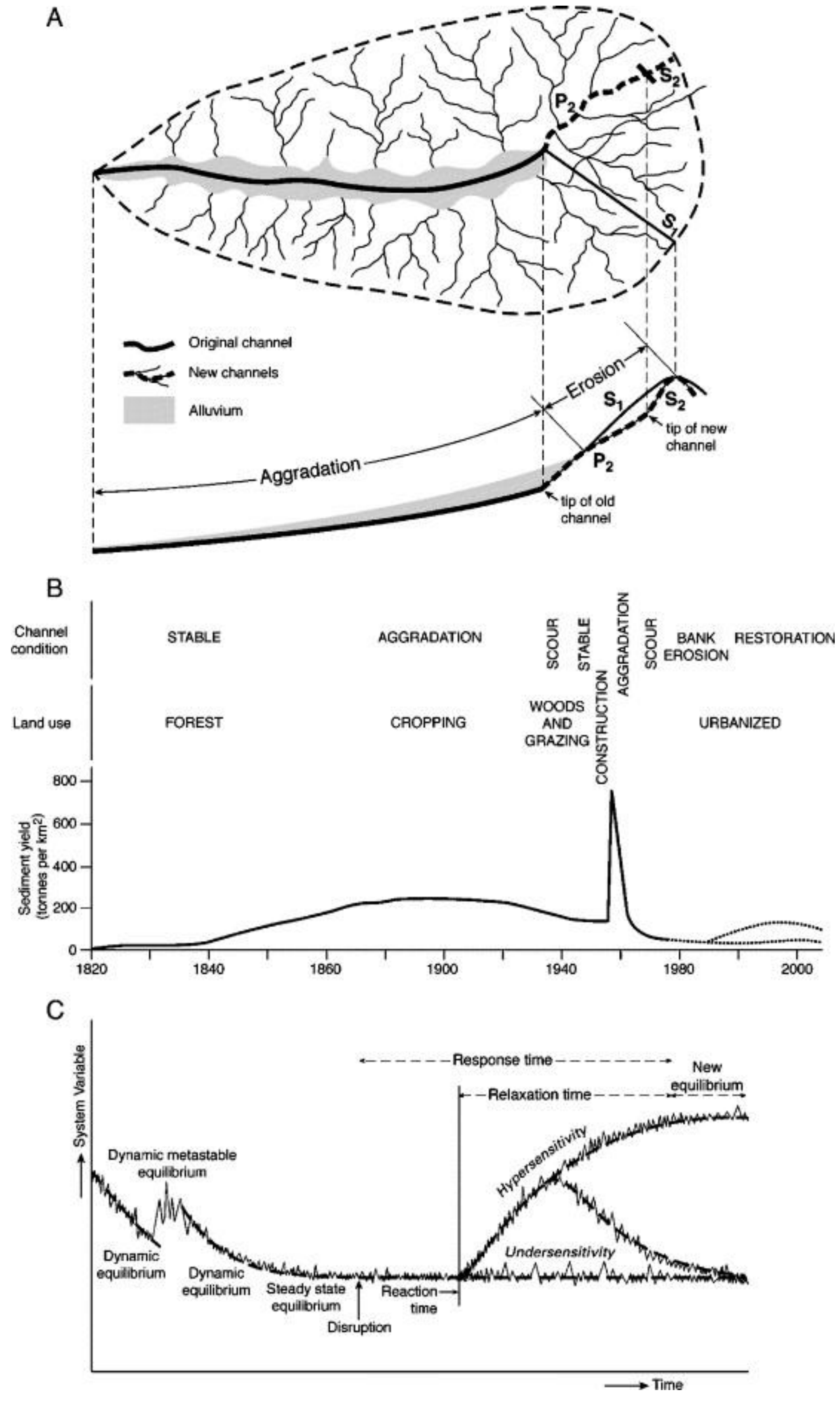


Figure 1). Foundations for studies of the human impact upon river channels (Gregory, 2006). 1a. is redrawn from Strahler (1956); 1b. is adapted fromWolman (1967); and 1c. incorporates ideas from Graf (1977) and Schumm (1979). (from Gregory, 2006).

Human impacts can largely contribute to channel change as highlighted by Figure 1a., 1b. and 1c. Channel change is largely influenced by sediment yield as exemplified in Figure 1b. Aggradation occurs as a result of land use change and is influenced most significantly by the construction stage of urbanisation. Wolman (1967) demonstrates that agricultural practice can increase sediment yields by over 200 tonnes per km^2 whilst grazing can cause scour and bank erosion. These land use practices can result in equilibrium threshold changes over time, where a river jumps from one type of equilibrium to another due to changes in erosion and sediment supply. Geomorphological impact assessments study the impact of catchment alterations including deforestation, cropping, grazing and changes in conservation practices, which can considerably influence the delivery of water and sediment to the channel and hence adjust the pattern of natural forming channel morphology (Warner, 1984). The following example will help illustrate the impact of grazing on river ecosystems.

Livestock impact local morphology and functioning of geomorphological processes on a reach scale by causing either stabilisation or erosion to bank processes effecting habitat structure (Trimble & Mendel, 1995). Livestock compact the sorted substrate, destroying invertebrate habitats as well as enhancing siltation, eutrophication and vegetation growth. A balance between land-use practice and naturally functioning riverine ecology needs to be addressed to manage river catchments sustainably. The loss of a number of rare and nationally scarce invertebrate species such as specialist beetles that thrive in exposed riverine sediment (ERS) habitats is not sustainable (Hyman, 1992, 1994; Rotheray & Robertson, 1993; Godfrey, 1999). Flood defence systems and river regulation across the UK have also caused similar effects to exposed riverine sediment (ERS) as a result of changes in flood frequency and magnitude (Brewer *et al.*, 2001). Michener and Haeuber (1998) explain that catastrophic events such as flooding provide long-term benefits to the system as they reset the system which helps sustain a diversity of patches in various stages of succession.

A study by Sadler *et al.* (2004) has provided evidence to suggest that rivers with more ERS appear to have more specialist species and a greater numbers of rarities with high conservation value. To reintroduce natural biodiversity in disturbed watercourses, ecological habitats must not be ignored and restoration must seek to improve habitats for species identified by the life history in terms of temporal and spatial heterogeneity of a catchment (Southwood, 1977). Various ways which land-use can influence the behaviour of channel processes and form is demonstrated in Figure 2. (Petts, 1983).

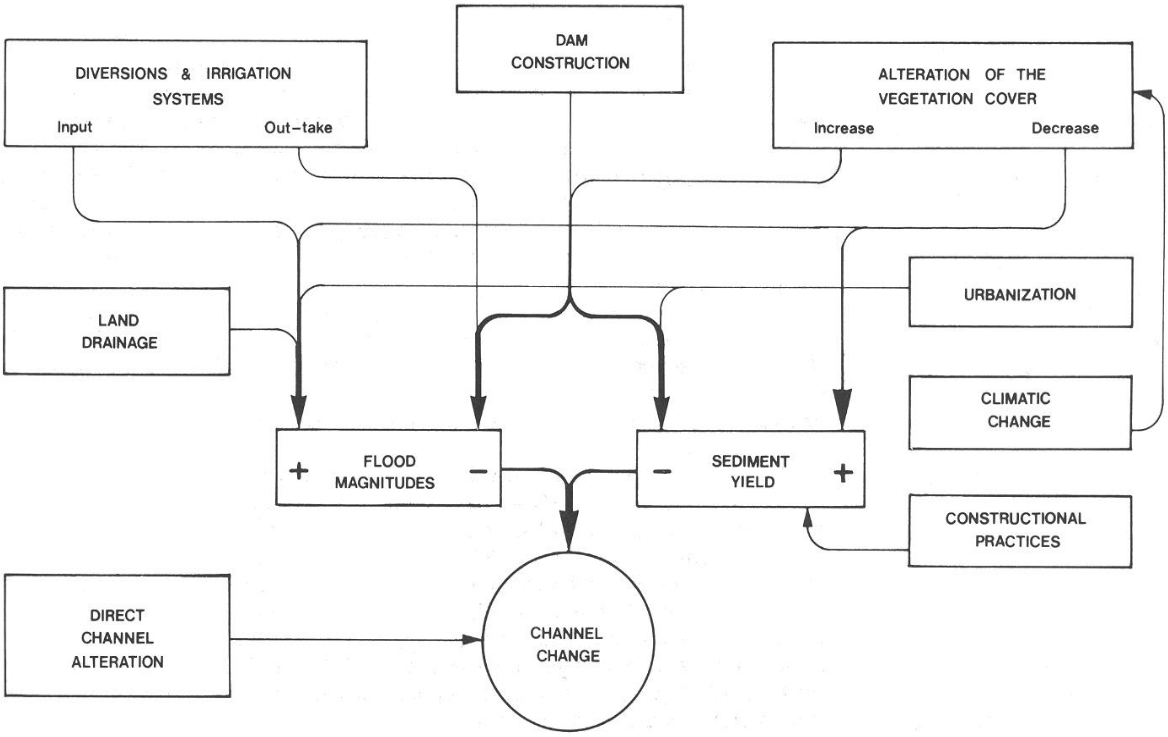


Figure 2. The impact of man upon channel processes and form (Petts, 1983).

Anthropogenic impoundment such as dams trap sediment and alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers (Kondolf, 1997; Tockner *et al.,* 1998; Greenwood *et al.,* 1999). Dams can trap up to 90 percent of the total sediment load and can reduce flood peaks by 90 percent (Petts, 1979) and globally there are more than 45,000 registered dams over 15 metres high (World Commission of Dams, 2000). Dams which modify sediment load and discharge also adjust the channel cross-section by creating incision below the dam and channel narrowing (Petts, 1979). Sediment which would naturally be transported as suspended load, and stored downstream as ERS is prevented by this ramped disturbance. For example, the construction of the Fort Peck dam in the 1930s along the Missouri River, eastern Montana, substantially altered the magnitude, frequency and temporal distribution of flows causing bank instability and bed degradation of up to 3.6 metres (Shields *et al.,* 2000; Simon *et al.,* 2002). Consequently dams can cause a sizeable change to the channel morphology as the longitudinal continuity of the river system is interrupted (Kondolf, 1997). Rakovan and Renwick (2011) suggest that the reduction of sediment supply relating to the construction of impoundments combined with climate change may exacerbate this imbalance by increasing sediment transport capacity, including peak flows.

Riparian vegetation has been directly affected by deforestation worldwide in order to provide a platform that is favourable to some human activities (Fischer *et al.,* 2000; Allan, 2004). In Britain, deforestation began around 5000 years ago and most of Britain's forests were cleared by 2000 years ago with extensive areas used for agriculture (Wolman, 1967). Vegetation is one of the key controllers regarding sediment supply to rivers and if removed, can influence channel morphology, rates of erosion and deposition and by extension, the entire sediment budget of a reach (Allan, 2004). The importance of vegetation is frequently highlighted in geomorphology and ecology literature (Abernethy & Rutherfurd, 1998; Beechie *et al.,* 2010). The removal of floodplain and riparian vegetation for agricultural practice can cause a large increase in sediment supply to the river channel due to high levels of soil erosion (Wolman, 1967). Research carried out by Micheli *et al.* (2004) found agricultural floodplains to be 80 to 150 percent more susceptible to erosion than riparian forest floodplains, and in the UK alone an estimated 2.2 million tonnes of topsoil is eroded annually, significantly affecting water quality and aquatic biodiversity through the silting up of watercourses (Environment Agency, 2004). The removal of riparian vegetation therefore causes an immediate response on a localised reach scale, whilst also causing an immediate catchment scale response, as the river responds to the changes in sediment supply as a system.

Deforestation has a spatial impact on the whole river system. Degradation and in particular bank erosion is likely to occur in the deforested areas, whilst aggradation is likely to occur further downstream in the catchment (Wolman, 1967) potentially causing a loss of productivity from soil erosion, an increase to water treatment costs, damage to property and dredging stream channels (Environment Agency, 2007). Investigations exploring the impact of land use and related human activity on sediment yields need to examine the overall sediment budget of a catchment rather than simply the sediment output (Walling, 1999). From one land-use change, two potential problems are probable which are likely to hinder the ability of the river to act as a conveyor of water and sediment. However, by re-introducing riparian vegetation, an increase in the overall catchment's response time to precipitation events will occur, lowering peak discharges and reducing associated erosion processes (Anderson *et al.,* 2006).

The outcomes of previous studies described in this section indicate that there is a requirement for more sustainable techniques in river management and restoration. Literature suggests that conventional engineering has caused many river ecosystems to degrade and even collapse as a result of profound sediment-related implications, resulting from anthropogenic influences and land use changes.

This thesis focuses on an ‘ecosystems approach’ to river management and restoration. The characteristics of an ‘ecosystems approach’ will be defined and explained in detail within section 1.5. The link between ‘geomorphology’ and ‘ecosystem services’ will be explained in greater detail in chapter two by using a ‘geomorphological framework’ for providing ecosystem services for lowland rivers. This will help emphasise the importance of geomorphology in ‘providing’, ‘supporting’ and ‘regulating’ ecosystem services in lowland riverine environments, whilst also explaining how degraded riverine environments may influence this delivery.

1.3. Approaches to river ecosystem management

The water cycle provides ecosystem functions (Table 1.) which are of central importance to sustainability (Everard, 2004). However, unsustainable decisions regarding river systems often occur as the result of a perspective solely driven by human utility (Gardiner & Perala-Gardiner, 2000; Boon *et al.*, 2000) as explained in the previous section.

Problems that are tackled using a 'single issue' basis may overlook catchment-scale processes causing adverse effects across the system. A catchment-scale approach can promote holistic thinking, and an ecosystem-focussed approach adds a temporal dimension which can reflect the inherent sustainability of restoring ecosystem function as a method for delivering water quality and other wider benefits (Zalewski *et al.*, 1997; Everard & Powell, 2002).

Water cycle provides:	
Ecosystem functions:	*Benefits:*
Hydrological Ecological Physico-chemical functions Geomorphological	Economic Recreational Aesthetic Educational Spiritual

Table 1. Ecosystem functions of the water cycle (adapted from Everard, 2004).

At present it is widely accepted that 'natural conditions' promote long-term sustainability that creates an aesthetically attractive environment as well as a functioning environment which retains the physical habitats vital for wildlife and biodiversity (Sear *et al.*, 2010). These conditions would also provide social goods and services which human life is dependent upon (Postel & Richter, 2003). A 'geomorphological approach' to river management has been developed over the past two decades through applied fluvial geomorphology (Sear and Arnell, 2006). Geomorphological guidance has shown to be both relevant and complementary to conventional engineering practice through its ability to identify the cause of sediment-related river maintenance (SRRM) problems for flood protection or bank stability (Sear *et al.*, 1995). A 'geomorphological approach' involves understanding geomorphological 'processes' and aims to enhance natural characteristics of a reach by reintroducing natural processes and morphology such as pools and riffles whilst using a sustainable approach to tackle long term erosion, deposition or sediment transfer problems. The benefit of using a 'geomorphological approach' is that it is accustomed to dealing with a variety of spatial and temporal scales and as such shares similarities with an ecosystem approach and can therefore assist river management.

1.3.1. The role of river restoration in ecosystem management

The 'River Habitats Survey', carried out between 1994 and 1997 established that only 15 percent of UK lowland rivers could be classified as "pristine" and only 29.7 percent as "semi-natural" (Raven 1998a). Therefore, restoration is likely to be required on a large scale, to meet 'Water Framework Directive' (WFD) requirements which aim to "prevent further deterioration and protect and enhance the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems" (E.U., 2000).

River restoration is described as 'the complete structural and functional return of the river to a pre-disturbance state' (Cairns, 1991). However, exact historical reconstruction is undesirable due to the dynamic nature of river systems causing continuous catchment changes (Berger, 1990; Sear, 1996). River restoration projects aim to move the river towards the least degraded and most ecologically dynamic state possible for that particular watercourse. It is important to acknowledge that the term 'ecological' is loosely used and includes hydrological, biological and geomorphic aspects of natural systems (Palmer *et al.,* 2005). Successful stream restoration requires the understanding of basic geomorphic principles such as addressing the underlying processes that determine channel form, system evolution and watershed context (Kondolf, 1995). River restoration complies with the complex scientific nature of aquatic and terrestrial riverine environments and aims to work with nature rather than against it as many previous 'hard' management strategies have done (Wohl *et al.,* 2005).

Restoration can describe methods used for 'quick fixes' such as engineering fish habitats or bank stabilisation at a reach scale or river-basin scale manipulations of ecosystem processes and biota over many decades (Wohl *et al*., 2005). River restoration can be applied at different spatial scales effectively which consider the key linkages (hill slope, floodplain, upstream/downstream connectivity and groundwater connectivity) beyond just the channel reach.

Reach-scale:	Length of river (<1km) in which dimensions and features relate characteristically to identifiable sediment sources and sinks. A reach may be demarcated by tributary inputs under certain conditions of climate, river regulation or land use (Newson, 2002).
Catchment-scale:	Includes the land surface as well as the network of streams and rivers within it (Sear *et al.,* 2010). Topographic boundaries of a river catchment also contain most of the available sediment sources and supply links to the river network (Sear *et al.,* 2010).

Figure 3. Definitions of 'reach-scale' and 'catchment-scale'

Sustainable river management requires historical data to achieve reach-scale or catchment-scale restoration. Temporal changes over time can influence river morphology and biological communities (Poff, 1997). Factors such as the natural timing, magnitude, frequency and the rate of change in flows (natural flow regime) (Poff *et al.,* 1997) are each fundamental in governing the ecological processes along the stream (Wohl *et al.,* 2005). This is also fundamental when managing ecosystem services as various 'geomorphological functions' provide varied potential for enhancing particular ecosystem services. For example, creating a multi-channel reach to help enhance floodplain connectivity and provide habitat provision for a more diverse species population within a catchment that has no historical recognition of this form could result in the channel adjusting to its previous form.

Restoration techniques that primarily focus on enhancing a singular ecosystem service, for example, restoring a particular habitat characteristic to meet perceived "good" habitat conditions, favour engineered solutions such as bank stabilisation (riprap) and rock weirs (pool or riffle building) which attempt to create an artificial and unnaturally static habitat (Wohl *et al.,* 2005; Beechie *et al.,* 2010). Stabilisation may be beneficial in restoring a given habitat for a particular species, but other ecosystem services such as carbon sequestration or sediment dynamics may be negatively impacted at that particular reach. Palmer *et al.* (2005) also explain that river restoration projects that are labelled a success should not always be assumed to be an ecological success. The most effective river restoration projects lie at the intersection of ecological success, stakeholder success and learning success (Figure 4.) which encourage the management of other ecosystem services.

Figure 4. Effective river restoration projects (Palmer *et al.*, 2005)

As explained in chapter 1, natural conditions promote long-term sustainability (Brierley and Fryirs 2008; Sear *et al.*, 2010). Naturally functioning geomorphological processes dynamically sculpt and create dynamic morphological forms which characterise terrestrial riverine landscapes. ‘Natural’ river conditions can be described as the conditions that are appropriate for a given landscape or setting including operational characteristics expected in that particular setting (Brierly & Fryirs, 2005). If fluvial and geomorphological processes were absent, diverse ecosystems would not exist in riverine environments. De Groot (2006) uses the term ‘ecosystem functions’ to explain the capacity of natural processes and components in providing goods and services that satisfy human needs. Geomorphological ‘processes’ can be classified as ‘ecosystem functions’ as they provide the physical platform for ecological growth and contribute largely towards the delivery of a set of other ecosystem services such as flood control, water regulation and erosion control. Therefore, many ecosystem functions such as geomorphological processes hold the potential to contribute towards the delivery of multiple ecosystem services, not just ecological benefits in river ecosystems. Restoring degraded functions towards more natural conditions will encourage long-term sustainability, therefore more efficiently benefiting human needs.

There are growing numbers of restoration projects that are taking a more holistic approach to river management. For example, the WRT (Westcountry Rivers Trust) has undertaken restoration projects in the South West of England such as the River Dart, Tale and the Axe

Valley catchment (Westcountry Rivers Trust, 2002b; Westcountry Rivers Trust, 2003). The WRT has worked closely with the farming community and riparian owners to help provide cost-effective methods to improve water quality, fisheries and river bank protection measures (Everard, 2004). Significant improvements to river habitat are anticipated in the River Tale catchment due to rapid regeneration of vegetation, erosion defences, and sites for silt trapping and in-river purification processes. Further management is planned, addressing access for migratory salmonoids (Everard, 2004). These projects have applied a systems approach where the focus has been primarily on the delivery of multiple services. The contribution of geomorphology as a 'function' for delivering services that provides benefits to humans will be explored as part of my research later on in the thesis. The following section will explore the need for sustainability and how ecosystems have been classified to help identify the linkages between ecosystems and human well-being.

1.4. Resource exploitation and sustainable development

Globally, over-exploiting natural resources is degrading many ecosystem services, reducing biodiversity and causing economic implications as explained by Repetto and Gillis (1988) where government subsidies were introduced as a result of living beyond our means. A lack of understanding and man's incapability to manage natural resources cautiously in the past, has led many people to believe that it is more suitable to think of resources as managing humans than the opposite, the larger and the more immediate are prospects for gain, the greater the political power that is used to assist unrestrained exploitation (Ludwig *et al*., 1993). Politicians and governments ally themselves to generate large and instant gains by resource exploitation, but this approach can result in over-exploitation, leading to the point of collapse or extinction. Initial over-exploitation is often not detectable until it is severe and often irreversible (Ludwig *et al*., 1993). A prime example is wasteful forestry practices which resulted in many old-growth forests being destroyed throughout the world by rapid harvesting. This outcome was caused as a result of governments eventually subsidizing the export of forest produce to delay the unemployment that is consequential when local timber supplies run out or become uneconomic to harvest (Repetto and Gillis, 1988). In other words people are living beyond their means.

However, realisation that land, water and air are not infinite resources has consequently resulted in changes to the methods in which we manage our natural resources. According to the Millennium Ecosystem Assessment (MA) (2005), at a global scale, 60% of the world's ecosystem services are being depleted or have been damaged by human exploitation or mismanagement, and for some; this has resulted in exacerbation of poverty and disparities across groups of people (Corvalan *et al*., 2005). Both the scale and significance of climate change and biodiversity loss have now been fully recognised (MA, 2005; IPCC, 2007), and it has also been established that both are as a consequence of human over-exploitation of natural resources (UNDP, 2007).

'Sustainable development' (Harris, 2003) and 'sustainable' (Brundtland, 1987) management of natural resources have been introduced due to the growing stress we put on our natural resources. The primary aim of 'sustainable development' is to enable all people throughout the world to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations (The DfES Sustainable Development Action Plan

2005/06), whilst providing a platform for decision making and management, advocacy, participation and consensus building and research and analysis (Parris & Kates, 2003). The developments of sustainable policies are building blocks that can be used to progress towards sustainability.

1.5. Approaches to ecosystem classification

An ‘ecosystem services approach’ has been adopted due to the increasing number of modified ecosystems at a global scale. Humans have modified ecosystems more in the last 50 years than in any comparable phase of time in history (MA, 2005). Land use and habitat change have resulted in simplification of ecosystems as humans have modified ecosystems primarily focussing on single ecosystem services such as food production (MA, 2005). The protection of singular ecosystem services which seem more sufficiently important can cause other ecosystem services to deplete resulting in the delivery of a single service rather than the delivery of a broad range of ecosystem services. This impacts the ecosystem on a geographical scale much wider than the original modification and insufficient funding/investment for conservation has resulted in an average wild habitat and population decline of 0.5-1% per annum (Balmford *et al.*, 2003).

The publication of the ‘Millennium Ecosystem Assessment’ (MA) in 2005 has generated widespread scientific debate about the importance of the linkages between ecosystems and human well-being. The central focus for assessment is human well-being but the MA (2005) recognises that biodiversity and ecosystems also have intrinsic value and that people make decisions regarding ecosystems based on considerations of both well-being and intrinsic value (MA, 2005). The MA (2005) was undertaken in response to the call in 2000 by the UN Secretary-General Kofi Annan, to “assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being” (MA, 2005).

The natural environment provides people with produce and services that are essential to human wellbeing. The MA (2005) defines ‘ecosystem services’ as “the benefits people obtain form the ecosystem”. The MA is a powerful stimulus which has encouraged current interest in ecosystem service research, but the concept of ecosystem services has a longer history in environmental research than many may think. Following Mooney and Ehrlich (1997), Cork *et al.* (2001) traced the development of a similar concept back to 1970 in the Study of Critical Environmental Problems (SCEP, 1970) which introduced the term ‘environmental services’. Haynes-Young and Potschin (2009) believe that the elements of an ‘ecosystem services’ concept was developed even earlier where a list of services was proposed for the SCEP study in 1970. Shortly after Holdren and Ehrlich (1974) also used a list of services in which they termed ‘public service functions’.

Consequently, as a response to the publication of the MA, there has been considerable interest in calculating levels of depleting ecosystem services at regional and national scales. For example, in some parts of the UK it is still possible to find ecosystems that are functioning naturally and producing ecosystem services such as woodlands. However, humans continue to modify ecosystems by anthropogenic action. Urbanisation for example, makes it incredibly difficult to detect the provision of many ecosystem services (Parliamentary Office of Science and Technology, March 2007). An investigation carried out by Stokstad (2011) concluded that some 30% of ecosystem functions are currently declining in the UK. To help prevent declining ecosystems, scientific appraisals have been developed in response to the MA to illustrate the trends of the world’s ecosystems and the types of services they provide whilst constructing methods to restore, conserve and enhance ecosystems.

Ecosystem services are increasingly being promoted as a method for evaluating the ‘benefits’ humans gain from natural resources and have been developed as a branch of science and policy since the late 1980s (Costanza *et al,.* 1997; De Groot *et al.,* 2002; Abel *et al*., 2003; Chee, 2004; Groffman *et al.,* 2004; Eamus *et al.,* 2005; Kremen, 2005; MA, 2005; Farber *et al.,* 2006; Wallace, 2007; Fisher and Turner, 2008; Fisher *et al.,* 2009). Ecosystem services provide an outcome-based language which helps various organisations and stakeholders communicate together about common desirable outcomes of value and the importance to the constituencies that they offer (Everard, 2009).

The MA (2005) grouped the various types of ecosystem services into four standardised categories:

Type of Service	*Definition of Service*	*Examples of Service*
Provisioning	The products obtained from ecosystems.	Food Fibre Genetic Resources Bio-chemicals, natural medicines, etc. Ornamental resources Fresh water
Regulating	The benefits gained from the regulation of ecosystem processes.	Air quality regulation Climate regulation Water regulation Erosion regulation Disease regulation Pest regulation Pollination
Cultural	The non-material benefits people obtain from the ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience.	Cultural diversity Spiritual and religious values Recreation and ecotourism Aesthetic values Knowledge systems Educational values
Supporting	Ecosystem Services that are necessary for the production of all other Ecosystem Services.	Soil formation Photosynthesis Primary production Nutrient Cycling Water Cycling

Table 2. Definitions and examples of the four categories of ecosystem services (adapted from the MA, 2005).

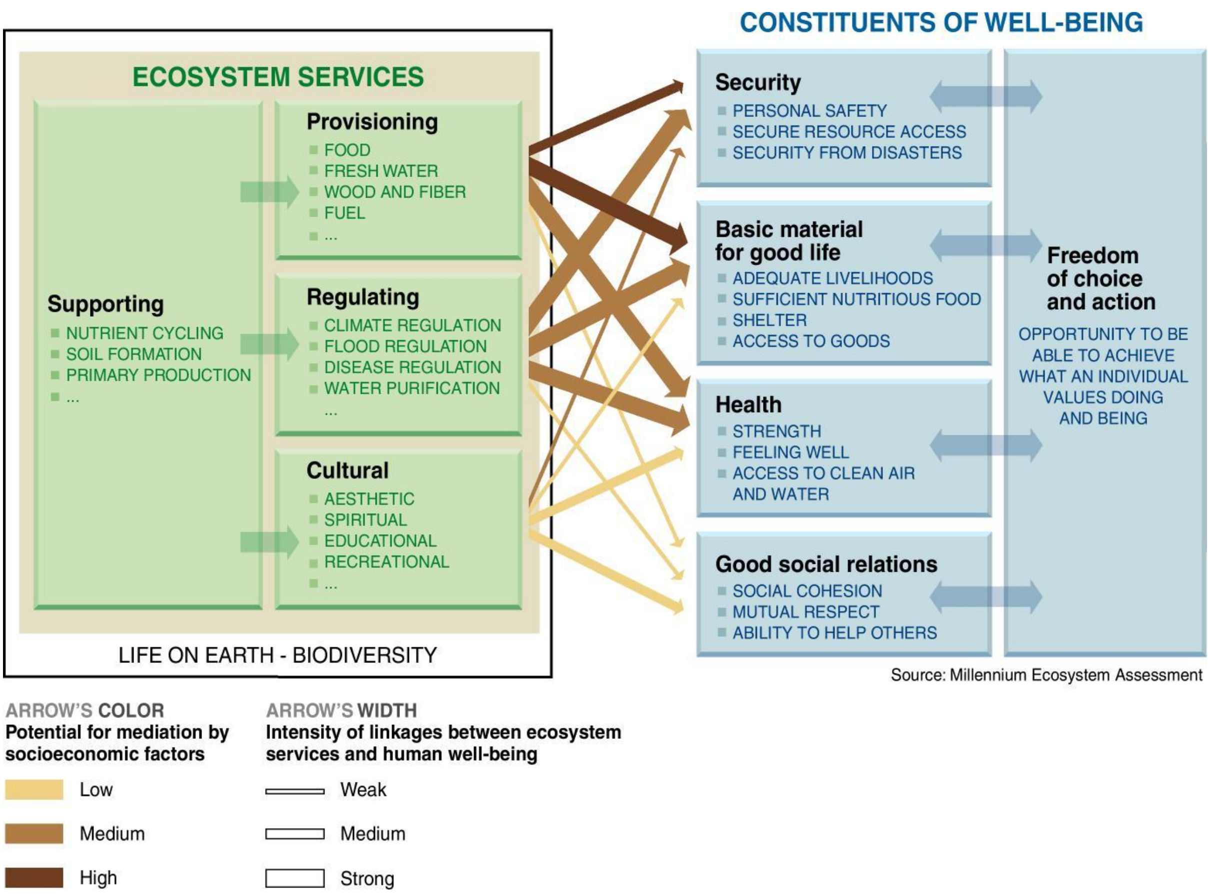


Figure 5. The linkages between 'ecosystem service' and 'human well-being' (MA, 2005)

The results of the MA have been taken up by the wider policy community on a global scale that has particular concern about the implications of the various management methods which relate to the way decisions affecting natural resource systems are made. An 'ecosystems approach' (EsA) is one method of environmental assessment.

Introduced by the Convention on Biological Diversity (CBD), an EsA is "...based on the application of appropriate scientific methodologies focused on levels of biological organization which encompass the essential processes, functions and interactions among organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of ecosystems" (Convention on Biological Diversity, 2006). An EsA is a planning paradigm founded on the basis of ecosystem services which aims to optimise benefits to many beneficiaries (including future generations). The EsA is consistent with the CBD definition – 'a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way' (Convention on Biological Diversity, 2005). The EsA also emphasises the importance of a wider, social and economic context for making decisions about biodiversity and ecosystem services. The MA strongly supports the EsA as a foundation for new sustainable policy formulation. The EsA aims to optimise the use of an ecosystem without damaging or depleting it and to achieve long term sustainability by combining sustainable development with economic value and human well-being. The emphasis of the EsA is directed to maintaining the health of an ecosystem rather than concentrating on the more focussed aspect of biodiversity. Management that only selects a limited subset of ecosystem services is not consistent with the ecosystems approach as it ignore potential conflicts with other services. It should also be stressed that this approach is not developed for achieving short-term economic benefits.

Leading environmental organisations are taking further steps to embed the EsA in policy-making and delivery. For example, Defra (2007a) has implemented the following principles:

- Taking a more holistic approach to policy-making and delivery, with the focus on maintaining healthy ecosystems and ecosystem services.
- Ensuring that the value of ecosystem services is fully reflected in decision-making.
- Ensuring environmental limits are respected in the context of sustainable development, taking into account ecosystem functioning.
- Taking decisions at the appropriate spatial scale while recognising the cumulative impacts of decisions.
- Promoting adaptive management of the natural environment to respond to changing pressures, including climate change.

Defra (2007a) believes that moving towards an EsA will bring about a number of important benefits:

- More effective delivery of our environmental outcomes.
- Better-informed decisions that take full account of environmental impacts, helping us to achieve sustainable development.
- Better prioritisation and more efficient use of our resources.
- More effective communications and greater awareness of the value of the natural environment and ecosystem services it provides.

Careful management of ecosystem services is vital because ecosystem services are not explicitly protected by EU legislation but directives do provide protection for some aspects (Parliamentary Office of Science and Technology, March 2007). For example, the 'EU Water Framework Directive' (2000) requires all of the inputs and demands made on a river system to be managed to make sure good ecological status is obtained. The 'EU Habitats' and 'EU Wild Birds Directive' protect species and habitats that are listed in their annexes. The UK government's 'Sustainable Development Strategy' (2005) aims to target individual components of ecosystems such as species at risk often in small pockets of high-value habitat. The result of not complying with these regulations or damaging the status of these species or habitats may result in financial liability under the 'Environment Liabilities Directive'. However, future policies may need to consider whole ecosystems that are at risk and therefore generate policies for larger scales (Parliamentary Office of Science and Technology, March 2007). This action will therefore enhance whole ecosystems not just individual species and therefore over time will help enhance biodiversity and other fundamentally important ecosystem services.

Despite the positive progress made into ecosystem service research, ecosystems are poorly understood, scarcely monitored and in many cases are deteriorating (Daily *et al.*, 2000; Daily *et al.*, 2009). Despite some conservation successes (especially at local scales) and increasing public and government interest in living sustainably, biodiversity continues to decline (Rands *et al.*, 2010). Unfortunately due to our limited understanding of the roles natural ecosystem services play in generating ecosystem goods and benefits in the marketplace, the overall importance of ecosystem services are only widely appreciated upon their loss (Daily *et al.*, 2000). Daily (1997) believes that if current patterns are to continue without increased awareness, then humanity will significantly alter the Earth's remaining natural ecosystems within a few decades. To enhance our understanding of ecosystems, the interactions between key processes/functions and services need to be quantified (Daily *et al.*, 2000). It is through advanced scientific research that processes and functions operating within ecosystems can be better understood.

There is certainly a requirement to use the ecosystems approach in policy making. However, there are significant gaps in scientific knowledge highlighted by Daily (2000) regarding the provision, distribution and value of ecosystem services which will be discussed in further detail in section 1.7.

1.6. Ecosystem service classification: problems and uncertainties

Defining and classifying ecosystem services has been the goal for many publications (Daily, 1997; MA, 2005; Boyd and Banzhaf, 2007; Wallace, 2007). Classification of ecosystem services has experienced ambiguity in many key definitions and terminology, including ecosystem 'processes' and 'services'. Wallace (2007) noted that the classification systems employed by leading practitioners such as Costanza *et al.* (1997), De Groot *et al.* (2002), Millennium Ecosystem Assessment (2005) and Farber *et al.* (2006) mix processes (means) for achieving services with services themselves (ends) creating complications for decision makers. The key problem arising from these enlightening publications is the inconsistent use of terminology and the misinterpretation of ecosystem services and what they really are. The various classifications and terminologies are explored in this section.

1.6.1. Existing ecosystem service classifications

The language and definitions surrounding the concept of ecosystem services has taken many forms. For example, Figure 6. is a reproduction of the representative ecosystem service as defined by Daily (1997) as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life".

- Purification of air and water
- Mitigation of droughts and floods
- Generation and preservation of soils and renewal of their fertility
- Detoxification and decomposition of wastes
- Pollination of crops and natural vegetation
- Dispersal of seeds
- Cycling and movement of nutrients
- Control of the vast majority of potentially agricultural pests

Figure 6. Daily's list of ecosystem services (adapted from Boyd & Banzhaf, 2007)

Daily's list of ecosystem services (Figure 6.) illustrates that both 'conditions' and 'processes' as well as the 'actual life-supporting functions' such as pollination and nutrient cycling in the framework for identifying ecosystem services (Fisher *et al.*, 2009).

Wallace (2007) uses the MA (2005) definition of ecosystem services “the benefits people obtain form the ecosystem”. Wallace is interested in managing the landscape and ecological processes to deliver ecosystem services and more importantly how land managers can manage the landscape to provide these benefits (Fisher and Turner, 2008). However, Wallace (2007) believes the existing framework of the MA mixes ‘ends’ and ‘means’. The ‘means’ are the functions of the ecosystem that work to achieve ‘ends’ or more commonly known as ecosystem services.

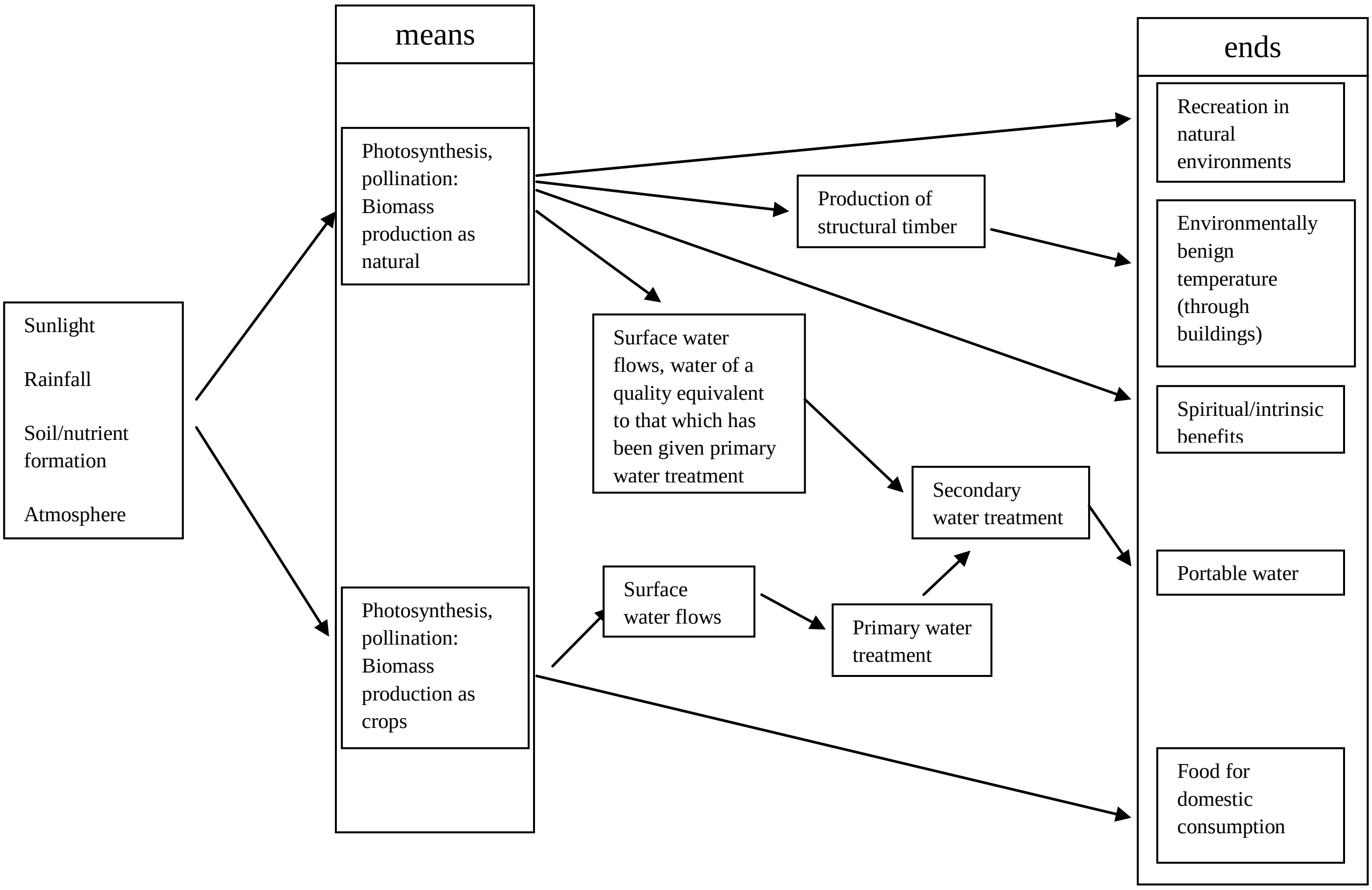


Figure 7. Simplified scheme of the ecosystem pathways for delivering five ecosystem services (adapted from Wallace, 2007).

Figure 7. illustrates the ecosystem pathways (means) for delivering five ecosystem services (ends). Photosynthesis, pollination, biomass and surface water flows are not ‘ends’, rather they are ‘means’ (processes/ecosystem functions) to achieve ‘ends’ (ecosystem services) such as recreation, environmentally benign temperature, spiritual/intrinsic benefits, potable water, and food for domestic consumption. Wallace (2007) believes that to achieve the overarching

goals of management, the decision maker must distinguish between the ‘means’ and ‘ends’ because management of the ‘means’ will provide food, fibre for construction, or spiritual experiences. Wallace (2007) also indicates that a single ‘means’ may support a number of ‘ends’ and therefore have a higher value. For example, Figure 7. lists photosynthesis as a ‘means’ which contributes towards providing ‘ends’ such as potable water, food for domestic consumption, recreation, intrinsic benefits and environmentally benign temperature.

Boyd and Banzhaf (2007) also highlight a fatal problem with the existing framework especially relating to ‘regulating’ and ‘cultural’ (Table 3.). The MA has listed services in ‘regulating’ and ‘cultural’ that do not fall within the Boyd and Banzhaf (2007) definition of services. Boyd and Banhaf (2007) define ecosystem services as the “directly consumed ecological components of ecosystems”. Therefore when applying the Boyd and Banzhaf framework they merely represent a list of ‘functions’ and ‘benefits’ (e.g. spiritual and religious values and pest regulation).

Illustrative Benefit		**Illustrative Ecosystem Services**
Harvests	Managed commercial	Property populations, soil quality, shade and shelter, water availability.
	Subsistence	Target fish, crop populations.
	Unmanaged marine	Target marine populations.
	Pharmaceutical	Biodiversity.
Amenities & fulfilment	Aesthetic	Natural land cover in viewsheds.
	Bequest, spiritual, emotional	Wilderness, biodiversity, varied natural land cover.
	Existence benefits	Relevant species populations.
Damage avoidance	Health	Clean air, water purification.
	Property	Wetlands, forests, natural land cover.
Waste assimilation	Avoided disposal cost	Surface and groundwater, open land.
Drinking water provision	Avoided treatment cost	Aquifer, surface water quality.
	Avoided pumping Transport cost	Aquifer availability.
Recreation	Birding	Relevant species population.
	Hiking	Natural land cover, vistas, surface waters.
	Angling	Surface water, target population, natural land cover.
	Swimming	Surface water, beaches.

Table 3. Services associated with particular benefits. (adapted from Boyd & Banzhaf, 2007)

Table 3. identifies the differences between 'benefits' and what Boyd and Banzhaf (2007) define as 'ecosystem services'. When comparing Boyd and Banzhaf (2007) to the MA's standardised categories of ecosystem services (Table 2.) or Daily's list of ecosystem services (Figure 6.) it is apparent to see that a clear definition of what ecosystem services are is

required with the use of consistent terminology. Differentiating between services such as ‘regulating’ and ‘provisioning’ is incredibly important when decision making. For example Hein *et al.* (2006) generated a category which combined ‘regulating’ and ‘provisioning’ services into one group. It was then later recognised that when valuing ecosystem services many of the ‘regulating’ services support more than one service leading to double counting which creates problems when calculating the value of a service.

Fisher and Turner (2008) concur with Boyd and Banzhaf (2007) to the extent that ‘ecosystem services’ are not ‘benefits’ and that they are different. Fisher and Turner (2008) propose that recreation is not a service provided by ecosystems, but rather a ‘benefit’ of which ecosystems provide important inputs. Therefore, ‘benefits’ are the many ways in which human well-being is enhanced through the process and functions of ecosystems via ecosystem services (Fisher & Turner, 2008). Recreation relies heavily on other inputs such as human capital and built capital and is classed as a benefit because it directly relates to changes in human welfare (Fisher and Turner, 2008). Wallace (2007) and the MA (2005) place ‘benefits’ under the same umbrella as ‘ecosystem services’. Similarly to Hein *et al*. (2006) this leads to the problem of double counting (Fisher and Turner, 2008).

Boyd and Banzhaf (2007) and Wallace (2007) declare that only the direct end points are ‘ecosystem services’, but others (Fisher and Turner, 2008; Fisher *et al.*, 2009) believe that ecosystems do not have to be utilised directly and that so long as human welfare is affected by ecological processes or functions then they are services. This enables ecosystem organisms or structures as well as ‘processes’ and/or ‘functions’ to be included as ecosystem services as long as they are consumed or utilised either directly or indirectly by humanity (Fisher *et al.*, 2009). This method allows connections to be made between human welfare and nature throughout an ecosystem, not just through the endpoint (Fisher and Turner, 2008). This theory is similar to those of Daily (1997) and the MA (2005) who make this connection through the word service (Fisher and Turner, 2008).

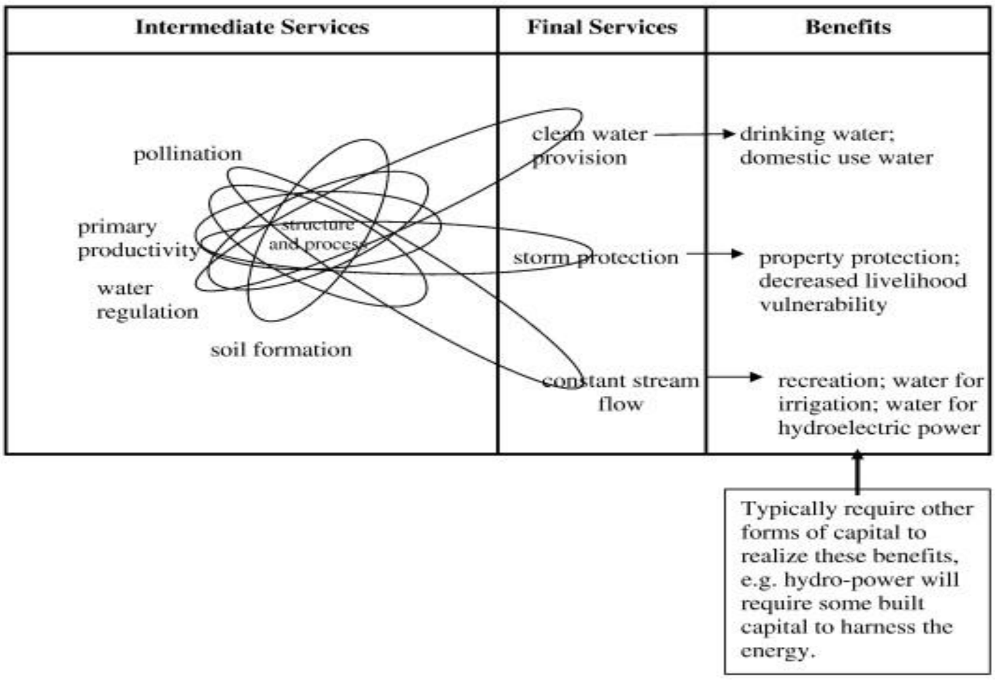


Figure 8. Conceptual relationship between intermediate and final services, also showing how joint products (benefits) can stem from individual services (Fisher *et al*., 2009).

Other frameworks have been established such as Fisher *et al.* (2009) who introduced the terms 'intermediate services' and 'final service'. 'Intermediate services' can stem from complex interactions between ecosystem structure and processes and lead to the delivery of final services, which in combination with other forms of capital provide human welfare benefits (Fisher *et al*., 2009).

Recent literature (Wallace, 2007; Boyd and Banzhaf, 2007; Fisher and Turner, 2008) suggests that the ecosystem service framework introduced by the MA is a generic framework which defines services, but confounds practical development. Boyd and Banzhaf (2007) also state that the MA provides very little guidance on techniques to measure ecosystem services, therefore making it difficult to accurately apply this framework practically. However, because there is not an agreed method of categorising ecosystem services the MA framework is widely accepted and is seen as a useful starting point. Since the publication of the MA, methods to help place true values of ecosystems and the services they can provide have been explored with substantial practical guidance and case studies (Eftec, 2006; Defra, 2007a; Defra, 2007b; Everard, 2009; Everard, 2010). This type of practical guidance is essential in attaining a full range of environmental impacts more systematically, linking ecological effects to changes in human welfare (Defra, 2007a).

An important step for progressing ecosystem research is that scientists and stakeholders can agree on consistent terminology that will enable them to differentiate between ‘ecosystem services’ and ‘benefits’. This way we can learn to manage and protect these ecosystem services via policies to help maintain or enhance the value of the related benefits (Fisher and Turner, 2008). However, the main underlying problem which has stalled the development of accounting units in ecology is the difficulty in measuring actual processes; it is much easier to measure outcomes of processes (Boyd and Banzhaf, 2007).

Section 1.6. identifies a collection of frameworks produced by scientists to classify ecosystem services. This section shows how ecosystem services research has become an important area of investigation over the past decade. It is clear to see that since the publication of the MA (2005) that the ecosystem service concept has been an evolving concept (Carpenter *et al.,* 2006; Sachs & Reid, 2006). The evolution of ecosystem services has, and currently still is being undertaken by scientists who are frequently examining the validity of early frameworks. Existing ecosystem service definitions are being analysed alongside ways in which the concept can be utilised by a wide range of stakeholders including scientists, economists, practitioners, policy makers, land managers and environmental educators (Fisher *et al.,* 2009).

Section 1.6. has highlighted through the use of multiple frameworks that a singular classification scheme is unlikely to be helpful as the dynamic complexity of ecosystems combined with the innate nature of ecosystem services should have us thinking about several different types of classification schemes (Costanza, 2008). Each ecosystem consists of multiple complex interactions among species and their abiotic environment - complex use and alteration patterns and various perceptions by beneficiaries (Fisher *et al.,* 2009). Therefore, a singular classification framework should be met with caution (Fisher *et al.,* 2009). Taking this point into consideration, the ‘geomorphological framework’ explained in chapter 2 is designed to identify the influence of geomorphology in delivering ecosystem services in lowland rivers. The ‘geomorphological framework’ can be used as one of several classifications to help identify the dynamic complexity of riverine ecosystems whilst identifying the services which they provide.

1.7. Valuing nature

The term 'value' has multiple definitions and meanings across various disciplines. This thesis uses the definition by Costanza (2000) where 'value' relates to "the contribution of an action or object to user-specified goals, objectives or conditions". The term 'valuation' is referred to as "the process of expressing a value for ecosystem goods or services such as flood control, biodiversity or recreational opportunity" (Farber *et al.,* 2002). The value of nature can be calculated by integrating the concept of ecosystem services to environmental management and exploring the various roles it can play in managing the links between human and natural systems. The MA (2005) found out that "nearly two thirds of the services provided by nature to humankind are found to be in decline worldwide. In effect, the benefits reaped from our engineering of the planet have been achieved by running down natural capital assets". 'Valuation' is especially significant when undertaking decisions about conservation and ecosystem restoration because without this knowledge, potential exploitation of resources could happen (Howarth and Farber, 2002). An ecosystem service approach is attracting increased attention as a way of providing a platform to communicate societal dependence on ecological life support systems (Daily, 1997; De Groot *et al.,* 2002).

Interactions between organisms and their 'physical habitat' (ecological assets) result in 'ecological processes' (ecological functions) that operate at various scales to deliver 'ecosystem services' that have value to people (Parliamentary Office of Science and Technology, March 2007). The values that they provide people with include the set of ecological functions that are fundamental for human survival, such as crop pollination, pest control and by providing aesthetic and recreational pleasure which enhances human well-being (Daily, 1997; Daily *et al*., 2000).

Efforts to calculate the value of ecosystem services play numerous roles in managing the links between human and natural systems (Howarth & Farber, 2002). In practice there are two valuation methods: economic and non-economic. However, calculating the 'economic value' of an ecosystem and its services has been a challenging procedure. Costanza *et al.* (1997) attempted to estimate the aggregate economic value of ecosystem services which would account for all of the benefits human beings would gain from natural environments. The VES (value of ecosystem services) method was established by multiplying the level of each environmental service by a shadow price that represents the marginal value of the services. The outcome of the study suggested that ecosystem services provide a global benefit of $33 trillion per year which is 83% higher than the gross world product (Howarth and Farber, 2002). Costanza *et al.* (1997) clearly demonstrate how important ecosystem services are in terms of economic values. However, many of the figures calculated for the economic value of the biosphere lie outside of market prices and therefore underline the importance of nonmarket services and the chain of effects from ecosystem services to human welfare. Costanza *et al.* (1997) understate the payment required to compensate people for the loss of all ecosystem services. However, the loss of all ecosystem services would result in the extinction of the human species – a cost that a rational person would most likely regard as indefinably large (Pearce, 1995).

The importance of ecosystem valuation varies with opinion. Heal (2000) believes that "the emphasis on valuing ecosystems and their services is probably misplaced". Heal (2000) believes that economics alone cannot estimate the importance of natural environments to society and believes that only biology can do that. A prime example of this type of problem is the diamonds and water paradox which confounded economists throughout the 18th and 19th centuries. Water is clearly more important to human society than diamonds, but diamonds carry a far greater market price than those fetched by water. Nonetheless, as a result of population growth and rising prosperity, a greater demand for water is required resulting in a large price increase for the supply of water (Heal, 2000). The explanation for this was proposed by Englishman Alfred Marshall during the 18th century; price is set by supply and demand. Therefore, it should not be expected that a resource of great importance will have a high market price. Biology alone cannot 'value' the importance of the natural environment, but economic 'value' can be a useful tool.

A number of ecosystem services are particularly difficult to quantify due to their intangible benefits and multiple value options. Problems also exist when a resource can be used for multiple purposes (Anderson *et al.*, 2007). While ecosystem valuation can improve the basis of welfare measurement, it sheds less light on a number of social and ecological services (Howarth & Farber, 2002) generated by ecosystems which do not have a market price and therefore are not traded and cannot be accounted for by using a market good valuation method. To understand how economics can address and quantify less tangible societal values, nonmarket services are explored in section 1.7.1.

A method to represent the ‘ecological’ concept of value has also been introduced (Farber *et al.,* 2002). This is a method used to express the non-economic ‘value’ of natural ecosystems and their components which is represented in terms of their contribution to human survival since there is no conscious goal being pursued (Farber *et al.,* 2002). If the concept of ‘value’ is limited to the degree to which an item contributes to an objective or condition in a system then the causal relationships between different parts of a system can be highlighted, which can show how one species type is ‘valuable’ to the survival of another species (Farber *et al.,* 2002). For example, the value of natural stream bed substrate which creates habitat for salmon in fresh water streams. This type of non-economic valuation method applies a more qualitative approach rather than solely focussing on assigning economic values and helps identify and understand people’s preferences (Defra, 2007a).

Valuation of ecosystem goods and services is further confounded by the different perspectives of ecologists and economists (Straton, 2006). Many ecosystem services cause difficulties to the modern neoclassical approach (supply and demand, exchange values) to determining value due to their complex nature and considerable nonmarket values (Straton, 2006). In neoclassical economics something has value because it contributes to the maximisation of that individual's utility but ignores the biophysical and ecological processes that sustain ecosystem goods and services. A study carried out by Gren *et al.* (1994) tested various environmental economic approaches for valuing wetlands and concluded that only part of a wetlands value can be captured in monetary terms. An ecologist’s perspective tends to ignore the social processes and human preferences that guide resource use (Straton, 2006). Nonetheless, ecological concerns and market strategies can modify the way humans perceive and relate to nature in a way that in the long run may be counterproductive for conservation purposes (Rees, 1998; Martínez-Alier, 2002; Robertson, 2004; McCauley, 2006; Soma, 2006; Spash, 2008; Kosoy & Corbera, 2010). Therefore understanding how societal dependence relates to ecological life support systems can help progress the nature of ecosystem management.

1.7.1. Nonmarket services

Nonmarket services are those which do not have a monetary value and therefore cannot be traded within a market. The ‘Hicksian consumer surplus measure’ can help identify people’s ‘willingness to pay’ (WTP) or willingness to accept compensation (WTA) for welfare loss

(Hicks, 1964). WTA addresses the amount of compensation necessary for an individual so that they could attain an improved utility level in case the provision of the public good does not take place. A loss in welfare would result in a compensating variation which refers to the amount of money income that is required to compensate the individual for the welfare loss experienced (Hicks, 1946). WTP accounts for the maximum amount a person would be willing to pay via their income for a good or service to prevent its loss from occurring in the future (Bateman & Turner, 1993). WTP is a technique that can indirectly place a value to a non-market service via a CVM (contingent valuation method) to illustrate its importance to human welfare and is recorded through the use of a survey (Portney, 1994; Hanemann, 1994). The CVM method is an extensively used nonmarket valuation method which is used in the areas of environmental cost-benefit analysis and environmental impact assessment (Mitchell & Carson, 1989; Cummings *et al.,* 1986). CVM can estimate WTP of services such as nonmarket values (Choe *et al.,* 1996; Loomis & du Vair, 1993) or non-use values (Walsh *et al.,* 1984; Brookshire *et al.,* 1983). The method was first established by Ciriacy-Wantrup (1947) who was of the opinion that the prevention of soil erosion can generate 'extra market benefits' that are public goods in nature, and therefore, these benefits can be estimated by using the individuals' WTP.

The CVM method has come under severe criticism mainly around two aspects: validity and the reliability of results (Smith, 1993; Freeman, 1993). Validity can be broken up into three sections. 'Content validity' refers to the capability of the instruments included in the scenario to record the value in an appropriate manner during the CVM experiment (Venkatachalam, 2004). 'Criterion validity' may be assessed in terms of another measure, such as a market price which could be used for the same commodity and therefore considered a criterion (Venkatachalam, 2004). 'Construct validity' can be broken into two forms: 'convergent validity' and 'theoretical validity'. 'Convergent' refers to the correspondence between two measures of the same theoretical construct and if an experiment is 'theoretically valid' it means the results conform to the underlying principles of economic theory (Venkatachalam, 2004). 'Reliability' meaning the extent to which the WTP amounts recorded are due to random sources (Mitchell & Carson, 1989). The following paragraph discusses how errors/biases can cause implications to the validity and reliability of the CVM method.

The reason behind much of the criticism is because economic research has demonstrated both theoretically and empirically that the WTA value is always greater than the WTP value when used for the same subject (Shogren *et al.,* 1994; Hanemann, 1991; Brookshire & Coursey, 1987; Coursey *et al.,* 1987; Knestch & Sinden, 1984; Bishop & Heberlein, 1979; Willig, 1976). This therefore begs the question: which measure should be used in a CVM survey? (Mitchell & Carson, 1989). Another issue associated with WTP is highlighted by Farber *et al.* (2002) regarding flood control provided by wetlands. For example, if flood damage in an area was $1 million, society is prepared to pay $100,000 to reduce the probability of flooding by 10 per cent to restore/maintain wetlands. However, suppose the wetlands reduce flooding probabilities by 20 percent. When wetlands services are free, society receives $200, 000 million in services for nothing (Farber *et al.,* 2002). Therefore, the owner of the wetland could receive this amount of social value if a capture mechanism was in place. Capture mechanisms work well for ecosystem goods such as food production and raw materials but less well for nonmarket trading services.

Another method for calculating the value of services that do not have market prices is through hedonic price indices. Hedonic prices (HP) are defined as the "implicit prices of attributes and are revealed to economic agents from observed prices of differentiated products and the specific amounts of characteristics associated with them" (Rosen, 1974). Service demand may be reflected in the prices people will pay for associated goods. For example, soil fertility is not a good that has a market price. On the other hand, farms can be bought and sold. Farm prices can be calculated along with prices per hectare of the farmland which can be compared with data collected on the fertility and quality of the soils within the farm. The correlation between land price per hectare and the quality of the soil will calculate how much fertility will add onto the price of the land. So indirectly we can estimate the price for soil fertility (Heal, 2000).

Services could also be replaced with man-made systems. For instance, natural waste treatment can be replaced with costly treatment systems (Farber *et al.,* 2002). A replacement cost (RC) is another method that can be used to estimate the value of natural services with no market price. Chichilnisky and Heal (1998) provide an example of how RC has been used to value natural services in New York. In 1996 the US government had to make a decision whether to invest in natural capital or in physical capital. Consider the Catskill watershed which requires restoration to preserve the natural characteristics and prevent pollution from sewage, fertilisers, and pesticides. Restoration would cost between $1 billion and $1.5 billion but an alternative plan was also considered which would replace the watershed with a filtration plant. The cost of constructing the filtration plant could potentially rise to about $9 billion, with operating and eventual replacement costs on top of that. So therefore, an investment of $1 billion to $1.5 billion to restore the watershed would save an investment of around $6 to $8 billion in physical capital. As the cost of replacing the watershed is $9 billion could this be its value? (Chichilnisky & Heal, 1998). Other problems concerned with the construction of the filtration plant is that it will not support biodiversity, sequester carbon or provide recreational activities which are all other ecosystem services provided by the original watershed. This creates a problem when applying an ecosystem service approach, as one service may be enhanced (water purification) but others are degraded (biodiversity, carbon sequestration, recreation). Therefore, when applying Brundtland's (1987) definition of sustainability, the construction of a filtration plant does not pass as being sustainable because present day development will affect future generations to meet their needs.

Generally, RC are not a convincing method of valuing the natural ecosystems and the services they provide because replacements very rarely replace the entire original system which therefore may mean some services may still be undervalued (Heal, 2000). RC can also misinterpret WTP or WTA valuation concepts because social benefits that may be lost when ecosystem services are replaced are less than the cost of replacement for those services; or when the benefits gained from the alternative are less than those provided by the original ecosystem services (Farber *et al.*, 2002).

The travel cost (TC) method is also an approach to valuing environmental services where service demand may require travel, these costs can reflect the implied value of the service (Farber *et al.,* 2002). The method estimates how much people value an environment by calculating how much people pay to visit a particular environment. The overall cost will reveal how much people value an environment and therefore reflect the benefits that the environment provides to people. If people are willing to spend $500 to visit a forest and spend their time there, then it must provide them with benefits of at least this value (Heal, 2000). Costs would include admission fees such as those at National Parks, and transport costs. Therefore, TC will vary between different people due to varying distances covered by people to visit particular environments. The total value of services provided by the environment can be calculated by adding together all of the values attributed to it by all of the users.

Total Economic Value (TEV) is a framework used to value ecosystem services and comprises of 'use' and 'non-use' values. The TEV method refers to the total gain in wellbeing from a policy option regarding people's WTP or WTA. 'Use' values can be broken up into three groups: 'direct', 'indirect' and 'option' values. Defra (2007a) describes 'direct' values as those where individuals make actual use of an ecosystem service which can either be consumptive use (e.g. food, timber) or non-consumptive use (recreation, landscape amenity). 'Indirect' values are described as where individuals benefit from an ecosystem service supported by a resource rather than directly using it (Defra, 2007a). Examples of indirect values include climate regulation, water regulation, soil retention, nutrient cycling and pollution filtering. Option values are the value which people place on having the option to use the resource in the future even if they do not use the resource at the present day (Defra, 2007a). This value can be either direct or indirect in nature. An example would be a national park where people who have no intention to visit it may still be willing to pay to keep that option in the future. This value is a kind of insurance value in which a value is placed on an ecosystem service for maintenance purposes to ensure this service is available for future uses.

'Non-use' values are given to an ecosystem service to ensure that the natural environment is maintained. It is difficult to capture and place a 'price' for non-use values; however in some cases they can be more important than 'use' values (Defra, 2007a). 'Non-use' values can be divided into three components: 'bequest', 'altruistic', 'existence' values. 'Bequest' values are attached to an ecosystem resource based on the fact that the ecosystem resource will be passed on to future generations (Defra, 2007a). 'Altruistic' values are placed to an ecosystem resource based on the availability of an ecosystem resource to others in the current generation, whilst 'existence' values are derived from the existence of an ecosystem resource, even if there is no planned use of it (Defra, 2007a).

As previously mentioned there are two types of valuation methods: economic and non-economic. A number of economists (Boyd & Banzhaf, 2007; Fisher & Turner, 2008) have a specific goal to 'price' benefits provided by ecosystem services by obtaining a monetary value in terms of direct or indirect utilisation (Cornell, 2010). These benefits can be calculated by market prices, hedonic prices, replacement costs and travel costs which are all based on actual transactions. A problem which tends to hinder this technique is that it does not reveal the social importance the services provide, or the extent of the losses that we would experience if these services were removed (Heal, 2000). It is almost impossible to attach a specific value to some of the experiences we have in nature, such as viewing a beautiful sunset. Ecosystem services are so varied in their composition; it is often difficult to examine them on the same level due to a combination of qualitative and quantitative data and different measuring units (Martinez-Alier *et al.,* 1998). This point is summarised by Eftec (2006) who found that most environmental policy makers deal with gaps in value by 'informed guesswork' because many natural environments have no monetary value or there is not enough environmental data to support economic valuations. Sometimes, even where economic values exist, they are not accessible. Many reports (notably, Eftec, 2006; Jacobs, 2008; Graves *et al.*, 2009; Raffaelli *et al.,* 2009) conclude that fundamental data about ecosystem functions is needed before ecosystem valuation can be assessed. Therefore, economic value of ecosystems is not sufficient to estimate the importance of environments to society, but the use of economics can help devise institutions that will offer incentives for the conservation of important natural systems and will mediate human impacts on the biosphere so that these are sustainable (Heal, 2000).

The role of nonmarket valuation techniques plays a large part in placing values to services that potentially could be deemed as less important as market goods which have an economic value. However, when valuing nature it should be emphasised that ecosystem valuation is an aid to decision-making not an alternative. There are many different techniques to place values to nonmarket goods and services, but as will be revealed in section 1.7.2. there are still many research gaps regarding quantification and monetary valuation of important services. A study by Cornell (2010) revealed that after the publication of the MA (2005) there are about 8 to 9 times as many published articles on the ISI Web of Knowledge database talking about ecosystem services rather than valuing them. This statistic helps emphasise the gaps in environmental data and ecosystem functions which hinder the ability to place values to a collection of ecosystem services.

1.7.2. Valuing nature: case study

The WRT coordinated a 4-year 'Sustainable Practice Project On the River Tamar' (SUPPORT) catchment in 2000. The outcome of the Tamar 2000 project resulted in 615 ha of the river corridor being restored and 25 km of riverside fencing and the identification and control of 67 areas of accelerated erosion through measures agreed with farmers (Everard, 2003). Cost benefit values were calculated at a catchment scale with benefits calculated as either direct (to participating farmers) or indirect (to local community, tourism, angling and the value of the river system as a national and international resource). To encourage sustainable land use practice to improve habitats, economic incentives were introduced to farmers and land-owners (Westcountry Rivers Trust, 2003). Future policies should help protect and restore ecosystem functions which operate at large scales, not just ecosystem functions at smaller local scales (Everard, 2003). Case studies such as the Tamar enable generic learning to be taken forwards and, as importantly, help environment agencies learn more about the benefits of using ecosystem services in its work (Everard, 2009). Table 4. is a summary of results from the Tamar catchment case study (Everard, 2009) based on an 'ecosystems approach'.

Ecosystem Service	***Annual Benefit Assessed***	***Research Gap / Note***
Provisioning Services		
Fresh water	**£304,000**	
Food (e.g. crops, fruit, fish, etc.)	**£265,319**	Value not used = Employment in farms
ADDENDUM SERVICE: Fish stocks	**£8,269**	
Fibre and fuel (e.g. timber, wool, etc.)	**£2,511**	Unquantified value = *Miscanthus* planting Value not used = Employment in woodlands
Genetic resources (used for crop/stock breeding and biotechnology.)	**No net value ascribed**	
Biochemicals, natural medicines, pharmaceuticals	**No net value ascribed**	
Ornamental resources (e.g. shells, flowers, etc.)	**No net value ascribed**	
Regulatory Services		
Air quality regulation	**It was not possible to value this Ecosystem Service**	Quantification and valuation of air quality regulation
Climate regulation (local temperature/precipitation, GHG sequestration, etc.)	**£2,455,304**	Unquantified benefits = upland peat Unquantified benefits = microclimate effects Unquantified benefits = implications for estuarine salt marsh Research need: This work has exposed the fact that, despite some simple tools, there are complexities inherent in the dynamics of carbon sequestration,

		methanogenesis, nitrous oxide production and other mechanisms important for greenhouse gas dynamics under different soil types and wetting and oxygen regimes. This needs to be teased out including a digest useful to practitioners
Water regulation (timing and scale of run-off, flooding, etc.)	**Benefit not assessed**	Quantification of contribution to hydrology
Natural hazard regulation (i.e. storm protection.)	**£12,500**	
Pest regulation	**Benefit not calculated**	
Disease regulation	**No value ascribed due to methodological difficulties**	Value not used (to avoid double counting) = animal disease Research gaps include assessing human & shellfish contamination
Erosion regulation	**£7,151**	Contribution from sites to catchment erosion risk
Water purification and waste treatment	**Value not ascribed in order to avoid double-counting**	
Pollination	**Ecosystem service not quantified**	
		Cultural Services
Cultural heritage	**£2,511**	Methods required for hedonic property values
Recreation and tourism	**£317,966**	
Aesthetic value	**Assumed no net contribution from *Tamar 2000***	
Spiritual and religious value	**Assumed no net contribution from *Tamar 2000***	
Inspiration of art, folklore, architecture, etc.	**Assumed no net contribution from *Tamar 2000***	
Social relations (e.g. fishing, grazing or cropping communities.)	**Benefit not ascribed a monetary value**	Methods required to value social networks
Supporting Services		
Soil formation	**£6,269**	Research gap includes more direct measure of soil formation
Primary production	**No net value ascribed**	
Nutrient cycling	**£66,032**	Nitrous oxide generation is a major research gap

Water recycling	**£360,360**	
Photosynthesis (production of atmospheric oxygen.)	**Assumed to be value-neutral**	
Provision of habitat	**£69,114**	Research gaps include benefits from broader habitat restoration
ADDENDUM SERVICE: Resilience of salmonid stocks	**Benefit acknowledged as significant but not valued**	

Table 4. A summary of the annual 'benefits' gained from 'ecosystem services' in the Tamar catchment case study (Everard, 2009)

The summary of results from the Tamar Catchment clearly identifies that an ecosystems approach can identify multiple benefits which can help establish a multi-functional funding stream. The framework links specific reach scale activities on a catchment scale to ensure practices are sustainable. For example, reach scale erosion control can help mitigate a wider catchment problem of enhanced sediment load. Some instruments are already available, and involve using existing directives and legislation more sufficiently (such as the Habitats Directive, WFD, Floods Directive, Water Act, Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA) to deliver appropriate management measures for good ecological status, beneficial ecosystem services and key species (UK National Ecosystem Assessment, 2011).

A fundamental problem highlighted by the Tamar catchment case study is that many key services such as air quality regulation or pollination regulation are not quantified and therefore have not undergone economic valuation. This is because these services do not have a 'direct' monetary value or market price. It is likely that specific ecosystem structures and processes (i.e. air quality regulation) have an important functional role in an ecosystem, and, therefore, have 'value', but they may not have 'direct' or 'indirect' value in market economies (Farber *et al.,* 2002). Without a 'value' there may be a danger that these services are overlooked resulting in other services taking priority during decision making (Haines-Young & Potschin, 2009). Future economic valuation is also unclear due to fluctuating climate and market values. For that reason, are economic values only good for short-term changes and not for long term benefits? (Daily *et al.,* 2009).

Another limitation was outlined by Everard (2009) from the Tamar catchment case study; the key impacts and interactions of services were not calculated. An example of this is explained by Everard (2009) where tourism was identified as generating increased revenue due to increased numbers of visitors but conversely tourism creates higher levels of temporary pollution, use of resources (water), more travel miles (carbon) etc. These are some of the key problems of the current MA framework which has been highlighted by the Tamar catchment case study. It is also important to acknowledge that 'carbon sequestration' techniques are not instantaneous so consideration has to be given to the fact that they will be acting on future CO_2 levels not current levels. Therefore this factor should be taken into account when considering efficiency.

A collection of river ecosystems has undergone an ecosystem assessment and the results that are presented in Table 5. highlight the monetary value of catchment scale and reach scale ecosystem services and annual benefits.

Catchment	Ecosystem Service	Annual Benefit (approx)
River Tamar (Catchment scale) (Everard 2003; 2009)	Provisioning	£587,000
	Regulating	£2,475,000
	Supporting	£502,000
	Cultural	£320,000
	Gross annual 'Benefit'	**£3,875,000**
River Glaven (Catchment scale) Sea trout restoration (Everard, 2010)	Provisioning	£20,000
	Regulating	£67,000
	Supporting	£21,000
	Cultural	£167,000
	Gross annual 'Benefit'	**£275,000**
Upper Bristol Avon (Reach scale) Buffer zone assessment (Everard, 2010)	Provisioning	£500
	Regulating	£1,800
	Supporting	£1,600
	Cultural	£4,600
	Gross annual 'Benefit'	**£8,600**
Mayes Brook (Catchment scale) Restoration assessment (Provisional figures from EA not yet published from Everard 'Applying ecosystem services in practice' presentation 22nd September, 2010)	Provisioning	£0
	Regulating	£26,500
	Supporting	£30,600
	Cultural	£337,000
	Gross annual 'Benefit'	**£394,000**

Table 5. Case study data on the gross annual 'benefits' for a selection of UK watercourses (adapted from Everard, 2010)

The results displayed in Table 5. have been obtained from the annual 'benefit' assessment, providing evidence that monetary values can be derived from a collection of ecosystem services. However, the annual 'benefits' gained from the 'provisioning' services are particularly lower than the other services. This could suggest that riverine ecosystems are primarily better at delivering 'supporting', 'regulating' and 'cultural' services than ‘provisioning’ or it could mean that there are problems with quantifying and/or valuing ‘provisioning’ services. Therefore, the annual ‘benefit’ figures do not show a fair representation of the values derived from ‘provisioning’ services. This is one of the major setbacks of ‘valuing nature’ via the concept of ecosystem services which we discuss in greater detail in chapters 4 and 5.

It is clear to see that sustainable development has put a social demand on valuation methods (Stagl, 2007). Previous research has indicated that ecosystem services are multidimensional which require testing using various valuation tools for this context. The techniques described in section 1.7. are not new in themselves; it is the appropriate application of valuation techniques to ecosystem services what remain challenging (Defra, 2007a). Some valuation methods may be better suited to particular services than others, whilst other services may require more than one valuation technique depending on the context (e.g. direct-use values and travel costs of cultural services). The ecosystem framework emphasises the importance of dealing with an ecosystem as a whole, because changes to one part of an ecosystem will have consequences on the whole system. However, neither the scientific basis, nor the policy and finance mechanisms have been developed for incorporating natural capital into resource and land-use decisions on a large scale (Daily *et al.,* 2011).

2.0. Aims and Objectives of Research

Rivers can provide many services to humans, including water supply for domestic and industrial use, fish habitat and recreation, just to name a few of the ecosystem services delivered by the Tamar catchment (Everard, 2009). Chapter two has set out to explain how geomorphology can help deliver ecosystem services in lowland rivers. The aims and objectives of this research are explained in sections 2.1. and 2.2.

2.1. Aims

- To establish the links between 'geomorphology' and the delivery of multiple riverine 'ecosystem services'.
- To introduce existing approaches to riverine ecosystem management including river restoration.
- To introduce a 'geomorphological framework' for providing ecosystem services for lowland rivers.
- To highlight costs and benefits of geomorphology.
- To explore respondents' 'willingness to accept government funding' for 'geomorphologically diverse' rivers whilst highlighting the potential 'benefits' that can be gained.
- To test the following hypotheses using a 'willingness to accept government funding' method for a lowland river case study:

    1. The general public *do* value 'geomorphological diversity' and that they are willing to accept government/EU funding to enhance and restore 'Geomorphological Functions' (GF) for 'non-use' and 'option value' 'benefits' which derive from 'Final Ecosystem Services' (FES).
    2. The general public *do not* value 'geomorphological diversity' and feel that the current government/EU funding is unjustified in comparison to the 'benefits' derived from 'Final Ecosystem Services' (FES).

2.2. Objectives

- *To provide a summary of existing 'ecosystem service' frameworks and concepts.* The first chapter of this thesis provides a summary of the key concepts and frameworks of environmental management, whilst introducing terminology from existing ecosystem service academia alongside case study material. The aim of this section is to explain how preceding environmental management has led to the development of an ecosystem service approach. This section will introduce the potential problems and limitations of existing ecosystem service frameworks.

- *To highlight the role of 'geomorphology' in riverine environments***.** The second chapter of the thesis will focus on riverine environments and in particular the geomorphology. Many rivers are managed primarily for the generation of a singular or perhaps a small collection of ecosystem services such as clean water or fish habitat as a measure of good ecological status as required by the 'EU Water Framework Directive'. The methods implied verge away from a restricted conceptual model by identifying the contribution of 'geomorphology'. The relationship between 'geomorphological processes' and 'morphological form' and the delivery of multiple 'ecosystem services' will be explored.

- *To introduce a method that values 'geomorphology' as a means to delivering 'ecosystem services'.* The third and fourth chapters of the thesis attempt to value riverine geomorphology as a method of illustrating its importance to delivering a range of ecosystem services. This can be helpful for highlighting the importance of geomorphology to other disciplines. The aim is to try and attempt to quantify and if possible place monetary values to 'Geomorphological Functions' (GF) through river restoration and to try and strengthen the understanding between various disciplines, especially as an Ecosystem Services approach aims at improving decision making.

- *Explore the 'benefits' provided by riverine 'ecosystem services' (case studies)*. The fourth chapter of the thesis concentrates on introducing the role of geomorphology and fluvial geomorphology to ecosystem services research whilst highlighting some of the various ways in which geomorphology contributes to the delivery of ecosystem services and benefits. A hypothetical example combined with restoration case studies will be used to exemplify these relationships.

2.3. The requirement for a 'geomorphological framework' for providing ecosystem services in lowland rivers

The application of geomorphology is explained in this chapter along with its capacity to provide, support and regulate riverine ecosystem services and provide direct and indirect benefits to human well-being. Many restoration projects aim to improve the delivery of a collection of ecosystem services such as habitat restoration or flood control, but many other less familiar ecosystem services are impacted and degraded if not managed carefully. This chapter will help identify the ways geomorphology can influence the delivery of multiple ecosystem services. Multiple FES such as those identified by Fisher *et al*. (2009) (Figure 8.) are largely influenced by geomorphology in riverine ecosystems and through understanding the application of river restoration, we can begin to place values on natural processes and functions.

The value of 'geomorphologically diverse' rivers will be calculated by comparing the existing hydromorphological condition of a reach with the cost of re-introducing more natural 'geomorphological functions' via restoration. A cost-benefit analysis can help weigh the monetary 'value' of geomorphology against the 'benefits' derived from FES.

Montgomery (1999) signifies the relationship between 'geomorphological processes' and 'riverine ecosystems'. Riverine ecosystems are largely influenced by geomorphological processes which shape and sculpt physical habitats (Figure 9.). Disturbance to geomorphological processes (e.g. increased sediment load as a result of bank instability) can have a direct impact on the riverine ecosystem, largely influencing the ecosystem structure and the delivery of ecosystem services.

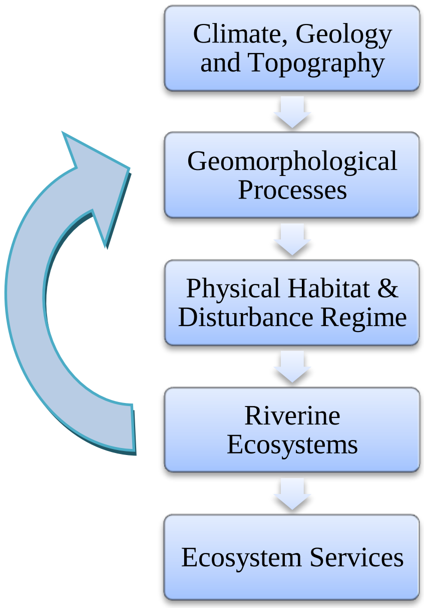


Figure 9. Schematic representation of the relationships between 'geomorphological processes', 'habitat structure', 'riverine ecosystems' and 'ecosystem services' (adapted from Montgomery, 1999).

The application of 'geomorphology' for delivering riverine ecosystem services differs from previous concepts stating that ecosystem services are only the direct end points (Wallace, 2007; Boyd and Banzhaf, 2007). The application of geomorphology to riverine ecosystem services takes a similar approach to Fisher *et al*. (2009) who believe ecosystem services do not have to be utilised directly, so long as human welfare is affected by ecological processes or functions then they can be classed as services.

Figure 10. demonstrates the relationship between 'ecosystem services' and 'benefits'. 'Benefits' are not the equivalent to 'ecosystem services'; 'benefits' require other multiple forms of human, social or built capital (Fisher *et al*., 2009). Fisher *et al*. (2009) approach is necessary because it enables ecosystem organisms or structures as well as geomorphological processes and form to be classed as ecosystem services as long as they are consumed or utilised either 'directly' or 'indirectly' by humanity (Fisher & Turner, 2008; Fisher *et al*., 2009). Section 2.3.1. has used a case study of the Platte River to help identify the types of ecosystem services a 'geomorphologically diverse' river ecosystem can deliver.

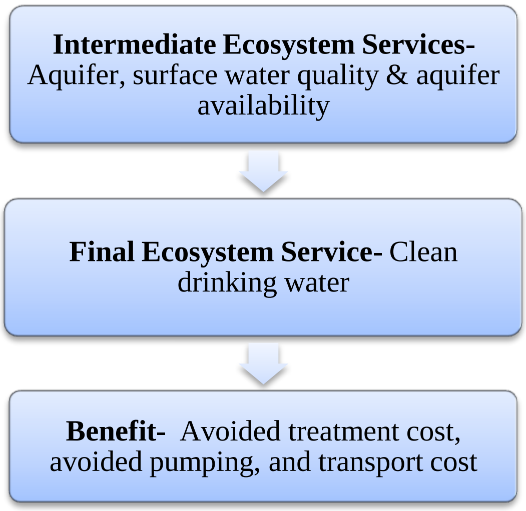


Figure 10. Relationship between ‘ecosystem service’ and ‘benefits’ (adapted from Boyd and Banzhaf, 2007 and Fisher *et al*., 2009).

2.3.1. Multiple ecosystem services: Platte River restoration case study

Loomis *et al.* (2000) used a ‘Contingent Valuation Method’ (CVM) which consisted of a questionnaire or interview to generate a realistic but hypothetical market or referendum, allowing respondents to indicate their ‘Willingness to Pay’ (WTP) (Mitchell & Carson, 1989) for the ecosystem services of the South Platte River in the United States. Three ecologists worked with two economists to define what ecosystem services were being provided by the South Platte River. The ‘US Geological Survey’ and ‘US Fish and Wildlife Service’ were used to obtain background data on water quality and fish/wildlife concerns. ‘Edge to edge’ agriculture and irrigation has degraded the rivers ability to deliver multiple ecosystem services. Once restored, Loomis *et al,* (2000) suggest that other key ecosystem services can be delivered including:

1. Dilution of Wastewater
2. Natural Purification of Water (Figure 11.)
3. Erosion Control
4. Habitat for Fish and Wildlife

However, current management of the Platte River is not sustainable and land management has polluted the river course (Figure 11.) Current management suggests that only a select few of the multiple ecosystem services are being managed whilst others are ignored and are depleted as a consequence.

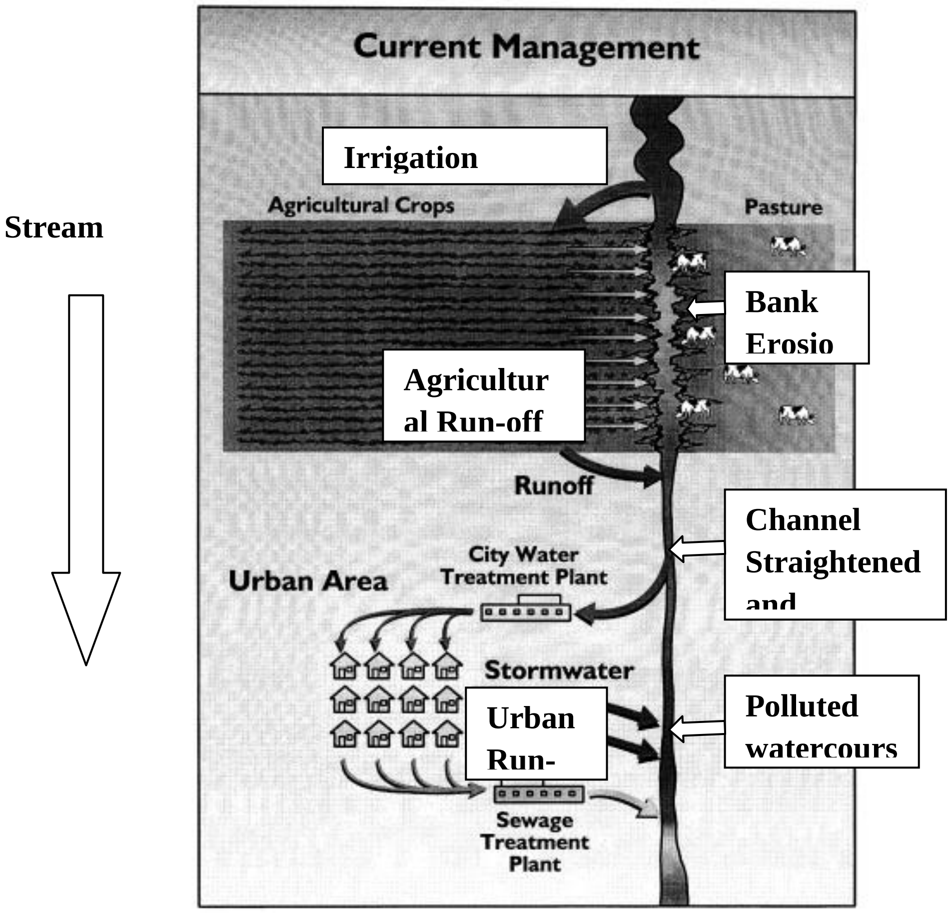


Figure 11. Diagram of current management of the Platte River (adapted from Loomis *et al.*, 2000)

If carefully managed, a restored Platte River has the potential to provide a host of ecosystem services. For example, Figure 12. illustrates the influence of riparian vegetation towards the natural purification of water. Run-off from urbanised streets and arable fields can cause various pollutants to enter the water course. However, riparian vegetation can help prevent such problems as pollutants are absorbed and broken down by plants and bacteria to less harmful substances (Lowrance *et al.,* 1985; Osborne & Kovacic, 1993; Loomis *et al*., 2000; Everard, 2010). Grasses and other smaller riparian plants filter pollutants that are attached to suspended soil particles and then deposit them in the floodplain (Lowrance *et al.,* 1984; Tabacchi *et al.,* 1998 Loomis *et al*., 2000). Riparian vegetation can also help prevent soil erosion as roots help stabilise river banks preventing them from slumping (Osborne & Kovacic, 1993; Barling & Moore, 1994). Therefore, riparian vegetation influences stream water chemistry through a range of diverse processes including direct chemical uptake and indirect influences such as by supply of organic matter to soils and channels, modification of water movement and stabilisation of soil (Dosskey et *al.*, 2010).

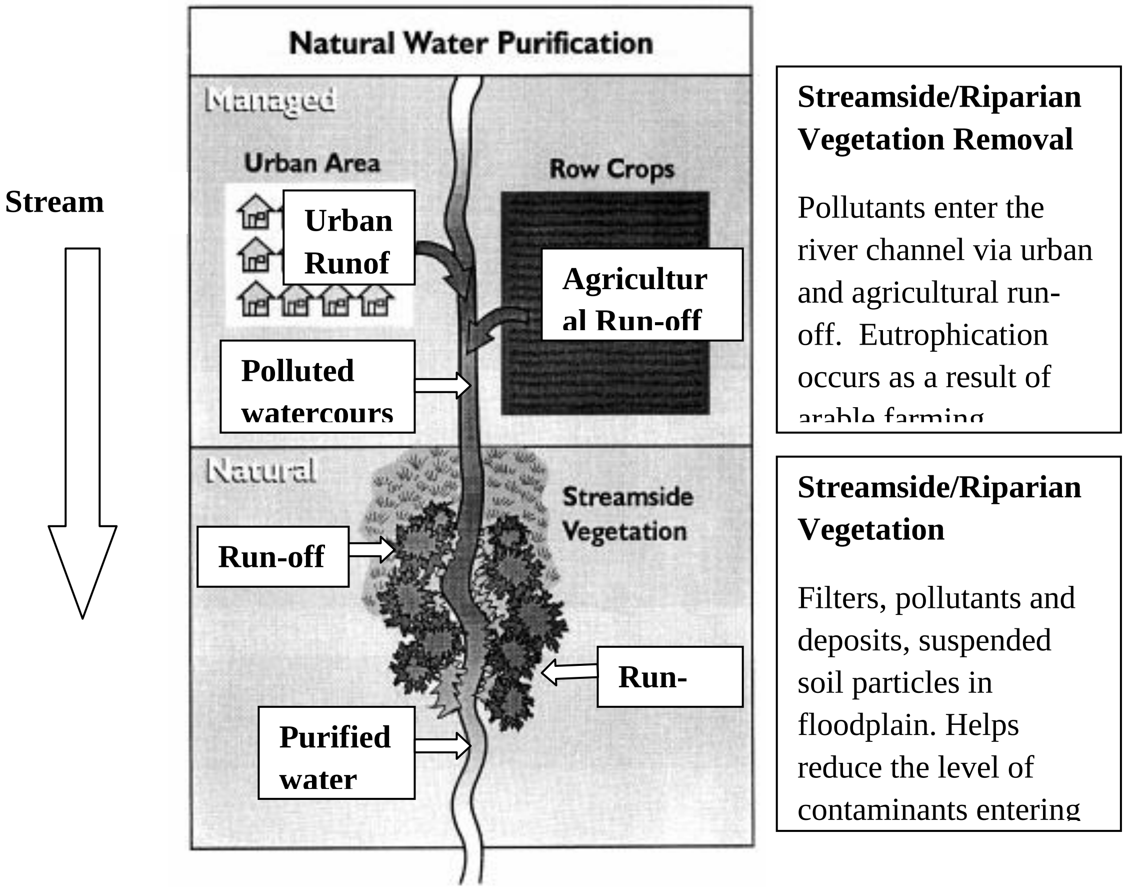


Figure 12. Hypothetical example of natural 'water purification' as an individual Ecosystem Service (adapted from Loomis *et al.*, 2000)

Riparian vegetation can also intercept precipitation and store water, slowing down the process soil saturation and overland flow which can significantly lower the flood peak discharge at a given reach. For example, Arizona residents value riparian corridors and will pay more to live near a densely vegetated river partly due to the attraction of the evapotranspiration rates as well as shady conditions (Bark-Hodgins *et al.*, 2006). However, vegetation in a channel is often considered undesirable as it may reduce the discharge capacity of a floodplain and markedly increase the flood stage of a river. Removing all vegetation is the most direct way to minimize flood risk; however, it significantly impacts the ecology of riparian areas (Leu *et al.*, 2008).

Tree trunks and branches which fall into the stream create habitat diversity for fish and macroinvertebrates and shade created by the vegetation canopy can prevent excessive warming of the water which is vital for species survival (Allan & Castillo, 2007). Riparian vegetation can also provide valuable habitat for avian species in homogeneous agricultural landscapes (Smith *et al.,* 2008). The infall of branches, leaves and invertebrates provides a major source to stream-food web (Allan & Castillo, 2007). Therefore, riparian vegetation alone can significantly impact the delivery of 'erosion control', 'water purification', 'habitat provision', 'flood control' and 'sediment dynamics'.

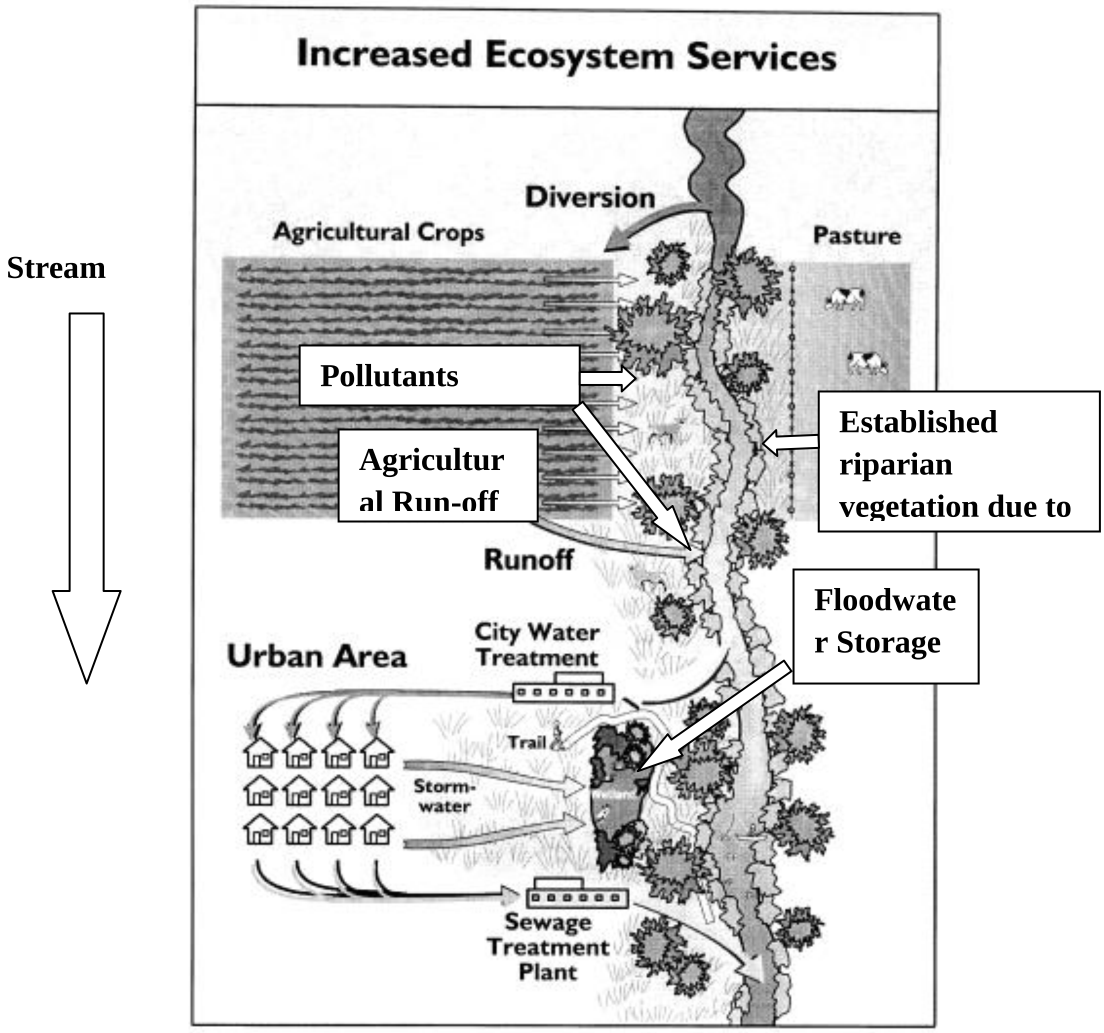


Figure 13. Increased ecosystem services generated by land management and river restoration (adapted from Loomis *et al*., 2000).

The delivery of multiple ecosystem services generated by river restoration diagram (Figure 13.) also includes the creation of a wetland environment via restoration. Lateral connectivity generates and maintains the wetland environment. Wetland environments act as a store for storm water and can reduce the peak discharge of the stream whilst also reducing the need for reservoirs upstream to remain partially empty and thus increasing the benefits they could provide when full (Opperman *et al.,* 2009). Wetlands are also a natural water purifier as they help reduce the levels of nutrients (nitrogen and phosphorus) caused by agriculture entering the stream by storing additional nutrients, reducing the impact on water quality. Peat acts as a store for carbon content leading to lower greenhouse gas emissions which contributes to long term climate regulation (IPCC, 1996; Sahagian & Melack, 1998; Ferrati *et al.*, 2005).

Terrestrial wetland ecosystems are important habitats for flora and fauna habitats such as marshes, fens, bogs, wet grasslands, floodplains and mudflats which provide breeding grounds for migratory fish, birds and other terrestrial wildlife (Dawson *et al.,* 2003). Therefore, floodplain wetland environments have the potential to significantly impact the delivery of 'nutrient control', 'water purification', 'flood control', 'habitat provision' and 'carbon sequestration'.

What is evident from Loomis *et al.* (2000) is land management and river restoration can have a large impact on the regulation, provision and support of multiple ecosystem services. Riparian vegetation has impacts on more than just one ecosystem service, such as 'water purification' and 'flood control' as explained previously. Figure 14. displays the conceptual linkages between riparian vegetation and ecosystem services.

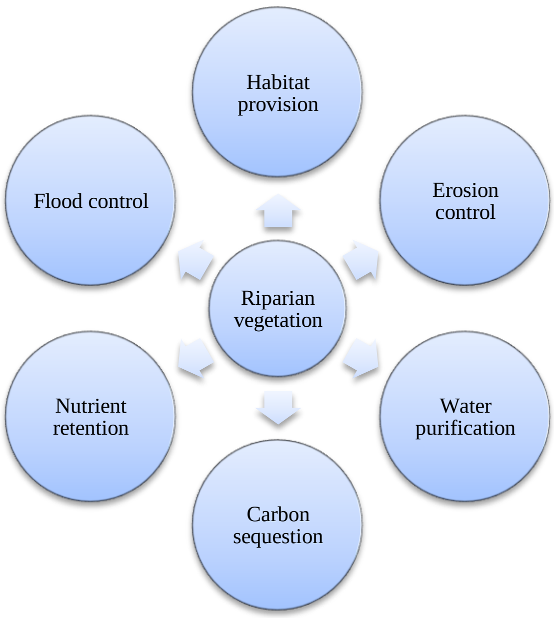


Figure 14. Highlighting the links between 'riparian vegetation' and 'ecosystem services'

The link between 'geomorphology' and the delivery of 'FES' will be explored in greater detail in section 2.4. Figure 14. displays the basic relationship between potential characteristics derived from geomorphology and FES from Platte River.

Desirable geomorphological characteristics		**Final Ecosystem Services (FES)** (as defined by Fisher *et al*., 2009)
Riparian vegetation Wetlands	→	Dilution of wastewater
Riparian vegetation Wetlands	→	Natural purification of water
Riparian vegetation	→	Erosion control
Exposed Riverine Sediment (ERS) Floodplain connectivity Longitudinal connectivity Large Woody Debris (LWD) Natural bed substrate Meandering planform Pool-riffle sequences Riparian vegetation	→	Habitat provision (fish and wildlife)

Figure 15. The relationship between 'geomorphology' and 'Final Ecosystem Services (FES)' for a restored Platte River.

By applying a similar ecosystem service 'classification' approach to Fisher *et al.* (2009) the four key ecosystem services delivered by a restored Platte River (Loomis *et al.* 2000) are categorised as FES. Over time, processes and functions of the FES can form a variety of benefits as displayed in Figure 16.

Final Ecosystem Service (FES)	**Benefit**
Dilution of wastewater →	Lower sewage treatment costs
Natural purification of water →	Drinking water Domestic use water Irrigation
Erosion control →	Property protection Decreased livelihood vulnerability
Habitat provision (fish and wildlife) →	Recreation More productive fisheries

Figure 16. 'FES' and the potential 'benefits' that they could provide to human well-being for the Platte River (FES extracted from Loomis *et al*., 2000)

By studying the linkages between 'geomorphology', 'ecosystem services' and 'human benefits' a better understanding of how the functions operate to help deliver FES. Figure 17a. conceptually illustrates the relationship between 'geomorphological functions' and 'FES' for the Platte River, also showing how joint products ('benefits') can stem from individual ecosystem services. 'Geomorphological functions' (GF) explain the capacity of geomorphological processes and functions in providing goods and services that contribute towards human well-being. The term GF has been adapted from De Groot's (2006) term 'ecological functions' described in chapter one. River restoration can be used as an important tool to add monetary values to GF. The process of applying river restoration to the ecosystem service framework for riverine environments will be explained in more detail in section 2.4.

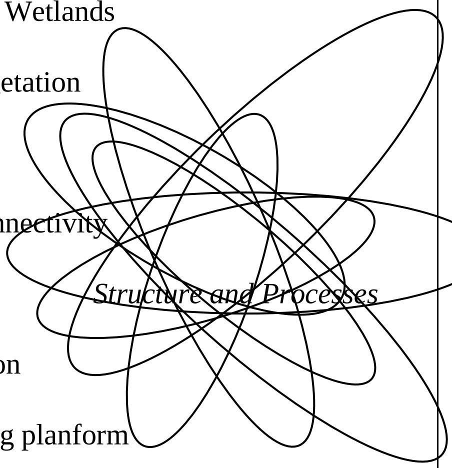
Geomorphological Function (GF)	Final Ecosystem Services (FES)	Benefit
Wetlands Riparian vegetation ERS Floodplain connectivity LWD Bank erosion Meandering planform Multi-channel form Longitudinal connectivity Bed Material  	Dilution of wastewater Purification of water	• Domestic drinking water • Reduced pumping costs • Reduced sewage treatment costs • Outdoor recreation
	Erosion control	• Property protection • Decreased livelihood vulnerability
	Habitat provision	• Non-use value of biodiversity (existence value) • Outdoor recreation • Education

Figure 17a. Conceptual relationship between 'geomorphological functions' and 'final ecosystem services' for the Platte River, also showing how joint product 'benefits' can stem from individual ecosystem services (adopted from Turner *et al*., 2009).

Figure 17a. identifies potential interactions between GF that can influence the delivery of FES. The conceptual model aims to highlight that through a combination of GF interactions, FES are delivered. The model shows that some, but not all GF are required to contribute to the delivery of FES. The combinations of GF and their influences on FES will be explored in more detail during chapter 4. This is also dependant on catchment properties and local reach scale conditions. For example, LWD would be a highly significant influencing factor in wet woodland streams compared to streams which stretch across open plains. Therefore, the GF listed are not associated with every natural lowland river type.

2.4. A 'geomorphological framework' for providing ecosystem services in lowland rivers

Numerous research studies have incorporated an 'ecosystems services' approach to floodplains, wetlands and drainage basins (e.g. Postel & Carpenter, 1997; Zedler & Leach, 1998; Hansson *et al.*, 2005; Zedler & Kercher, 2005). Many of these studies have examined the role of economics, hydrology, ecology and sociology (e.g. Daily, 1997; Loomis *et al.*, 2000; Nelson *et al.*, 2009; Opperman *et al.*, 2009; Pert *et al.*, 2010) but this study is primarily focussed on examining the significance of geomorphological processes and form in 'provisioning', 'regulating' and 'supporting' ecosystem services. It is important to note that this thesis does not largely focus on new techniques to calculate benefits or tackle issues relating to double counting.

This chapter aims to provide a framework that highlights the importance of 'geomorphology' in delivering ecosystem services whilst introducing a method in which geomorphological processes and form can be given a cost.

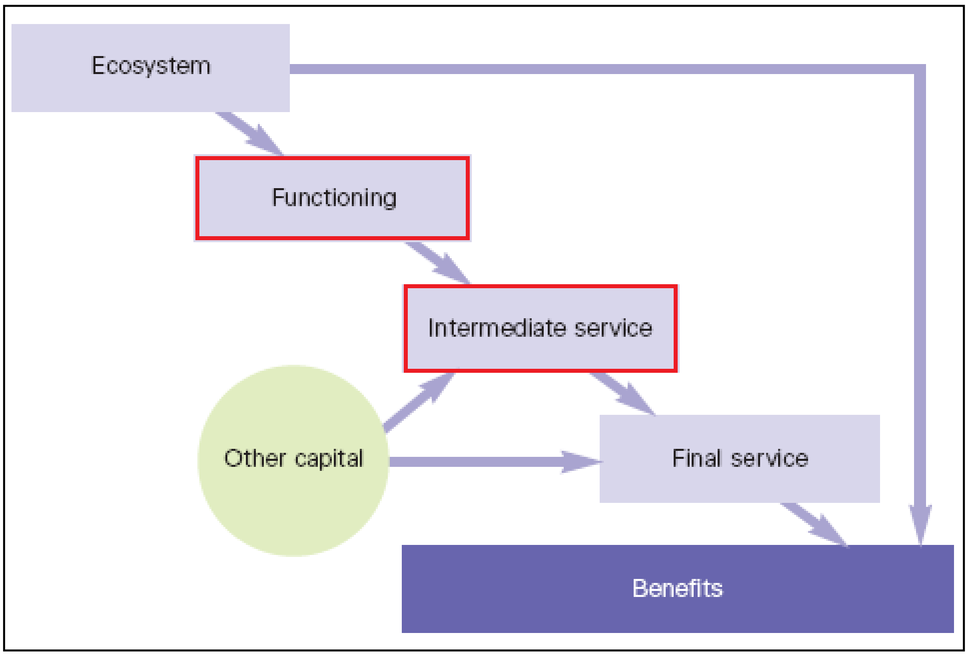


Figure 17b. Conceptual framework for decision-making (adapted from RSPB, 2010)

Figure 17b. demonstrates the pathway from which an ecosystem provides human 'benefits'. The functioning category is highlighted in Figure 17b. as this is the section where the application of geomorphology will be of importance. However, as defined by Turner *et al.*

(2009), when processes have beneficial outcomes for people, they become services. It is the interaction between numerous 'geomorphological functions' that helps provide 'intermediate services'. As explained in the previous chapter, 'benefits' are commonly generated in combination of other inputs and capital such as human knowledge or equipment (Fisher *et al.*, 2009; RSPB, 2010). We must also turn our focus towards 'function' (Figure 17b.) to help develop and further our scientific knowledge on how ecosystems interact to provide 'benefits' to human well-being.

The details of a devised framework for the application of 'geomorphology' in the delivery of multiple riverine ecosystem services will be explored. As explained in chapter 1, reach scale geomorphological forms are associated by the term 'geomorphological functions' (GF). It is the interactions between GF that are imperative to the delivery of many riverine 'final ecosystem services' (FES). The GF listed in 2.4.1. significantly influence geomorphological processes at a reach scale and may result in catchment scale degradation if removed or adjusted via anthropogenic change. Section 2.4.1. contains information regarding the characteristics of reach scale riverine GF.

The need for taking an 'ecosystem services' approach to 'geomorphology' is crucial in maximising rivers' potential to deliver multiple ecosystem services. In this research the GF of lowland rivers have been studied to help identify their contributions towards delivering multiple ecosystem services. An ecosystem services approach to geomorphology will:

- Explore ecosystem services on a reach scale for lowland rivers whilst contributing to our understanding of ecosystem services and their spatial distribution.
- Identify reach scale processes which contribute towards the delivery of an array of services, not just those with ecological benefits in lowland rivers.
- Help enhance our understanding of the links between land and water management and ecosystem service provision.
- Help highlight the 'cost' of GF.
- Help identify benefits gained from restoration across multiple ecosystem services.

This type of approach will allow us to develop our understanding of the functions and processes that create the fundamental backbone for many ecosystem services.

2.4.1. 'Geomorphological functions' (GF) and their characteristics

This section identifies reach scale GF and describes their characteristics in terms of sediment dynamics and geomorphological processes. The GF have been identified and described with the use of existing literature. The GF are divided into three sections:

1. The first GF described are 'geomorphological form', which portray the features and forms of lowland river channels and floodplains.

2. The second group of 'GF' contains reach scale 'influencing characteristics' which have the potential to significantly adjust the morphology at a reach. The influencing characteristics have the ability to adjust local reach scale geomorphological processes which can result in morphological changes to lowland rivers.

3. The third group of 'GF' is 'connectivity'. 'Connectivity' occurs as a result of 'geomorphological form' and 'influencing characteristics' that also are dependent on the existing hydromorphology at the lowland study reach.

2.4.1a. Geomorphological Form

Meandering planform:

The evolution of meandering channels involves the complex interaction of fluid dynamics, sediment transport, and bank erosion (Duan & Julien, 2010). Meandering channels consist of one single channel which are complex systems and are characterised by a sequence of bends which have a sinuosity greater than 1.2 (Sear *et al.*, 2010). The dynamic evolution of a meandering planform can lead to the formation of oxbow lakes during flooding as well as short circuiting chute cutoffs (Gargliano & Howard, 1984; Lewis & Lewin, 1983). In the UK channel planform is relatively stable with little movement across the floodplain (Sear *et al.*, 2010).

Erosive behaviour of meandering channels (Miall, 1977):

- Channel incision
- Meander widening

Depositional behaviour of meandering channels (Miall, 1977):

- Point-bar formation

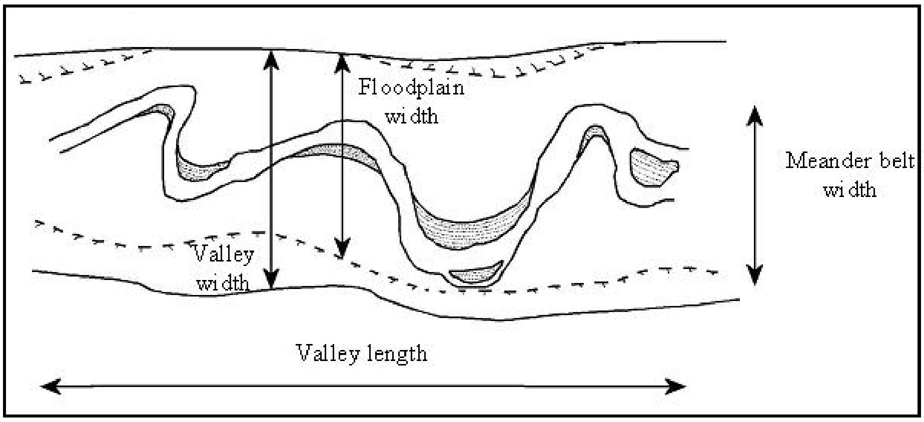


Figure 18. A meandering planform within its valley (Sear *et al.*, 2010)

'Active meandering' rivers are some of the most dynamic and sensitive parts of the landscape (Hooke, 2007). These channels are bordered by floodplains and characterised by pool-riffle sequences and point bars (Sear *et al.*, 2010). Riparian vegetation often colonises bars and riparian corridors. Bed material is predominantly gravel (Sear *et al.*, 2010).

'Passive meandering' are low slope channels which flow through more resistant materials such as clay. Channels are typically incised and have low high/width ratios. Pool-riffle sequences are often present but in association with other bed forms such as glides and runs (Sear *et al*., 2010). Stable beds are also a characteristic of passive meanders with fine sediment.

Multi-channel form:

Multi-channel form is characterised by large scale zones of sediment accumulation. Areas susceptible to sediment accumulation often include geological controls such as a rock step, glacial moraine or alluvial fan which reduce the gradient of the valley gradient (Sear *et al*., 2010).

'Braided channels' consist of two or more channels with bars and small islands (Miall, 1977). In most examples "a single dominant channel can generally be distinguished within the overall braided pattern, although in some sections there are several principal channels" (Rust, 1972, p. 223). ‘Braided channels’ are typically characterised by channel division and alluvial islands and the channel cross section is typically controlled by the discharge and sediment load provided by the drainage basin (Leopold and Wolman, 1957). Woody debris is an important influencing characteristic in island formation, but high width/depth ratios due to an abundant bedload generally influence the channel threads by the formation of bars.

Erosive behaviour of braided channels (Miall, 1977):

- Channel widening

Depositional behaviour of braided channels (Miall, 1977):

- Channel incision
- Meander widening

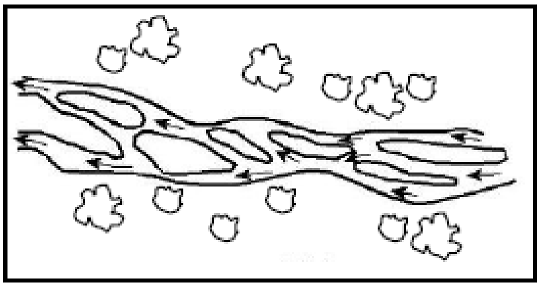


Figure 19. Conceptual braided channel diagram. (Sear *et al*., 2010)

‘Anastomosed channels’ are two or more channels with large stable islands (Miall, 1977). They have a sinuous and divided planform. Makaske (2001) defines anastomosed channels as “an anastomosing river is composed of two or more interconnected channels that enclose floodbasins” which excludes the phenomenon of channel splitting by convex-up bar-like forms that characterise braided channels. Makaske (2001) also suggests that this type of channel seems to form under relatively low-energetic conditions.

Anastomosed channels are often separated by vegetated surfaces which are a similar elevation to the floodplain surface (Sear *et al*., 2010). They differ from braided channels as the channel functions appear like separate reaches. Deposition and accretion of fine sediment occurs in the floodplain of these channels which causes a deep accumulation of cohesive sediments in the floodplain (Sear *et al.,* 2010).

Erosive behaviour of anastomosed channels (Miall, 1977):

- Slow meander widening

Depositional behaviour of anastomosed channels (Miall, 1977):

- Slow bank accretion

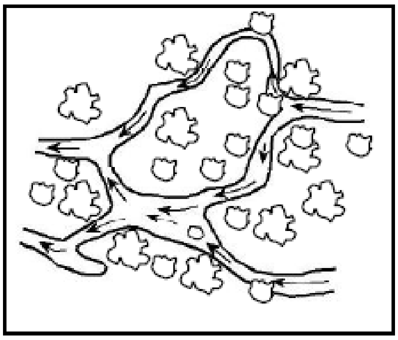


Figure 20. Conceptual anastomosed channel diagram. (Sear *et al*., 2010)

However, this type of river is difficult to identify in current lowland UK river channels due to the long history of channel management.

Riffle-pool sequences:

Riffle-pool sequences are the characteristic reach-scale bedforms of mixed and gravel-bedded rivers (Clifford, 1992) which exist in meandering partially confined and unconfined states. Riffles and pools are characteristic of low to moderate gradient streams and are a well-researched topic in fluvial geomorphology (Richards, 1976; Clifford & Richards, 1992; Sear, 1996; Thompson *et al.*, 1999) and aquatic ecology (Gorman & Karr, 1978; Brown & Brown, 1984; Giller & Malmqvist, 1998). Clifford (1992) identified three distinct stages in the process of riffle-pool sequence:

1. Local scour of a single pool creates
2. Deposition downstream, which then
3. Generates the next-downstream flow irregularity

Riffle-pool sequences are morphological forms that result from scour and deposition. Pools are topographic depressions covered with finer sediment, while riffles are topographic highs covered with coarser bed material; these two features are defined relative to each other (O'Neill & Abrahams, 1984; Montgomery & Buffington, 1997). They are located in uniform patterns on a reach scale as illustrated by Figure 21. In general, finer material that is characteristic of the bulk of the normal bed load resides in the deep sections, or pools, below flood stages whilst coarser material is transported at more in-frequent flows forming the shallow riffle sections (Lisle, 1979).

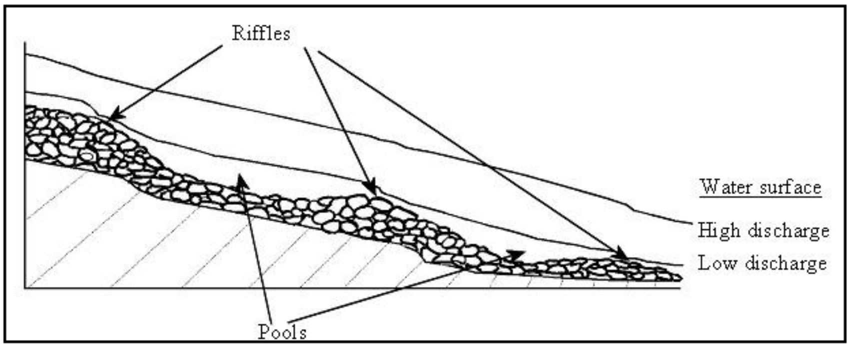


Figure 21. Long profile of a riffle-pool sequence (Sear *et al*., 2010)

Pools are features of scour which occur commonly at the outside of meander bends where velocity is highest. Riffles are shallower, faster zones, of steeper water surface slopes, with coarser, better-sorted or more interlocking bed material than intervening pools (Clifford, 1992).

Natural bed substrate:

Bed substrate is dependent on the local geological context of river catchment. Natural bed substrate includes sand, gravel, alluvium and chalk. Sediment sinks and stores are typically resting points for bed substrate. Fluvial processes sort through bed substrate creating various types of morphological forms (e.g. pool-riffle, point bars, cascades). Bed substrate is highly susceptible to changes throughout its existence. For example, in gravel bed rivers large floods can cause full gravel transport on high bars and significant morphological changes of islands (Surian *et al.*, 2009). The morphology which characterises an alluvial river channel is the consequence of sediment transport and sedimentation. However, the morphological style is determined by the quality and quantity of sediment delivered to the channel, although modulated by channel scale (Church, 2006).

However, channelisation and in particular, straightening the river planform has effected sediment transfer processes and in some cases has 'locked up' natural bed substrate or removed it from the system through dredging.

Natural bank material:

Bank material is dependent on the geological context of the river. However, naturally functioning streams are dynamic systems whereby multiple processes work in concert to cause what is referred to as "bank erosion" (Lawler *et al.,* 1997). Erosion is defined as the detachment and removal of particles or aggregates from the streambank surface (Lawler *et al.,* 1997) which in turn delivers soil directly to the stream channel. Substantial morphological changes (e.g. bank erosion of several tens of metres up to more than 100 m) are mainly associated with flood events (Surian *et al.,* 2009). The bed and bank material of the river are not only critical for sediment transport and hydraulic influences but also modifies the form, plan and profile of the river (Rosgen, 1994).

Exposed riverine sediment (ERS) – bars/deposits:

The floodplain is in a state of constant flux with repeated erosional and depositional processes resulting from inundation events (Junk *et al.,* 1989). ERS are highly dynamic depositional features that are formed from eroded material upstream and deposited in sheltered areas downstream. ERS are frequently inundated and remain relatively un-vegetated (Henshall *et al.,* 2009) such as bars. Along natural rivers, ERS have a patchy but regular distribution and spacing that relates to geomorphological setting (Petts *et al.,* 2000). ERS can help sustain connectivity by creating stepping stones of similar habitat which facilitates the dispersal of organisms (Ward, 1998).

However, sediment yields are highly variable and significant modification to the river network via land drainage or a change to the supply of sediment through changes in land management will alter the sediment yield of the catchment and correspondingly the river and floodplain environment (Sear *et al*., 2010). Thus the actions that threaten ERS operate on a variety of scales and include river engineering, flow regulation and livestock damage (Bates *et al.,* 2005).

Wetlands:

Wetlands form at the interface of aquatic and terrestrial ecosystems and have features of both (Keddy, 2010). Water is the dominant factor determining soil development and the types of plants and animal communities occupying it (Cowardin *et al.,* 1985). The "wetness" is the fundamental characteristics of a wetland. Yearly or seasonally abundant water is an essential element which controls the ecological characteristics of the wetland and its process of succession (Zhou *et al.*, 2008). This thesis concentrates on terrestrial wetlands such as mires, bogs and floodplains because the focus is on riverine environments. A wetland is dependent on precipitation, ground water, and water moving across the surface (Keddy, 2010). Floodplains are reliant on water moving across the surface whereas raised bogs are dependent upon precipitation (Keddy, 2010).

2.4.1b. Influencing Characteristics

Large Woody Debris (LWD):

Floodplain forests can contribute large quantities of woody debris to the river system (Abbe & Montgomery, 1996) creating debris dams. LWD is wood that is over 1 metre in length and larger than 0.1 metre in diameter (Platts *et al.*, 1987). Woody debris largely influences adjustment processes which can cause morphological change (Sear *et al.*, 2010) which in turn generate higher channel geomorphic diversity.

Geomorphologically, LWD influences pool formation, frequency, and type (Keller & Swanson, 1979; Andrus *et al.*, 1988; Bilby & Ward, 1991; Montgomery *et al.*, 1995; Abbe & Montgomery, 1996; Gurnell & Sweet, 1998; Kreutzweiser *et al.,* 2005) and is commonly associated with increased sediment storage (Thompson, 1995; May & Gresswell, 2003; Daniels, 2006). LWD can increase flow resistance (Shields & Gippel, 1995; Gippel *et al.,* 1996; Curran & Wohl, 2003; Bocchiola *et al.,* 2006; Manners *et al.,* 2007) and reduce sediment transport (Bilby & Ward, 1989; Nakamura & Swanson, 1993), whilst increasing longitudinal variation of both channel depth and width (Montgomery *et al.*, 2003).

Riparian and floodplain vegetation:

Riparian vegetation is the vegetation that is located within the riparian zone occupying the top and sometimes the face of a river bank within the active floodplain. "Floodplain forests develop through interactions between the vegetation and the physical processes that are active." (Gurnell, 1997 p.222). Riparian vegetation and fluvial-geomorphic processes and landforms are intimately connected (Hupp and Osterkamp, 1996) and vegetation dynamics within the riparian corridor are clearly influenced substantially by hydrological disturbance regimes (Tabacchi *et al*., 1998).

Some geomorphic processes may be only mildly affected by vegetation (e.g. mass wasting, extreme floods). In most situations, riparian-vegetation patterns are indicative of specific landforms and, thus, of ambient hydrogeomorphic conditions (Hupp and Osterkamp, 1996).

2.4.1c. Connectivity

Lateral connectivity:

Connectivity can be defined as "the ease with which organisms, matter or energy transverse ecotones between adjacent ecological units" (Ward *et al.,* 1999. p.129). Connectivity in rivers occurs when particles physically pass through the river channel system (Hooke, 2003). Lateral connectivity includes slope–channel and channel–floodplain relationships that drive the supply of materials to a channel network (Brierley *et al.,* 2006). The connectivity between the catchment land surface and the river network is moderated by the form of the valley in which the channel flows.

Floodplains are formed by processes of lateral and vertical accretion which deposit sediment in the valley floor whilst providing a supply of in-channel fine sediment (Sear *et al*., 2010). In unconfined channel/floodplains, interactions between the stream and the riparian zone result in overbank flows and wetlands (Sear *et al*., 2010). These interactions provide functions for a sediment store and create a diverse ecology and habitat between aquatic and terrestrial environments. They are characteristic of a natural/semi-natural reach. Semi-natural reaches contain dynamic floodplain geomorphology caused by erosion and deposition on the floodplain surface (Smith, 2006).

A channelised reach is disconnected from the floodplain, causing the dynamic nature of the floodplain geomorphology to change. Frequently flooded zones tend to be colonised by pioneer aquatic species but as connectivity decreases, terrestialisation of the vegetation occurs (Peacock, 2003). Agriculture/cultivation can also change the functions of a floodplain. A sediment store can become a sediment source by land use change which can cause a supply of sediment to the river network.

Longitudinal connectivity:

Longitudinal connectivity relates to the transfer of sediment from one zone to another as it moves through the system (Hooke, 2003). Longitudinal connectivity, such as upstream-downstream and tributary-trunk stream relationships drive the transfer of flow through a system and the ability of channels to transfer or accumulate sediments of variable quality on the valley floor (Brierley *et al*., 2006).

It is fundamental for the development of channel morphology that the transfer of sediment as well as water is allowed downstream from upstream reaches (Kondolf, 1997; World Commission on Dams, 2000). Rivers are dynamic systems so their form and characteristics naturally adjust over time. Sediment is eroded from scour pools and then transferred downstream and stored in sheltered channel sections which accumulate and form ERS.

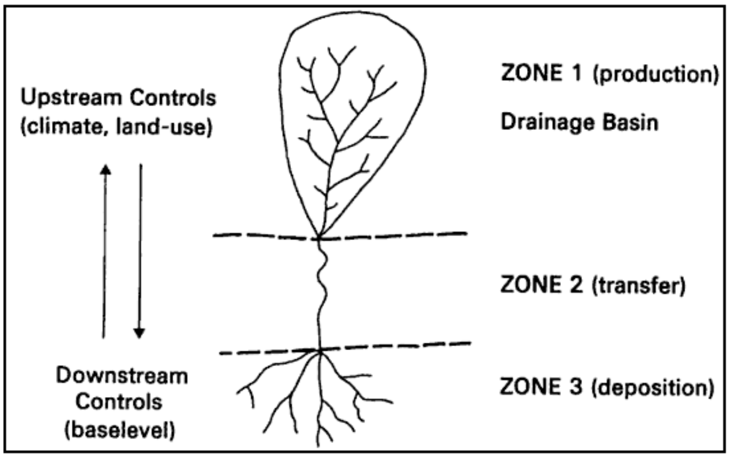


Figure 22. River Basin as a sediment transfer system (Schumm, 1977)

Channel morphology and stability reflect the net sediment budget with evidence of net erosion, net aggradation or a balance (Hooke, 2003).

2.4.2. 'Geomorphological functions' (GF) and the delivery of 'final ecosystem services' (FES) in lowland rivers

The relationships between GF and the delivery of FES are listed in Table's 6a., 6b. and 6c. and then elaborated on in Table 7. to illustrate how this relationship works. The list of 'FES' given in Table's 6a., 6b. and 6c. is a hypothetical list for a lowland river. The influence of each 'GF' in delivering 'FES' at a given reach is varied and is dependent on other contributing factors such as geological context and hydromorphology.

Geomorphological Functions (GF)	**Final Ecosystem Service (FES)**
Reach Scale	
Geomorphological Form:	
Meandering planform	Habitat provision / natural biodiversity Sediment dynamics Erosion control
Multi-channel form	Habitat provision / natural biodiveristy Sediment dynamics Erosion control
Riffle-pool sequences	Habitat provision / natural biodiversity
Natural bank material	Habitat provision / natural biodiveristy Erosion control
Natural bed substrate	Habitat provision / natural biodiversity
Wetlands	Habitat provision / natural biodiversity Carbon storage/ sequestration Flood control Water purification Nutrient retention

Table 6a. Hypothetical linkages between 'geomorphological form' and 'FES' for UK lowland rivers

Geomorphological Functions (GF)	***Final Ecosystem Service (FES)***
Reach Scale	
Influencing Characteristics:	
Large Woody Debris (LWD)	Habitat provision / natural biodiversity Sediment dynamics
Riparian vegetation	Habitat provision / natural biodiveristy Erosion control Water purification Nutrient retention Carbon storage/ sequestration Stream temperature regulation

Table 6b. Hypothetical linkages between 'influencing characteristics' and 'FES' for UK lowland rivers

Geomorphological Functions (GF)	***Final Ecosystem Service (FES)***
Reach Scale	
Connectivity:	
Longitudinal connectivity	Habitat provision / natural biodiversity Sediment dynamics Erosion control
Exposed Riverine Sediment (ERS)-bars/deposits	Habitat provision / natural biodiversity Sediment dynamics

Table 6c. Hypothetical linkages between 'connectivity' and 'FES' for UK lowland rivers

Collectively the 'GF' interact to produce river morphology which can help provide, support and regulate many ecosystem services in lowland rivers. It is now widely recognised that river morphology interacts with biological and geochemical systems to produce an array of physical and biological habitats (Sear *et al.*, 2010). River morphology also helps regulate the storage and transfer of sediment through the river network. Altering the processes that regulate the morphology through channelisation can impact the sediment delivery and cause rapid transfer of sediment load downstream (Sear, 1994).

'Geomorphological functions' (GF) operate on small space ($10^{-1} - 10^{1}$ km^2) and time scales ($10^{-1} - 10^{1}$ years) (Beechie *et al*., 2010). It is fundamental to recognise that FES such as water purification are greatly influenced by physical habitat features as well as other inputs such as dissolved nutrients, organic matter and sunlight (Beechie *et al*., 2010). These features can be largely influenced by the interactions of GF and the meso-scale processes (varying across the active channel width and at channel length intervals which are small multiples of channel width) operating within them (Figure 23.) Although GF operate at a reach scale, the FES can provide benefits on a catchment scale due to the dynamic nature of riverine environments.

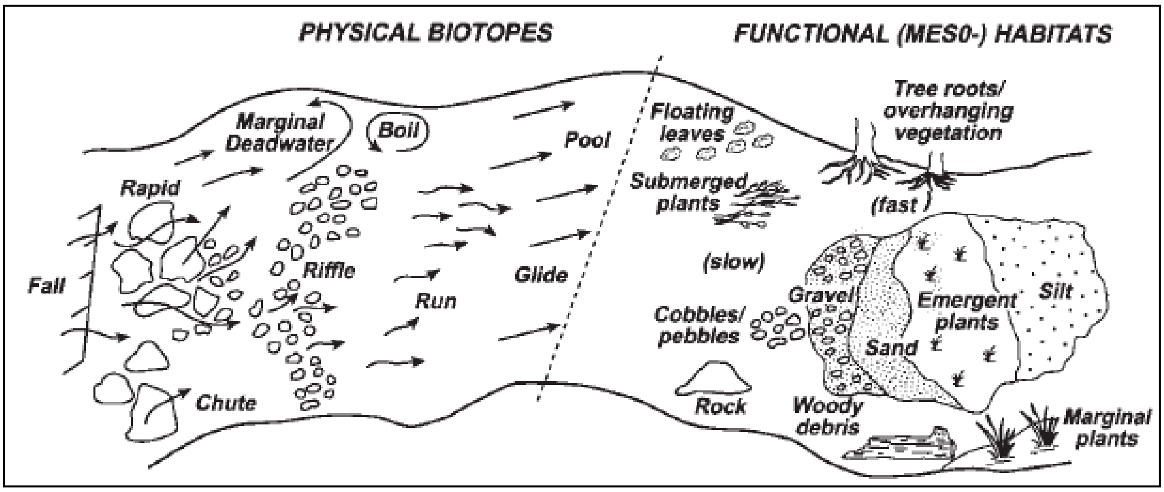


Figure 23. Physical biotopes and functional (meso-) habitats: a comparison for a hypothetical subreach (Newson & Newson, 2000)

FES are largely influenced by interactions between GF and the geomorphological processes which operate to create and sustain them (Table 7.). A single GF may also contribute to the creation of many FES. For example, (Figure 24.) illustrates the many GF which may influence and interact with one another to produce FES such as habitat provision. It is important to recognise that Figure 24. is a generic diagram and many of the GF may not be present in particular types of river. Figure 24. however, aims to demonstrate the possible GF interactions which could contribute to the generation of FES, in this case habitat provision. Their interactions and influences of GF to generating FES will be explored in more detail in later chapters.

This study aims to highlight and identify the importance of GF and how they can influence the generation of FES. This study also aims to provide a possible method of using restoration to help value GF processes and form. Therefore, it is not just the FES which has a monetary value, the interaction between geomorphological processes and forms which are fundamental to the generation of services also have values.

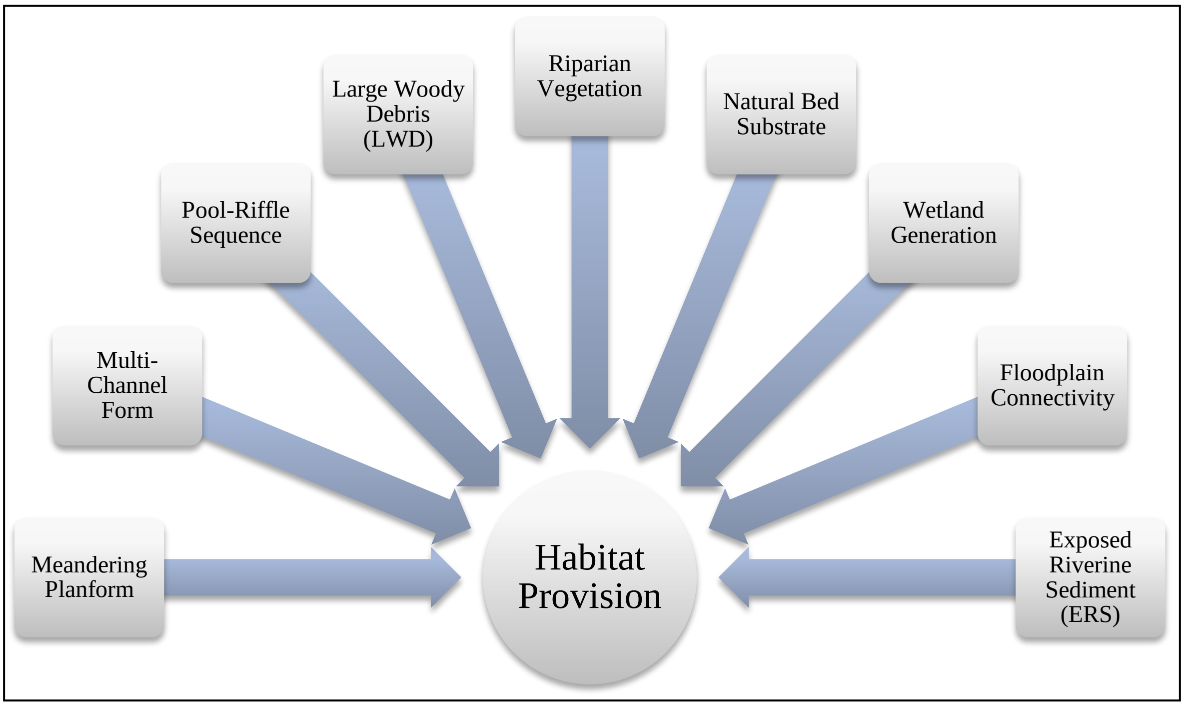


Figure 24. GF relationship diagram for 'habitat provision' for a UK lowland river

It must be stressed that Figure 24. is a generic illustration of potential GF that interact in various ways to generate habitat provision. Figure 24. contains geomorphological form, influencing characteristics, and connectivity. It is through multiple GF interactions that help deliver habitat provision. For example, a lowland river with a meandering planform and natural bed substrate with regularly distributed pool-riffle sequences throughout will create a habitat for fish. The meandering planform will also generate ERS through depositional processes in slower flowing sections of the river channel. Exposed riverine sediment provides primary regeneration sites for riverine pioneer tree species (Braatne *et al.*, 1996). ERS also provide habitat for insects such as beetle (Eyre & Luff, 2002; Eyre *et al.*, 2002). The active zone of flood plains provides a wide diversity of successional habitat conditions which are fashioned by a collection of fluvial and geomorphological processes. This example has been simplified to help illustrate how potentially desirable GF interact and work to generate habitat provision. The presence of riparian vegetation will also influence multiple FES including sediment dynamics, erosion control, flooding control and habitat provision. A more detailed summary of the relationships between GF and FES is provided in Table 7.

GF	FES	Relationship between Geomorphological Functions and Final Ecosystem Services
Meandering planform	Habitat provision / natural biodiversity	Flow regimes largely contribute to the formation of pools and riffles which provide varied environmental conditions essential for both aquatic and riparian communities (Poff *et al.*, 1997). Meandering planforms are characterised by point bars and exposed riverine sediment (ERS) which creates habitat for pioneering vegetation and invertebrates. However, the natural composition of native riverine ecosystems is closely associated with natural hydrologic variability but water agencies have inadvertently damaged riverine ecosystems and associated biodiversity (Richter & Richter, 2000) via channelisation and through straightening of meandering channels.
	Sediment dynamics	Meandering channels are dynamic systems in which geomorphic processes maintain and support native aquatic species. Scour pools and riffles are forms resulting from erosion and deposition and are common features of a naturally meandering planform. Flooding of meandering channels indirectly shapes riparian ecosystems through the influence of sediment erosion and deposition (Richter & Richter, 2000). Resulting floodplain forms such as cut-offs, meander bends, lateral migration and deposition of sediment on the floodplain surface shape successional dynamics which maintain local plant and animal diversity (Sparks, 1995).
Multi-channel form	Habitat provision	Frequent interactions with the floodplain within multi-channel rivers help maintain ERS and resets vegetation succession (Tabacchi *et al*., 1998). Islands and bars create a viable habitat for pioneering vegetation.
Pool-riffle sequences	Habitat provision	Riffle-pool morphology creates physical heterogeneity, creating a diverse macrohabitat for instream species (Gorman & Karr, 1978; Frissell *et al*., 1986; Palmer *et al.*, 1997; Giller & Malmqvist, 1998; Woodsmith & Hassan, 2005; Allan & Castillo, 2007). At the fish community level, riffle-pool sequences may improve biodiversity, allowing species with different habitat requirements

		to live together. At the population level, it authorizes age classes exhibiting different habitat preferences to develop in neighbouring habitat types. Lastly, at the individual level, it allows the expression of daily behaviour with pools providing nocturnal resting areas for trout feeding in riffle (Roussel & Bardonnet, 1997). Deep pools are essential habitat components which help prevent the reduction of fish populations during highflow (Tschaplinski & Hartman, 1983; McMahon & Hartman, 1989; Fausch & Bramblett, 1991). True riffles are major components of an active bed material transport process and their hydraulics reflect this (Newson *et al*., 1999; Sear & Newson, 2004). Using morphology instead of flow-dependent measures does not fully assess the complex physical and ecological relationships that define habitat but does eliminate subjective assessments and provide a strong, repeatable index of the potential for habitat (Keim *et al*., 2002).
Large Woody Debris (LWD)	Habitat provision / natural biodiversity	Wood and wood dynamics are a key control on channel and floodplain habitats influencing flood inundation, frequency, extent and duration (Sear & Millington, 2009). Natural river channels are hydraulically rough and woody debris in the channel is encouraged (Piegay & Gurnell, 1997) to the benefit of biodiversity. LWD contributes to the formation of 'pioneer' islands (Gurnell *et al*., 2000) as flood waters deposit large amounts of woody debris, fine organic material and inorganic sediments around a stranded tree for example. The storage, breakdown and regulated release of organic matter provide temporally and spatially regulated food sources for aquatic biota (Piegay & Gurnell, 1997).

Log jams are also an important habitat component which help prevent the reduction of fish populations during high flow (Tschaplinski & Hartman, 1983; McMahon & Hartman, 1989; Fausch & Bramblett, 1991). Together with long residence times of organic and inorganic material, a mosaic of physical habitats supporting diverse vegetation and ecology is generated (Sear & Millington, 2009).

The natural dynamics of instream LWD have also been recognised to play an important role in hydraulic processes associated with riffle-pool formation and stabilization of the channel indifferent types of streams, including lowland rivers (Gregory& Davis, 1992; Gregory *et al.*,1992; Langford, 1996).

The complex physical structure of woodland river channels provides a variety of habitat patches which can support numerous varieties of organisms such as macroinvertibrates and fish at different stages of their life cycle (Piegay & Gurnell, 1997). The removal of LWD correlates with the loss of diversity in both macroinvertibrates and fish. LWD has a very weak hydraulic influence within braided systems but has considerable significance for both aquatic and terrestrial habitat diversity (Piegay & Gurnell, 1997).

Overbank flow is concentrated by topography and by obstacles created by vegetation and dead wood leading to complex floodplain scour and deposition (Sear & Millington, 2009). Together with long residence times of organic and inorganic material, a mosaic of physical habitats supporting diverse vegetation and ecology is generated (Sear & Millington, 2009). Rare invertebrate and amphibian communities inhabit the temporary pools found in floodplain channels and pools resulting in high biodiversity (Nicolet, 1997; Davis *et al.*, 2007), whilst perennial secondary channels are important nursery habitat for juvenile salmonids (Beechie *et al*., 2005).

	Flood control via sediment dynamics	River channels containing LWD are capable of storing and transmitting sediments and organic matter in a well-regulated manner (Piegay & Gurnell, 1997). LWD influence the in-channel flow hydraulics which control the distribution of sediment and organic material transport and storage across the floodplain (Piegay & Gurnell, 1997). For example, the deepest pools along the Queets River are associated with LWD jams (Abbe & Montgomery, 1996). Hydraulically, LWD act as large roughness elements that provide a varied flow environment, reduce average velocity and locally elevate the water-surface profile. This can considerably increase flood travel time (Gippel, 1995). Sediment storage and transport influences the magnitude and distribution of pools and riffles and the overall increased stability of the river (Piegay & Gurnell, 1997). The removal of LWD causes an increase in sediment yield resulting in the development of bars and beaches which replace LWD as a sediment store (Abbe & Montgomery, 1996). Retaining LWD is not only of direct ecological and economic benefit, but it provides a buffer to slow movement of debris pieces rather than allowing them to move freely downstream to accumulate at more sensitive sites (Piegay & Gurnell, 1997).
Riparian vegetation	Habitat provision/ natural biodiversity	Tree trunks and branches generate habitat diversity when they fall into the stream. Shading caused by vegetation canopies prevents excessive warming which is vital for the survival of fish species and the in-fall of vegetation and invertebrates provides a major source to the stream-food web (Allan & Castillo, 2007). The removal of riparian vegetation and the introduction to human transformations of land cover and land use are key drivers towards the loss of biodiversity and ecosystem services (Haines-Young, 2009).
	Erosion control	The influence of the stream margin and its vegetation cannot be

		overstated (Allan & Castillo, 2007). For example roots stabilise banks which prevent slumping. It has been recognised through channel experimentation that vegetation can slow down the rate of widening and discourage channel cut-offs until a significant super elevation develops in braided channels (Tal & Paola, 2009). The removal of riparian vegetation can have a profound effect on bank erosion rates. For example, a study carried out in British Columbia suggested that major bank erosion was 30 times more prevalent on non-vegetated bends as on vegetated bends (Beeson & Doyle, 1995). Riparian vegetation reduces the impact of subaerial processes on soils and significantly increases a soil's resistance to fluvial scour (Wynn & Mostaghimi, 2006).
	Water purification	Riparian vegetation has a significant role to play in non-point source pollution abatement and water quality protection within watersheds in agricultural areas (Schlosser & Karr, 1981; Lowrance *et al.*, 1984; Lowrance *et al.*, 1997; Gregory *et al.*, 1991, Osborne & Kovacic, 1993). Riparian vegetation can act as a nutrient store preventing large levels of nitrates from entering the river channel (Lowrance *et al*., 1997. Riparian vegetation can buffer pollutant loading to streams from upland sources (Tabacchi *et al*., 1998). Therefore, restoration of riparian vegetation has the potential to improve water quality and provide other ecological functions (Naiman *et al*., 2005).
	Carbon sequestration	Vegetation such as riparian forests reduces CO_2 emissions and acts as so-called drains as they absorb CO_2 as described by the Kyoto protocol (Dubgaard *et al*., 2002). Riparian vegetation also has the potential to sequester large amounts of carbon dioxide when it is managed as an agroforestry system (Montagnini & Nair, 2004). However, little is known about the carbon sequestration potential of different natural herbaceous vegetation or hybrid poplar clones across a range of riparian soil fertility conditions (Tufekcioglu *et al*., 2003).

	Nutrient retention	Riparian vegetation has a significant role to play in non-point source pollution abatement and water quality protection within watersheds in agricultural areas (Lau *et al*., 2006; Fortier, 2010). The presence of riparian vegetated buffers tends to decrease nutrient loads to streams by reducing stream bank and soil erosion by enhancing sediment deposition, water infiltration, bacterial denitrification and nutrient accumulation by plant biomass (Lowrance *et al*., 1997). Riparian vegetation can assist in the removal of nutrients especially nitrogen (Peterjohn & Correll, 1984) from suspended sediment from: • Overland storm water entering laterally (Peterjohn & Cornell, 1984; Chescheir *et al*., 1991; Klarer & Millie, 1989; Lowrance *et al*. 1988; Mitsch *et al*., 1979; Parsons *et al*., 1994). • Flood water entering from the stream channel (Brunet *et al*., 1994; Hart *et al*., 1987; Hupp & Morris, 1990; Hupp *et al*., 1993; Johnston, 1993; Kleiss *et al*., 1989). A greater diversity of vegetation enhances productivity in plant communities which leads to greater nutrient retention (Tilman, 2000).
	Stream temperature regulation	Reduced soar radiation through riparian forests lowers stream water temperatures especially in low order streams (Brown & Krygier, 1970). Riparian vegetation also lowers soil water temperature and shallow groundwater through the process of evapotranspiration (Beschta, 1984; Sinokrot and Stefan, 1993). Water temperature is essential for a naturally diverse ecosystem; a continuing rise in stream temperature can cause adverse effects to channel biodiversity and may encourage foreign species to invade or even worse, a loss in aquatic biodiversity (Kaushal, 2010). An increase in stream temperature can even influence fish migratory patterns (Schlosser, 1991).

Natural bank material	Sediment dynamics	Bed and bank materials of the river are not only critical for sediment transport and hydraulic influences but also modify the form, plan and profile of the river (Rosgen, 1994). Natural bank materials provide fine sediment to the river system via erosion which is transferred downstream and deposited as ERS. The erosion and deposition of sediment largely contributes to the dynamic equilibrium of natural rivers. Sediment size and cementation strongly influence the erodibility of river banks, which is why erosion rates and channel planform are likely to vary significantly along the length of rivers (Wallick, 2006).
	Erosion control	Bank retreat is an important area of research within fluvial geomorphology and is a land management problem of global significance (Parker *et al.*, 2008). The properties of bank materials are important in controlling the stability of stream banks (American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modelling of River Width Adjustment & Thorne, 1998). Natural bank material provides a platform for pioneering vegetation to flourish. Riparian vegetation can prevent slumping and help stabilise the river bank. However, removal of riparian vegetation can largely influence stream bank erosion and channel change (Beeson & Doyle, 1995).
Natural bed substrate	Habitat provision/ natural biodiversity	Gravel bed rivers create a suitable microhabitat for macroinvertibrates and fish spawning. For example, salmon shape the gravel to form redds which the salmon use for spawning (Huet, 1959; Armstrong *et al*., 2003).
	Productivity and resilience	Increased siltation of streams as a result of channelisation reduces fish productivity and diversity (Berkman & Rabeni, 1987; Gilvaer, 1999). As the percentage of fine substrate increased on the Missouri, USA, the distinction among riffle, run and pool communities decreased, primarily because the number of individuals of typical riffle species decreased (Berkman & Rabeni, 1987; Rabeni & Smale, 1995).

Exposed Riverine Sediment (ERS)	Habitat provision/ natural biodiversity	The active zone of flood plains provide a wide diversity of habitat conditions which are produced by a collection of fluvial geomorphological processes and their interactions with vegetation (Malanson, 1993). A key component of physical habitat along braided river systems is the ERS within the active zone (Petts *et al.*, 2000; Bates *et al.*, 2005) which is built up of deposits of fine organic material and inorganic sediments. However, the habitat for both flora and fauna is unstable due to the erosion of islands during floods which cause the materials to be swept away downstream and re-incorporated into islands further downstream (Karrenberg *et al*., 2002). However, ERS is a primary regeneration site for riverine pioneer tree species (Braatne, Rood & Heilman, 1996) and meanders offer a more relatively stable habitat to plants and animals as a long time period is likely to elapse before newly deposited sediments are again eroded away (Karrenberg *et al*., 2002). ERS provides a successional habitat of high conservation value for invertebrates (Eyre & Luff, 2002). An investigation carried out by Sadler *et al.* (2003) found over 480 species of *Coleoptera* and a total of 81 species with a conservation status of Vulnerable, Rare or Nationally Scarce across England and Wales. Eyre *et al*. (2002) provided evidence from four highly managed catchments in the North of England and Scotland, a number of nationally rare and scarce invertebrate species that were recorded indicating that ERS appears to be important areas of relatively natural habitat within these highly managed landscapes. Actions that threaten ERS specialists function on a variety of scales and include river engineering, flow regulation and livestock damage (Bates *et al.*, 2005).
	Flood control via sediment	ERS is a natural sediment store within river channels which is crucial in preventing siltation downstream potentially causing flooding at more sensitive sites which may require dredging.

	dynamics	Channelisation, in particular straightening and ramped disturbance, prevents the formation of ERS because erosion and deposition processes are altered which can cause an increase in fine sediment.
Wetlands	Habitat provision/ natural biodiversity	A wetland is a permanently/semi permanently wetted area that forms a vitally important breeding, rearing and eating ground for many species of fish and wildlife (Cowardin *et al*., 1985). Existence and functioning of wetlands is crucial for adjacent terrestrial and aquatic ecosystems (Zhou *et al.,* 2008). Large diversity of terrestrial vegetation species.
	Carbon sequestration	Peat acts as a store for carbon content leading to lower greenhouse gas emissions and is Britain's most significant carbon store. Contributes to climate regulation. The erosion of peat leads to an increase in carbon dioxide release into the atmosphere whilst causing a higher organic matter content into water. A previous study (Euliss *et al*., 2006) demonstrates that wetlands are an important and previously overlooked biological carbon sink. In North America, it has been recognised that prairie wetlands have the potential to sequester more than twice as much carbon as conversion of all cropland to no-till agriculture (Euliss *et al*., 2006). Globally, wetlands account for the largest pool of stored carbon, representing 33% of the soil organic matter on only about 4% of the land surface area (Eswaran *et al*., 1993).
	Flood control	Floodplain wetlands have been lost across the UK for agricultural and urban development, and embankments have made rivers into drains. By restoring lateral connectivity, frequent inundations can benefit pastures and floodplain storage alleviates flooding in downstream towns by slowing the hydrograph. The floodplain can store storm water, lowering the peak discharge of the main channel, reducing flood impacts.
	Water purification	The erosion or replacement of peat will cause an increase in the cost for water treatment due to increased levels of organic matter content and an increase in water flow across the land. This is

		significant as land use in floodplains tends to have an immediate impact on water quality. Agriculture can cause nutrient (nitrate) leaching. Wetlands/peat can lower the levels of leaching by storing additional nutrients and reduce the impacts it will have on the water quality of the river.
	Nutrient purification	Reduction of nitrogen and phosphorus in the river channel will result in lower sewage treatment costs. Land use conversion from intensively cultivated land to natural lakes or wetlands can greatly reduce the emissions of nitrogen, phosphorus and ochre. The reduction in nutrient levels is a result of reduced leaching as well as the retention of nutrient in the river water when passing through the flooded areas (Dubgaard *et al*., 2002).
Lateral connectivity	Habitat provision/ natural biodiversity	Perhaps more than any other ecosystem, river ecosystems connect to and interact with surrounding landforms (Hynes, 1975). Geomorphological processes create dynamic and diverse habitats, both in-stream and within the riparian and floodplain ecotones (Sear & Newson, 2003).
	Flood control	Natural unaltered floodplains provide a space to store floodwater during high flows. Permeable floodplain soils help create semi-permanent wetlands, which can help prevent high magnitude flooding downstream.
	Productivity and resilience	Rivers which have an intact floodplain exchange organic matter and nutrients with nearby land. All fluvial ecosystems exhibit a high connectivity laterally, longitudinally and vertically (Allan & Castillo, 2007). Natural lateral connectivity increases productivity of fisheries compared with those where the floodplains are decoupled from the river by impermeable flood defences (Gilvaer, 1999).
Longitudinal connectivity	Habitat provision	Longitudinal connectivity allows in channel species to migrate up and downstream creating a host of possible habitats for species to colonise. However, dams are a ramped disturbance which disrupts

		this longitudinal connection and therefore determines the areas in which species (fish in particular) can populate.
	Erosion control	Dam and mill channels disconnect the sediment from being transported downstream. They have a significant impact on the geomorphological behaviour of river systems. Dams cause scour downstream due to increased stream power and cleaner flow which causes clear-water erosion. Bank erosion can occur upstream of the ramped disturbance due to the fluctuating water levels upstream (Downward and Skinner, 2005).
	Sediment dynamics	Dams prevent sediment from being transported and deposited downstream. Sediment accumulates behind dams and in mill ponds which act as sediment sinks (Downward and Skinner, 2005) instead of being naturally transported downstream and deposited as ERS.

Table 7. Relationships between GF and the delivery of multiple FES

From the evidence provided in Table 8. it is clear to see that geomorphology can play a large role in the delivery of FES. Geomorphological processes sustain the morphology which provides the platform to deliver FES whilst the influencing characteristics help regulate and support FES. For example, riparian vegetation can help lower turbidity and prevent large quantities of fine sediments entering the channel whilst also being a store for nitrates preventing them from entering the channel which helps towards the provision of clean water.

2.4.3 'Geomorphological slider' concept

When applying this framework to a study reach it is important to identify the current condition of GF. The 'geomorphological slider' concept is a pedagogical tool used in this study to demonstrate the conditions of GF on a reach scale. A reach scale position within a catchment helps identify the degree to which it is affected by disturbance events of various magnitude and frequency (Sear *et al.,* 1995). The tracking in which the slider moves up and down represents a continuum, with the top representing 'natural' geomorphological conditions and the bottom of the slider representing geomorphological degradation. The slider will be positioned along the tracking to represent the level of geomorphological 'naturalness' for each GF. So what is determined 'natural'? Whilst the concept of 'naturalness' continues to provoke debate throughout the academic world, this author has chosen to apply the definition provided by Brierley and Fryirs (2005) who use a geomorphic perspective. A geomorphic perspective views a 'natural' river as one that is appropriate for the given landscape or environmental setting, with a character and behaviour that is expected given the boundary conditions under which the river operates (Brierley & Fryirs 2005). So, the higher the slider is positioned along the tracking, the more 'natural' GF are present (for a given river context). If the slider is positioned at the bottom of the tracking, this represents complete modification of GF (for a given river context). For example, a reach that has become disconnected through flow regulation schemes will be positioned at the bottom of the lateral connectivity tracking because in geomorphic terms disconnected systems are more resilient to natural adjustment (Fryirs *et al.,* 2007). The position of the slider will be determined through the use of reconnaissance survey data that is collated at a reach scale. Once applied to a case study, the slider will represent both pre and post restoration GF conditions.

Figure 25. illustrates the position of the slider for a natural geomorphologically diverse lowland reach. The geomorphic principles of naturalness can fashion a basis for a self-sustaining resilient system (Fryirs & Brierley, 2009) and therefore the slider considers diversity and the range of dynamic behaviour. The 'geomorphological slider' continuum concept will help provide a reach scale overview for the level of GF naturalness pre and post restoration. Using Brierley and Fryirs (2005) definition of 'naturalness' it is clear to see that naturalness is not fixed in the past, it is a functional state that adjusts its character and behaviours in response to flow, sediment and vegetation fluxes (Hughes *et al.,* 2005).

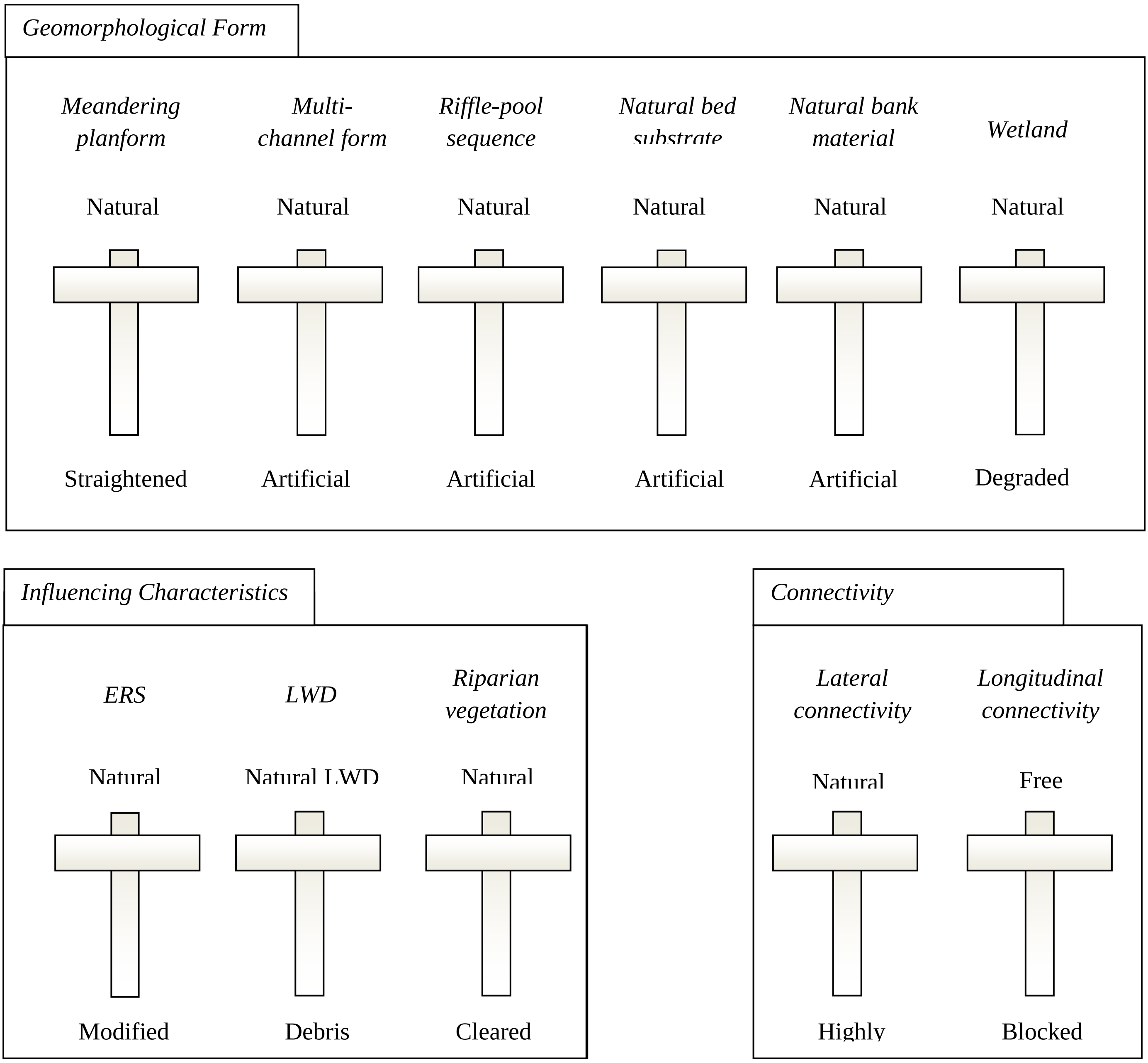


Figure 25. Geomorphological slider

2.4.4. Restoring geomorphological functions

As explained in chapter one, process-based restoration is the most effective method of restoring both natural and sustainable processes and form (Beechie *et al*. 2010). The slider positions of the GF exemplified in Figure 25. is an example of a natural geomorphologically diverse lowland river that has been unaltered by anthropogenic disruptions. Restoring GF can help re-connect and re-establish key processes that are central to the generation of FES.

However, there is a lag time between the beginning of process and form restoration and the recovery of certain GF (Hughes *et al*. 2005).

It is vital that the correct channel processes and forms are introduced within the correct channel type, as channel processes create and maintain channel form. If a desired channel form is not observed at a reach, it implies that current channel processes do not support such a form (Kondolf & Smeltzer, 2000). However, one of the challenges this type of framework will pose is the ability to put a certain value to GF features. River restoration can be used to help understand the relationship between geomorphological form and processes with riverine ecosystem services.

As pointed out by Boyd and Banzhaf (2007) services and benefits are different. As explained in section 1.6. of this thesis, a benefit is something that has an explicit impact on changes in human welfare, like more food, better hiking, less flooding (Boyd & Banzhaf, 2007). Table 8. provides an illustrative example of the relationships between a collection of FES and their associated potential benefits. Table 8. does not include every riverine FES or every associated benefit, but it aims to provide a general overview of the potential relationships between FES and benefits. Relationships between FES and benefits are explored throughout chapter four. The case study will also help quantify some the benefits whilst highlighting any research gaps required to fill particular values.

FES (Final Ecosystem Service)	Potential Benefit
Habitat provision/ diverse species community →	- Outdoor recreation – fishing (lakes and rivers), hiking, bird watching, boating, hunting etc. - Education. - Existence value/non-use value of biodiversity. - Harvesting (Trees). - Standing timber.
Water purification →	- Clean drinking water. - Saved pumping costs. - More productive fisheries. - Outdoor recreation – fishing (lakes and rivers), hiking, bird watching, boating, hunting etc. - Clean water for irrigation.
Erosion control →	- Prevention of bank stabilisation methods. - Lower 'risk' to riverside infrastructure. - Higher land/property prices.
Nutrient retention →	- Reduction of nitrogen, phosphorus and ochre load resulting in lower purification/sewage treatment costs.
Carbon sequestration →	- Store carbon content generating lower greenhouse gas emissions (local to global environmental benefit).
Productivity and resilience →	- More productive fisheries. - Outdoor recreation. - Natural biodiversity enhanced.
Flood control →	- Reduced flood damage costs/compensation costs. - Reduced flood risk.

Table 8. Hypothetical benefits provided by FES

3.0. Methodology

From exploring existing 'ecosystem service' research it is evident that there are numerous concepts and frameworks used to classify and value ecosystems (Costanza *et al.*, 1997; Daily, 1997; De Groot *et al.*, 2002; MA, 2005; Farber *et al.*, 2006; Boyd & Banzhaf, 2007; Wallace, 2007; Fisher & Turner, 2008). Existing ecosystem service research suggests that there are many other inputs to riverine environments which influence the types of ecosystem services present. An understanding of ecological theory can help us understand the essential habitat conditions for particular species whilst an understanding of hydrological processes can help distinguish suitable flow conditions for 'habitat provision', 'flood control' and 'erosion control'.

Nonetheless, this thesis focuses on the influence of riverine geomorphology such as planform, bed and bank substrate and geomorphological influencing characteristics such as riparian vegetation and large woody debris. Reach-scale channel morphology is influenced by the valley slope and confinement, bed and bank material and riparian vegetation as well as the supply of water, sediments and wood from upslope (Montgomery & MacDonald, 2002). Not only does the valley rule the stream, as Hynes (1975) put it, but increasingly, human activities rule the valley as explained in chapter 1. Centuries of human activity has caused alterations to stream geomorphology. By recreating or mimicking natural 'geomorphological functions' via river restoration, both flow and sediment dynamics will be impacted, influencing the delivery of ecosystem services.

As stated in the introduction of this thesis, the Fisher *et al.* (2009) concept has been adapted to help identify the relationship between 'geomorphology' and the delivery of lowland riverine 'ecosystem services'.

3.1. Valuing geomorphological functions (GF)

As explained in chapter 1, there are limits to economic valuation, whilst some of the benefits derived from ecosystem services lend themselves more successfully to monetary valuation than others (RSPB, 2010). This study aims to place monetary values to GF which help identify the importance of maintaining or restoring 'geomorphologically diverse' rivers and deliver a range of ecosystem services. Indirect values are also explored which help represent the benefits that people derive from nature.

3.1.1. Restoring GF

It is vital that the correct channel processes are introduced for the correct channel type. Channel processes create and dynamically maintain channel form, so if a desired channel form is not observed at a given reach, it implies that current channel processes do not support such a form (Kondolf & Smeltzer, 2000). Figure 26. conceptually illustrates how GF fit in with the 'ecosystem service' approach and the order in which they can influence the delivery of FES (final ecosystem services). FES is the ecosystem service that directly underpins or gives rise to a good.

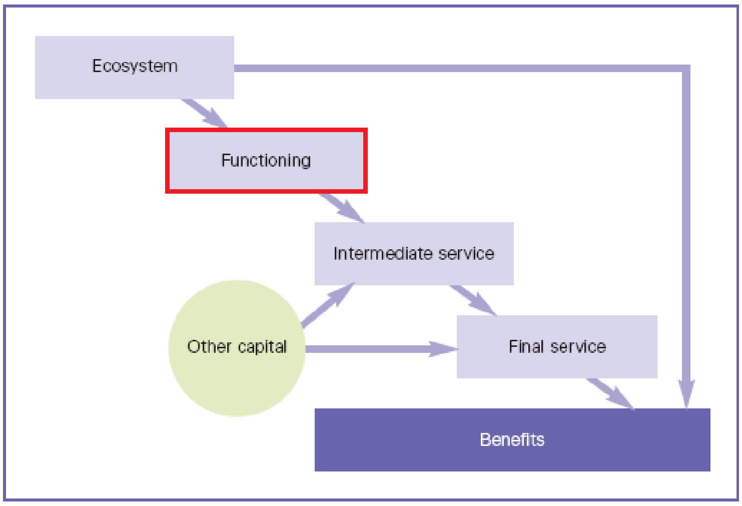


Figure 26. Conceptual model showing at which stage GF fit in with the 'ecosystem service' approach. (adapted from RSPB, 2010)

Table 9. displays the cost to restore a selection of GF. As GF consist of natural form/processes they are difficult to value but the following estimated restoration costs provided by the River Restoration Centre (RRC) help identify the direct costs to restore degraded GF and reintroduce 'geomorphological diversity' at a reach scale. Direct costs include the cost for labour, machinery and materials/equipment (augmentation/ removal). The costs to restore GF can be used as a method to value GF and will be measured by £/per km.

Geomorphological Functions (GF)	**Cost data for Restoring Geomorphological Features (Costs are based on straightforward and easy to access sites)**		
	<5m width	**5-10m width**	**10m+ width**
Meandering planform	£208,000 Re-alignement	£658,000 Re-alignment	£1,108,000 Re-alignment
	–	£16,000 Reconnecting old meanders	£23,000 Reconnecting old meanders
Multi-channel form	–	–	–
Pool-riffle sequences	–	£600,000 Riffle creation (based on 400m per km)	£155,200 Riffle creation (based on 400m per km)
Large Woody Debris (LWD)	–	£300 Introduction of x6 woody material	£900 Introduction of x6 woody material
Riparian vegetation	£86,000 Fencing (500m either side of channel)	£88,250 Fencing (500m either side of channel)	£90,500 Fencing (500m either side of channel)
	£95,000 Re-establishing riparian vegetation	£103,750 Re-establishing riparian vegetation	£112,500 Re-establishing riparian vegetation
Natural bed substrate	£108,000 Removal of artificial bed material	£333,000 Removal of artificial bed material	£558,000 Removal of artificial bed material
	–	£194,000 Import of gravel	£250,000 Import of gravel
	£88,000 Augmentation	£118,000 Augmentation	£148,000 Augmentation
Wetlands	£308,000	£733,000	£1,158,000
Lateral connectivity	£68,000 Removal of embankment	£178,000 Removal of embankment	£288,000 Removal of embankment
Longitudinal connectivity	£13,000 (per impoundment)	£61,750 (per impoundment)	£110,500 (per impoundment)
Exposed Riverine Sediment (ERS)- bars/deposits	–	–	£3,146 (£/m) Island creation
Bank erosion	£48,000 Removal of hard bank material	£68,000 Removal of hard bank material	£88,000 Removal of hard bank material

Table 9. Cost estimates for restoring geomorphological features per/km (adapted from River Restoration Centre, undated)

The ‘costs’ listed in Table 9. are estimates which highlight the costs for different sized rivers based on reach scale restoration (per/km). The cost estimates illustrate the cost for degraded channelised reaches which have undergone high levels of modification therefore lacking in many GF. The larger the river width, the more expensive it is to restore GF as more material and labour will be required. Table 9. displays replacement costs to restore or re-introduce GF. For example, a river reach (width <5m) that has been straightened using hard bank material has lost the ability to migrate within its floodplain and therefore the function of the river in providing sediment downstream from bank erosion and scour which is vital for the formation of ERS has been lost. To maintain flood defences the channel is annually dredged to prevent overbank flows. The cost to restore this reach to its previous natural geomorphological condition would include £208,000 for re-alignment and £48,000 to remove hard bank material. Additional costs to replant riparian vegetation (£95,000) and gravel augmentation (£88,000) will bring the total cost to restore the GF at this reach to £439,000. These costs include scoping the study, data gathering, design and preparation, implementation, measures and monitoring. The breakdown of costs will be explored with more focus in the chapter 4, whilst various levels of degradation will show how reaches would cost more or less by assessing different GF being absent. This is highlighted in the result section where restoration of GF in a hypothetical cost case study alongside restoration of GF in semi-natural reaches is explored.

The goal of many restoration projects is driven by ecological rehabilitation and flood protection in which planning and decision-making are carried out according to these objectives (Boon *et al.*, 2000; Zube, 1973; Daniel & Vining, 1983). To fully understand the benefits derived from restoration, it is important to know whether the aesthetic preferences of the general public match the ecological and hydrological objectives (Parsons, 1995; Nassauer, 2004; Zedler & Leach, 1998). Section 3.2. will introduce the method used to attain the general public’s aesthetic preference.

3.2. ‘Indirect values’ and ‘willingness to accept government funding’ for GF and lowland riverine FES

Although ecosystem service research is continuing to expand, many challenges remain to structurally integrate ecosystem services in landscape planning, management and design (De Groot *et al.*, 2009). There are gaps in ‘ecosystem service’ research which thwart our ability to quantify and place monetary values to a collection of services. A key drawback is the understanding of basic science needed to assess, project and manage flows of ecosystem services and effects on human well-being remain limited (Carpenter *et al.*, 2009). However, by ignoring the system as a whole and simply valuing readily-exploitable service will lead to exploitation economics (Everard, 2010). Therefore, non-monetary benefits gained from FES must be carefully considered before decision making to avoid 'silo thinking' and degradation to other services.

To gather indirect values, the general public's perception is explored in this thesis to discover whether respondents favour 'geomorphologically diverse' rivers. Social perceptions are shaped largely by culture and aesthetics (Junker and Buchecker, 2008). Values tend to be single, stable beliefs, which are used as a standard to evaluate action and attitudes. Values have two notable characteristics which differentiate them from most attitudes. First, they transcend objects and secondly, values are most central in a person's belief system. Values are the basis for evaluating beliefs (Heberlein, 1981).

A natural, dynamic, self-adjusting and "messy" river that supports a range of natural flora and fauna may be the opinion of some, but other respondents may take a mechanistic view and prefer the simplicity and hydraulic efficiency of a fully regulated, smooth, well-behaved channel that supports a limited range of aquatic flora and fauna (e.g. Kondolf, 2006). The principle aim is to discover whether respondents agree with the level of current funding provided by the government/EU to restore rivers and whether the current levels are justified regarding the 'benefits' derived from restoration through the delivery of FES.

To help capture indirect non-use values, a survey was designed to record respondents 'willingness to accept government funding' for GF. This was done by presenting the respondents with three photographic simulations of geomorphologically different river types and asking them a host of structured and semi-structured questions relating to the type they preferred and why. The survey also asked respondents to rank FES in order of importance to understand what the general public believes to be the most important FES (Table 11.). The results are measured by £/per km. The results from the survey will be explored in chapter 4.

3.2.1. 'Indirect value survey' for lowland riverine ecosystems

The purpose of this survey was to collect data that can be used to indirectly value lowland river FES, whilst finding out if respondents favoured 'geomorphologically diverse' rivers or whether they preferred channelised rivers in both urban and rural settings and their reasoning why. Once applied to a case study, the survey data will be used to calibrate the 'ecosystem service valuation model'. The aims and objectives of this survey are as follows:

Aim:

- To understand the general public's perspective on river type, restoration and riverine ecosystem services.

Objectives:

- To discover respondents' favoured geomorphological conditions (natural, channelised, culvert) and relate to GF
- To learn whether respondents' find the current cost to restore GF justifiable
- To collect 'indirect values' from the general public regarding option values and non-use values of riverine FES
- To see how respondents' value the importance of lowland river FES
- To establish the general public's views about the local authorities/government 'willingness to accept government funding' local to sustain/restore their preferred river type in the future.
- To explore respondents' perspectives across residents, visitors and age groups.

Survey design:

Understanding the interview methodology is an important step to understanding the context in which interviewer's gather qualitative information. Below is a concise description of the methodology used in this project.

There has been a large degree of debate over many years about the relative usefulness of interviewing as a form of data gathering. The main concern has been whether interviews can reveal objective 'facts' about areas of research, largely due to the context and subjective nature of narrative forms which are inherent in participant responses (Teski & Climo, 1995;

Grele, 1998; Perks & Thomson, 2006; Rubin, 1986). However, qualitative values which can be gained from interviewing techniques cannot be collected from other methods of data collection, which is why oral historians, sociologists and anthropologists have stuck with this method (Thompson, 2000).

The survey was constructed using Flowerdew and Martin (2005) as a guide so that the survey contained the correct elements and structure to optimise data collection both quickly and efficiently. The 'indirect value survey' was carefully designed using the set of research aims and objectives. In this case, a project designed to reveal value systems, which by their very nature are subjective, was ideally suited to using semi-structured interview information gathering techniques. The proposed target population is:

- *Residents*- are those who live within the study area and those who live within a five mile radius of the proposed site.

- *Visitors*- include day visitors and staying visitors (staying overnight for at least one night).

Survey Structure:

Section 1: Introduction	• Gender • Resident or visitor • Attraction to the area
Section 2: Riverine environments	• Preferred river type • 'Willingness to accept government funding' for chosen river type
Section 3: Ecosystem services	• Assessing the importance of riverine Ecosystem services • Is the current restoration cost justified?

The interviews were split up into three sections with the main focus of the first section being whether the respondent was a visitor or resident. The second section was focussed around the questions: A) what is your preferred river type (A, B or C) in a rural/urban context? B) How much would you be 'willing to accept government funding' to restore and maintain your chosen river type depending on rural/urban context. The third section had a focus on the delivery of ecosystem services. The central focus was to find out how respondents ranked ecosystem services in terms of their importance.

The interviews took place during June 2010 (peak holiday season) so that a mixture of residents and visitors could be interviewed. The surveys were conducted by sampling from a population (60 respondents') rather than contacting all of its members. The respondent is the unit of the study as the individual's opinions are of interest. The structure of the survey questions were carefully designed to prevent biased answers from respondents' and to avoid response errors. A combination of multiple choice, rating scale and agreement scale questions were use to record respondents' opinions and views. Only minimal information about the direction and expected outcomes of the project were mentioned by the interviewers in order to avoid subject contamination. A prime example of a bad survey design which can lead to response errors can occur when a respondent feels pressured into agreeing with the interviewer's ideas. This was reduced by leaving out leading or loaded questions.

To practice interviewing techniques, two pilot surveys were undertaken between April and May, 2010. Pilot studies were used to interview respondents' in the case study site Lyndhurst (New Forest, Hampshire). The pilot studies helped finalise the interview locations so that the time spent in the field undertaking the final survey was optimised. The pilot studies were also useful for rehearsing interview structure to ensure that the questions were unbiased and not misleading.

Interviews generally took place along the streets of Lyndhurst and at residents' door steps. The interviewer began by reading a project description and privacy notice assuring respondents that they would not be identifiable through the project reporting. The survey itself was designed to take no longer than five minutes of the respondent's time which is enough time to give them the maximum opportunity to respond whilst preventing 'fatigue' bias answers. The highly structured survey design was conducted in rapid succession to minimise respondent contamination and sustain the quality and consistency of the data throughout each survey.

The language tone of the questions has been designed not to put the respondent out of his/her depth. Key terminology such as 'carbon sequestration' and 'ecosystem services' were defined in their simplest terms to prevent confusion. However, oversimplifying questions could patronise and put off the respondent, so a clear balance was required.

It is important to understand the advantages and disadvantages for this type of survey as this will be reflected in the quality of the results. Flowerdew and Martin (2005) provide an overview of how effective interviewer-administrated surveys are regarding quality of data (Table 10.). 'Good' means the interview-administered survey technique is a useful and accurate method for collecting data whilst 'poor' means the technique is not useful at collecting reliable data. One of the main advantages of using an interviewer-administrated survey is that they are suited to handling complex questions as long as the quality of the interviewer's questions remains consistently unbiased (Flowerdew & Martin, 2005). This technique was chosen because the indirect value survey will provide data relating to the respondents attitudes, opinions and beliefs of riverine environments and therefore an interview-administrated survey is well suited.

	Interviewer-administrated surveys
Response rates	
General samples	Good
Specialised samples	Good
Representative samples	
Avoidance of non-response bias	Good
Control over who completes the questionnaire	Good
Gaining access to selected person	Satisfactory
Locating the selected person	Satisfactory
Effects on questionnaire design	
Ability to handle:	
Long questionnaires	Good
Complex questions	Good
Boring questions	Good
Filter questions	Good
Question sequence control	Good
Open-format questions	Good
Quality of answers	
Ability to avoid distortion due to:	
Interviewer biases	Poor
Influence of others on respondent	Satisfactory
Implementation	
Speed	Poor
Cost	Poor

Table 10. Advantages and disadvantages of interviewer-administrated surveys (adapted from Flowerdew and Martin, 2005).

Previous research studies have focussed on an individual ecosystem service and used a 'Contingent Valuation Method' (CVM) to gain indirect values. Bateman *et al*. (2010) used a stated and revealed preference method which showed the respondents various states of river conditions relating to water quality and how much they were 'Willing to Pay' (WTP) to maintain or restore those conditions. Bateman *et al.* (2010) concluded that many people visit rivers with high water quality. The 'marginal WTP' is illustrated in Figure 27. for the area of Bradford.

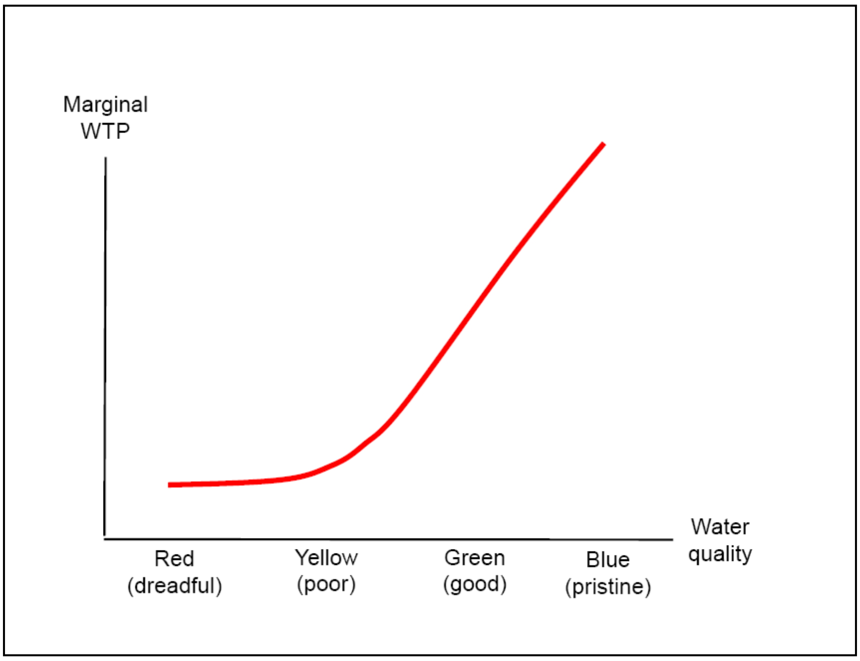


Figure 27. Marginal WTP against water quality (Bateman *et al.,* 2010)

Respondents are willing to pay more (through water bills) for good and pristine conditions as illustrated by Figure 27. Characteristics of good preference conditions include safe conditions for fishing and boating and pristine preference conditions also include safe conditions for swimming and fly fishing (Bateman *et al.,* 2010). The 'indirect value survey' will help highlight the general public's opinions on 'willingness to accept government funding' for 'ecosystem services' and 'geomorphologically diverse' rivers. The reality is that river restoration projects are government/EU funded so the 'willingness to accept government funding' will help identify the amount of money respondents expect government/EU to pay to enhance and restore 'geomorphological functions' and 'ecosystem services'.

Once the rank order is established respondents will use a percentage rank to illustrate how much of their 'willingness to accept government funding' will be granted for enhancing the delivery each FES (value is recorded from an earlier question in the survey). The ranking system will reveal respondents' 'willingness to accept government funding' for FES in relation to their importance to human well-being. The 'indirect' results can be compared with the actual cost to restore GF to illustrate whether the cost of restoration to improve the delivery of FES is deemed good value. The results will be measured by £/per km.

Riverine Ecosystem Services	Degraded River System	Restoration Results	Rank (Rural)	Rank (Urban)
Water quality	• Poor water quality	• Improves water quality		
Habitat provision	• Low levels of biodiversity	• High levels of biodiversity		
Flood control	• High flood risk	• Temporary flood water storage • Lower flood risk		
Carbon storage	• Low carbon storage capacity	• High carbon storage capacity		
Erosion control	• River bank failure causing loss of land and flooding downstream	• Helps prevent bank failure		

Table 11. Respondent's rank order of FES

Once 'direct' and 'indirect' values have been placed to GF, they can be compared to the direct and indirect benefits that stem from FES. The results from the 'indirect value survey' will help test the hypothesis introduced in chapter 2.

3.3. 'Benefits' of FES

It is crucially important to note that 'FES' are not equivalent to 'benefits'. As noted in Chapter 1, Boyd and Banzhaf (2007) pointed out that services are not benefits. Many publications (Wallace, 2007; MA, 2005) mix 'ecosystem services' with 'benefits'. A 'benefit' is something that has an explicit impact on changes in human welfare (Fisher & Turner, 2008), such as less flooding, water for irrigation, clean drinking water and recreational enhancement. The benefits humans gain from ecosystems are derived from the 'intermediate' and 'final ecosystem services' (Fisher & Turner, 2008).

The benefits that stem from FES can be calculated by considering the additional marginal values that can be gained from FES after restoring GF. For example, an increase in fishery productivity due to enhanced 'habitat provision' through the re-introduction of 'floodplain connectivity', 'longitudinal connectivity' and 'bed formations' (e.g. pool-riffle sequences). The increase in productivity as a result of GF restoration may also result in an increase in fishing memberships if not already fully subscribed. Member satisfaction could potentially increase due to the pleasant conditions and people may be willing to travel further for the experience (increase in travel cost). The changes in fishing experience post restoration could help illustrate the value for FES. Section 4.1 will show how 'indirect' benefits (non-use values) are calculated.

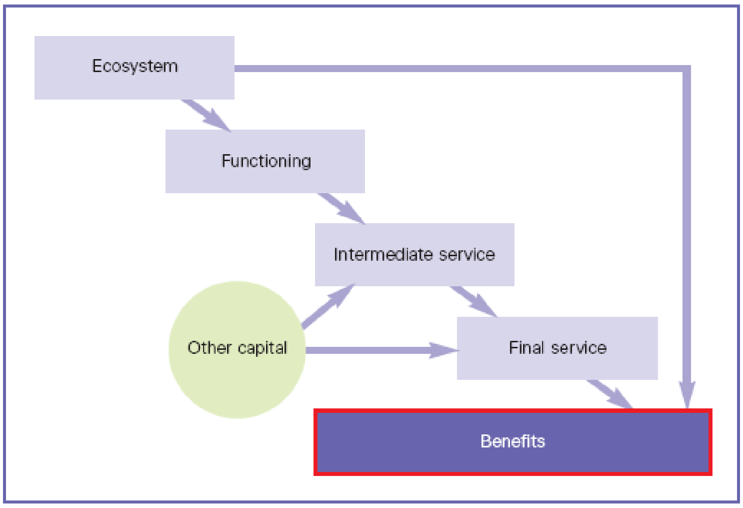


Figure 28. Conceptual model showing at which stage 'benefits' fit in with the ecosystem service approach (adapted from RSPB, 2010)

3.3.1. Calculating the marginal 'benefits' that stem from FES

This section explains the methods used to calculate the total marginal benefit gained from FES. 'Benefits' are the many ways in which human well-being is enhanced through the processes and functions of ecosystems via ecosystem services (Defra, 2007a). 'Direct observation methods' are benefits that are based on observable choices from which actual resource values can be directly inferred (Tietenberg & Folmer, 2003). 'Indirect values' are those which illustrate the respondent's 'willingness to accept government funding' for particular resources, providing a method for deriving values which cannot be collected in more traditional direct ways (Tietenberg & Folmer, 2003). This will identify respondent's maximum marginal 'willingness to accept government funding' to consume an additional good or service.

There are various economic methods that can be used to determine the values for ‘direct’ and ‘indirect’ methods. Table 12. identifies the observed behaviour and hypothetical valuation methods for both ‘direct’ and ‘indirect’ values.

Direct:

Use-values: reflects the current direct use of environmental resource.

Indirect:

Option-values: people’s ‘willingness to pay’ or ‘willingness to accept’ to preserve the environment for the ability to use it in the future.

Non-use values: reflects the common observation that people are more than willing to pay for enhancing or preserving resources that they will never use (Tietenberg & Folmer, 2003).

Methods	**Observed behaviour**	**Hypothetical**
Direct benefits stemming from FES	Market price Simulated markets	Contingent valuation
Indirect benefits stemming from FES	Travel cost Hedonic property values Hedonic wage values Avoidance expenditures	Contingent ranking

Table 12. Economic methods for measuring ecosystem and resource values (adapted from Tietenberg and Folmer, 2003)

Methods	**Values**	**Technique for valuing lowland riverine environments**
Direct benefits stemming from FES	Use-values	- Scientific research - Membership prices - Water treatment costs
Indirect benefits stemming from FES	Option-values Non-use values	- 'Willingness to accept government funding' - Ecosystem service ranking - Policy compliance - Transferable benefits - Carbon sequestration estimates

Table 13. Methods, values and possible techniques for valuing lowland riverine ecosystems

Indirect methods for placing monetary values to ecosystems involve 'option values' as well as 'non-use values'. For this reason, the 'willingness to accept government funding' method has been used to value the marginal 'indirect benefits' stemming from FES as well as respondents' marginal 'willingness to accept government funding' for GF restoration. This data will be used to make a comparison between actual cost of GF restoration and respondents' 'willingness to accept government funding' for restoration. Respondents' rank riverine FES in order of importance and then suggest their marginal 'willingness to accept government funding' for the delivery of each FES. Respondents' marginal 'willingness to accept government funding' compared with the marginal 'benefits' stemming from FES will indicate whether 'direct' monetary values are reflected through the respondents' 'willingness to accept government funding' or whether 'option values' and 'non-use' existence values are important contributing factors in the respondents' decision to pay. The relationships between 'GF', 'FES' and marginal 'benefits' are conceptually displayed in Figure 29.

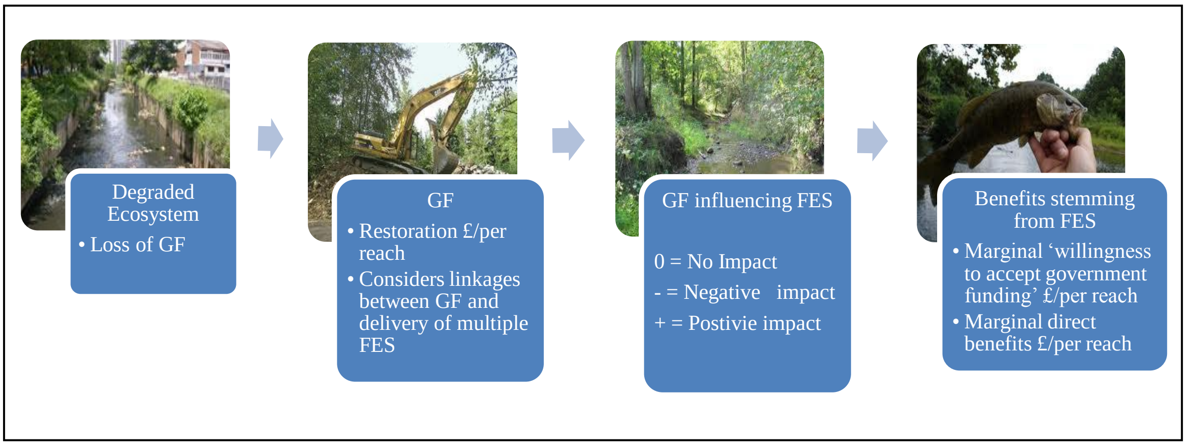


Figure 29. Conceptual relationship of a 'geomorphologically degraded' river ecosystem, to an ecosystem that delivers 'multiple benefits'

Table 14. indicates the delivery of reach scale FES and benefits in a degraded river ecosystem compared with the FES and benefits delivered post restoration in a more geomorphologically diverse river.

Pre-restoration FES	**Pre-restoration benefit**	**Post-restoration FES (after 10 years)**	**Post-restoration benefit (after 10 years)**
• Degraded habitat (due to channelisation). • Poor water quality (due to agricultural runoff and eutrophication).	• Agricultural output.	• Enhanced habitat provision. • Flood control (flood water storage). • Erosion control.	• Recreation (riverside walks, aesthetics, water sports). • Fishing membership (£ per annum). • More productive fisheries. • Standing timber value. • Saved water treatment costs. • Lower carbon emissions. • Reduced flood risk. • Reduced property damage risk.

Table 14. Examples of potential 'FES' and marginal 'benefits': Pre and post-restoration for lowland rural rivers

Table 14. displays hypothetical data regarding the delivery of FES and benefits pre and post restoration. This type of approach will help us better understand the relationship between GF and FES at a reach scale. However, monitoring and post-project appraisals should keep record on how the benefits respond over a temporal scale to ensure the delivery of multiple FES. This type of approach will not only better our understanding of the linkages between geomorphology and FES, but a 'geomorphological approach' will also study how the system dynamically adjusts and how FES in time will respond to these natural adjustments. Perhaps this method could lead us to improved long-term management solutions?

3.4. Calculating the 'total benefit' stemming from FES that is derived from GF

A cost-benefit analysis will allow the comparison of GF (cost to restore) against the benefits stemming from FES. The process of this technique requires the quantification of possible impacts of a proposed project. The impacts can be either physical or monetary and environmental valuation provides a way to compare alternative proposals (Environmental Economics, 2007). Due to the difficulty of quantifying and valuing benefits derived from FES, the total monetary benefit may be skewed and perhaps lower than its true representation. However, ignoring the system as a whole and only valuing readily-exploitable services leads to exploitation economics (Everard, 2010). Therefore non-monetary benefits must be carefully considered before decision making to avoid 'silo thinking' and degradation to other services (Everard, 2010). FES influenced by GF will be highlighted in this framework using the Defra (2007b) 'likelihood of impact' weighting system. This weighting system allows the assessment of GF at a reach scale whilst indicating its contribution in delivering multiple FES. This is a useful technique to help identify the impacts and linkages between GF and FES. This method will be explained in more detail during chapter 4 when this framework is applied to a case study.

4.0. Results

To examine how the application of ‘geomorphology’ can be applied to ‘ecosystem service’ research, a set of New Forest river restoration case studies has been tested. This chapter will explore the results of GF values, their impact on FES and the ‘direct’ and ‘indirect’ benefits that stem from FES. The first section will analyse some of the ‘indirect’ values collected through the contingent valuation method ‘willingness to accept government funding’. ‘Indirect’ values are explored in the first section to help test the associated hypothesis of this survey.

4.1. The New Forest Indirect Value Survey

The indirect value survey will help test the following hypotheses:

3. The general public value ‘geomorphological diversity’ and that they are willing to accept government/EU funding to enhance and restore GF for non-use and option value benefits which derive from FES
4. The general public do not value ‘geomorphological diversity’ and feel that the current government/EU funding is unjustified in comparison to the benefits derived from FES

Lyndhurst is a small town located within the New Forest, Hampshire. It has a population of around 2,973 recorded in 2001 (New Forest District Council, 2001) and is the administrative capital of the New Forest. Lyndhurst is an incredibly popular tourist location so it was an ideal location to carry out the ‘indirect value survey’ because there is a good mix of visitors as well as residents. To encourage a fair test, the survey sites are spread evenly throughout the whole of Lyndhurst. Through the knowledge gained from the pilot studies, it had been established that many visitors are found around the High Street and car parks, whilst many residents are at home in the residential areas of Lyndhurst such as Chapel Lane and The Meadows. The residential surveys were carried out door to door to gain a true reflection of the age groups and types of people that live in the area.

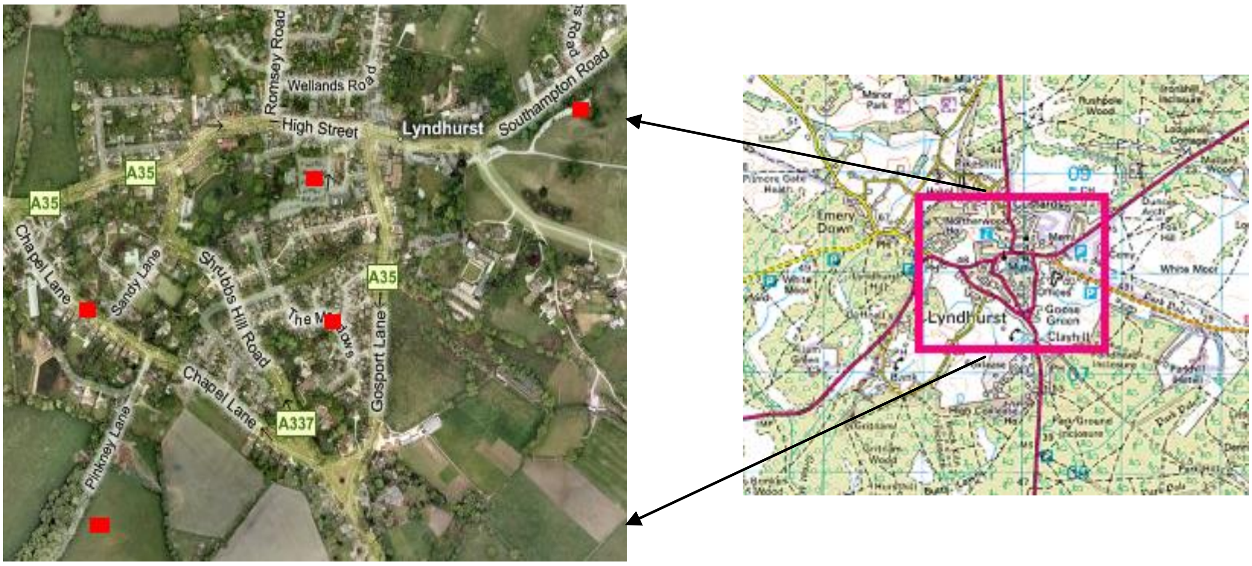


Figure 30. Survey Site - Lyndhurst, New Forest, Hampshire

Section 4.1. explores the indirect values of riverine environments. As explained in the methodology, the data gathered for this section is representative of indirect, option values and non-use values for riverine environments. The respondents were selected at random to help prevent biased results.

A) B) C)

Images A, B and C were used in the survey to see what type of river was the favoured in the a) New Forest and b) urban town or city. All three images are the middle course of the river, but each of the rivers has a very different geomorphological condition. The aim of the survey as stated previously was to collect ‘indirect’ values from the general public regarding ‘option values’ and ‘non-use values’ associated from the ‘benefits’ of river ecosystems. We can then begin to compare this data to the data on why respondents prefer particular river types and whether respondent's choice is aesthetically driven or functionally driven. This can then be compared to the geomorphological form of the given river type.

4.1.1. Respondents' river type choice

Section 4.1.1. will provide data regarding respondents' desired river type for New Forest rivers and urban rivers.

Tabulated statistics: Age, Gender

Row: Age
Column: Gender

	Male	*Female*	*All*
1	3	3	6
	2.800	3.200	6.000
2	6	9	15
	7.000	8.000	15.000
3	7	11	18
	8.400	9.600	18.000
4	7	6	13
	6.067	6.933	13.000
5	4	3	7
	3.267	3.733	7.000
6	1	0	1
	0.467	0.533	1.000
All	28	32	60
	28.000	32.000	60.000

Cell Contents: Count
Expected count

Tabulated statistics: Age, Visitor/Resident

Row: Age
Column: Visitor/Resident

	Resident	*Visitor*	*All*
1	1	5	6
	3.500	2.500	6.000
2	8	7	15
	8.750	6.250	15.000
3	8	10	18
	10.500	7.500	18.000
4	10	3	13
	7.583	5.417	13.000
5	7	0	7
	4.083	2.917	7.000
6	1	0	1
	0.583	0.417	1.000
All	35	25	60
	35.000	25.000	60.000

Cell Contents: Count
Expected count

Tabulated statistics: Gender, Visitor/Resident

Row: Gender
Column: Visitor/Resident

	Resident	*Visitor*	*All*
Male	18	10	28
	16.33	11.67	28.00
Female	17	15	32
	18.67	13.33	32.00
All	35	25	60
	35.00	25.00	60.00

Cell Contents: Count
Expected count

Key:

Age: 1=20-30, 2=31-40, 3=41-50, 4=51-60, 5=61-70, 6=70+

Table 15. New Forest survey respondents

The survey aimed to collect qualitative and quantitative data from a wide range of respondents by interviewing local ‘residents’ and ‘visitors’ to the New Forest. The most common age group of people interviewed at Lyndhurst was ‘Group 3’, aged 41-50 with a count of 18 people. This age group was also the most common age group of ‘visitors’ in Lyndhurst during 2001/2002 as recorded by Southern Tourist Board (Figure 31.). However, the results illustrate that the survey was carried out across all of the target age groups, with the most common age groups being ‘Group 2’, ‘Group 3’ and ‘Group 4’. There was also a fair divide between male and female respondents throughout all of the age groups. There were 10 more resident respondents’ than visitors with the majority of resident respondents’ aged between 31 and 60. The visitors’ ages were recorded in ‘Group 1’, ‘Group 2’, and ‘Group 3’ which suggests the majority was aged between 21 and 50. In total there were more male and female residents than visitor respondents’ throughout the survey. However, this may be because 10 more residents were interviewed than visitors, which may skew the results somewhat for this section.

	Lyndhurst	Lymington	Ringwood	Burley	Fordingbridge
Age:					
Under 45	30%	29%	25%	44%	35%
45+	70%	71%	75%	56%	65%
Social Grade:					
ABC1	79%	84%	73%	64%	68%
C2DE	21%	16%	27%	36%	32%
Working status:					
Full time job	67%	70%	57%	70%	61%
Retired	30%	27%	33%	21%	36%
Group type:					
Adults only	81%	86%	82%	64%	61%
Groups including Children	19%	14%	18%	36%	39%

Figure 31. Characteristics of groups making leisure visits to the New Forest towns/villages (Southern Tourist Board, 2001/2002)

Tabulated statistics: Age, NF River Type			
Row: Age Column: NF River Type			
	A	*B*	*All*
1	6 5.800	0 0.200	6 6.000
2	15 14.500	0 0.500	15 15.000
3	18 17.400	0 0.600	18 18.000
4	12 12.567	1 0.433	13 13.000
5	6 6.767	1 0.233	7 7.000
6	1 0.967	0 0.033	1 1.000
All	58 58.000	2 2.000	60 60.000
Cell Contents:	Count Expected count		

Tabulated statistics: Age, Urban River Type				
Row: Age Column: Urban River Type				
	A	*B*	*C*	*All*
1	1 1.300	4 3.100	1 1.600	6 6.000
2	4 3.250	9 7.750	2 4.000	15 15.000
3	6 3.900	7 9.300	5 4.800	18 18.000
4	2 2.817	6 6.717	5 3.467	13 13.000
5	0 1.517	5 3.617	2 1.867	7 7.000
6	0 0.217	0 0.517	1 0.267	1 1.000
All	13 13.000	31 31.000	16 16.000	60 60.000
Cell Contents:	Count Expected count			

Key:

Age: 1=20-30, 2=31-40, 3=41-50, 4=51-60, 5=61-70, 6=70+

Table 16. Respondents' age group tabulated with river type

The tabulated statistics for 'age group' against 'New Forest River type' suggests that the majority of those individuals, in fact 58 of the 60 interviewed recommend 'River Type A' as being their favoured river type for the New Forest. However, there was a much greater divide in opinion regarding urban river type. The results confirm that the most common choice for urban river type was 'River Type B' with 31 votes. The remaining opinions were split 13 and 16 respectably for 'River Type A' and 'River Type C'.

Tabulated statistics: Visitor/Resident, NF River Type			
Row: Visitor/Resident Column: NF River Type			
	A	*B*	*All*
Resident	33 33.83	2 1.17	35 35.00
Visitor	25 24.17	0 0.83	25 25.00
All	58 58.00	2 2.00	60 60.00
Cell Contents: Count Expected count			

Tabulated statistics: Visitor/Resident, Urban River Type				
Row: Visitor/Resident Column: Urban River Type				
	A	*B*	*C*	*All*
Resident	8 7.58	15 18.08	12 9.33	35 35.00
Visitor	5 5.42	16 12.92	4 6.67	25 25.00
All	13 13.00	31 31.00	16 16.00	60 60.00
Cell Contents: Count Expected count				

Table 17. New Forest visitor and residents' preferred river type

The tabulated statistics confirm that there were no votes for 'River Type C' in the New Forest. The majority of the votes (58/60) were happy to see 'River Type A' in the New Forest. The two other votes were from residents' who preferred 'River Type B'.

The votes for 'urban river type' were more evenly spread, with 'River Type B' being the most popular river type for an urban stream. On average, both residents' and visitors' preferred to see 'River Type C' than 'River Type A' in an urban environment. However, a much larger proportion of the visitors' preferred 'River Type B' (64% of voters) compared to residents' who were more evenly split between 'River Type B' (43% of voters) and 'River Type C' (34% of voters).

Tabulated statistics: Reason for NF choice, NF River Type					**Tabulated statistics: Reason for Urban Choice, Urban River Type**				
Row: Reason for NF choice Column: NF River Type					Row: Reason for Urban Choice Column: Urban River Type				
	A	*B*	*All*			*A*	*B*	*C*	*All*
Aesthetics	50 50.26	2 1.73	52 52.00		*Aesthetics*	13 8.67	23 20.67	4 10.67	40 40.00
Function	8 7.73	0 0.26	8 8.00		*Function*	0 4.33	8 10.33	12 5.33	20 20.00
All	58 58.00	2 2.00	60 60.00		*All*	13 13.00	31 31.00	16 16.00	60 60.00
Cell Contents:	Count Expected count				Cell Contents:	Count Expected count			

Table 18. River type and reason for respondents' choice

The tabulated statistics for the 'reason for New Forest river type choice' suggest that the majority of respondents' believe that 'River Type A' is more aesthetically attractive than the other river types. Many (52/60) of the respondents' choices for river type is based on how it looks rather than how it functions.

The responses to the 'reason for urban river choice' are slightly more varied. As explained previously 'River Type B' was the most popular choice for an urban environment. The basis for many respondents' choice of 'urban river type' was based on aesthetics rather than function of the river type. This is clearly illustrated in the tabulated results for 'River Type A' and 'River Type B'. However, respondents' who chose 'River Type C' assumed that 'River Type C' was more practical and functioned better at transporting water through an urban environment including reducing the flood potential.

Tabulated statistics: Visitor/Resident, Reason for NF choice			
Row: Visitor/Resident Column: Reason for NF choice			
	Aesthetics	*Function*	*All*
Resident	31 30.33	4 4.67	35 35.00
Visitor	21 21.67	4 3.33	25 25.00
All	52 52.00	8 8.00	60 60.00
Cell Contents:	Count Expected count		

Tabulated statistics: Visitor/Resident, Reason for Urban Choice			
Row: Visitor/Resident Column: Reason for Urban Choice			
	Aesthetics	*Function*	*All*
Resident	20 23.33	15 11.67	35 35.00
Visitor	20 16.67	5 8.33	25 25.00
All	40 40.00	20 20.00	60 60.00
Cell Contents:	Count Expected count		

Table 19. Visitor and resident reasons for river type choice

The tabulated statistics for 'visitor'/'resident' and 'reason for New Forest choice' suggest that both 'resident' and 'visitors' alike chose their 'preferred river type' based on aesthetics rather than function. Thirty one of the 35 'resident' respondents' based their 'reason for New Forest choice' on aesthetics whilst 21 of the 25 visitors also chose aesthetics as the reason behind their choice. Respondents' believed that an aesthetically attractive river was more important than its function in the New Forest as flooding was not an issue in the wilderness.

'Visitor/resident respondents' and their reason for 'urban river choice' show that 20 'resident' respondents' based their reason for choice on aesthetics, whilst 15 'resident' respondents' used the concept of function to influence their decision. Compared with 'visitors' reasons for urban river choice, 'residents' are much more evenly split between aesthetics and function. 'Visitors' have mainly based their choice on aesthetics and in this case have preferred 'River Type B'.

4.1.2. Respondents' 'willingness to accept government funding' for their desired river type

This section explores the amount of money respondents' think is justified for the government/EU to spend on restoring New Forest rivers to their chosen river type. The three categories were chosen on the basis of previous small scale (emergency and preventive) and large scale (enhancement) restoration costs across rural and urban contexts (Forestry Commission, 2008; River Restoration Centre, undated). Many moderate rehabilitation projects range between £1,000 and £10,000 in cost whereas major reach scale restoration costs a lot more - totalling between £20,000 and £50,000.

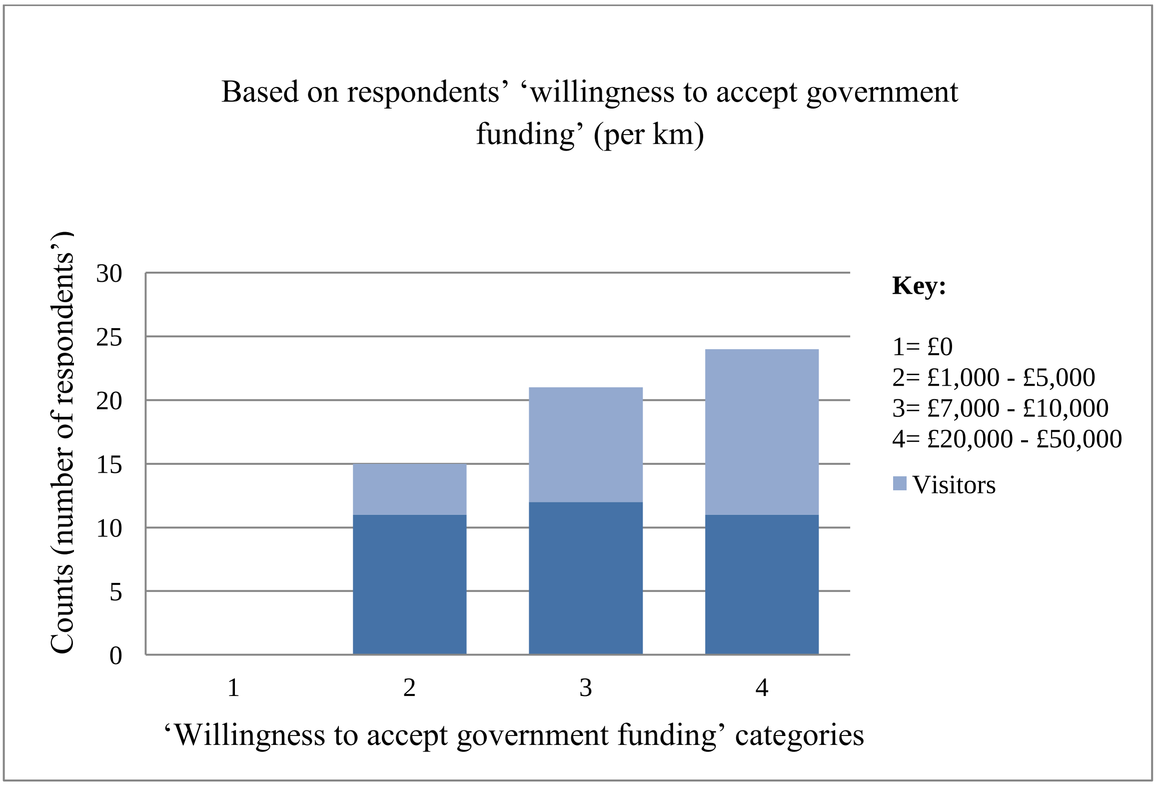


Figure 32. Respondents' 'willingness to accept government funding' for their preferred river type in the New Forest

The respondents were asked to state which of the four proposed categories would best illustrate their 'willingness to accept government funding' (per km) to restore and maintain their preference for either River Type A, B or C within the New Forest. 'Category 4', £20,000 - £50,000 has the highest recorded counts. The chart suggests that people are willing for the government to pay large sums of capital to ensure their preferred 'river type' exists within the New Forest in the future. In fact 45 respondents out of the 60 interviewed are 'willing to accept' more than £7,000 per km. The results suggest that 'visitors' are 'willing to accept' more to ensure that their chosen river type (River Type A) will be restored and preserved in the future. 'Natural beauty' and 'wilderness' of the New Forest is an important factor to tourism in the area which may be why visitors are willing to accept the largest sum of money to restore the area. This is represented in the purpose of visit, visitor tally.

Purpose of Visit	Count (Visitors only)
Natural Beauty	8
Shops	3
Tourist group trips	8
Visit family/ friends	6
	Total = 25

Table 20. Tally for discrete variables: purpose of visit

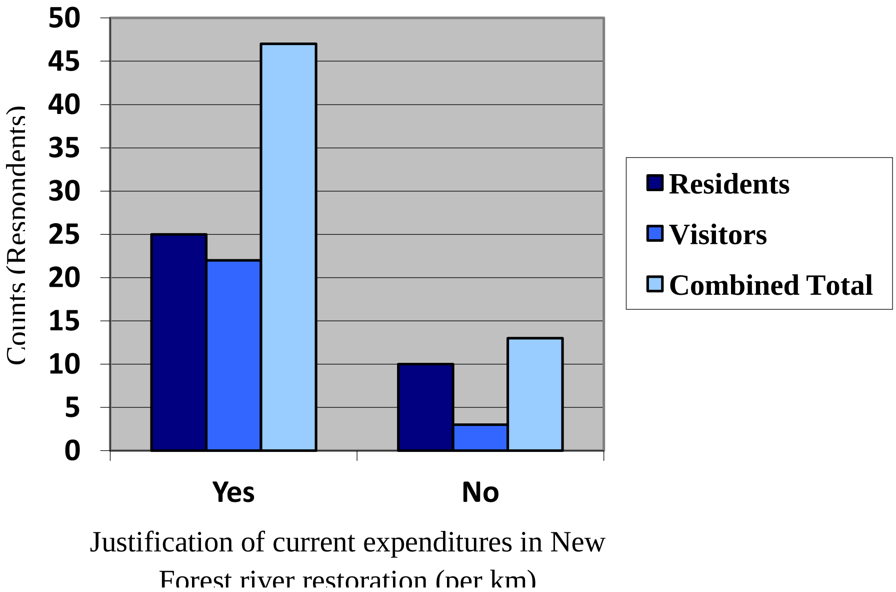


Figure 33. Justification of restoration: residents' and visitors'

The 'justification of restoration' chart displays the data obtained for both 'residents' and 'visitors' regarding their opinions on whether current expenditure in New Forest river restoration is justified. This question was asked after the respondents suggested their 'willingness to accept government funding' to prevent biased answers. The current restoration cost range in the New Forest is £7,000 - £44,000 per reach (Forestry Commission, 2008). This is the cost range that the respondents' had to base their justification on. It is clear to see from the chart that a large proportion (47 out of 60 respondents') believe that the money is being well spent.

Justification	*1*	*2*	*3*	*4*	*All*
Yes	35 27.417	12 9.400	0 6.267	0 3.917	47 47.000
No	0 7.283	0 2.600	8 1.733	5 1.083	13 13.000
All	35 35.000	12 12.000	8 8.000	5 5.000	60 60.000
Cell Contents	Count Expected Counts				
Key: **Columns: Justification Reason:** 1= Protecting the natural environment, 2= Benefit the community (attracts tourists), 3= Too expensive, 4= Money is better spent elsewhere					

Table 21. Tabulated statistics: justification of restoration, justification reason

The tabulated statistics illustrate that 47 of the 60 respondents believe that the money being spent on restoration within the New Forest (per/km) is justified. Thirty five of those respondents believe that 'protecting the natural riverine environment' should be the main driving force behind restoration, whilst 12 respondents believe that restoration will help drive tourism, which in turn will 'benefit the local community'. Thirteen respondents believe that the money being spent on river restoration in the New Forest is not well justified. In fact 8 respondents believe that restoration is far too expensive for the benefits it provides, whilst 5 respondents believe that the governmental money should be spent elsewhere and in other sectors.

4.1.3. Respondents rank order of importance; FES

Respondents were asked to put five riverine FES in order of their 'importance' in the New Forest, with 1 being the most important and 5 being the least. As a guiding principle, researchers used the ecosystem service categories found in the report 'Ecosystems and Human Wellbeing' (MA, 2005). The report outlines four categories of services ecosystems provide to people: provisioning, regulating, cultural and supporting. The results are based on the respondents' opinions alone.

FES 1: Water Quality

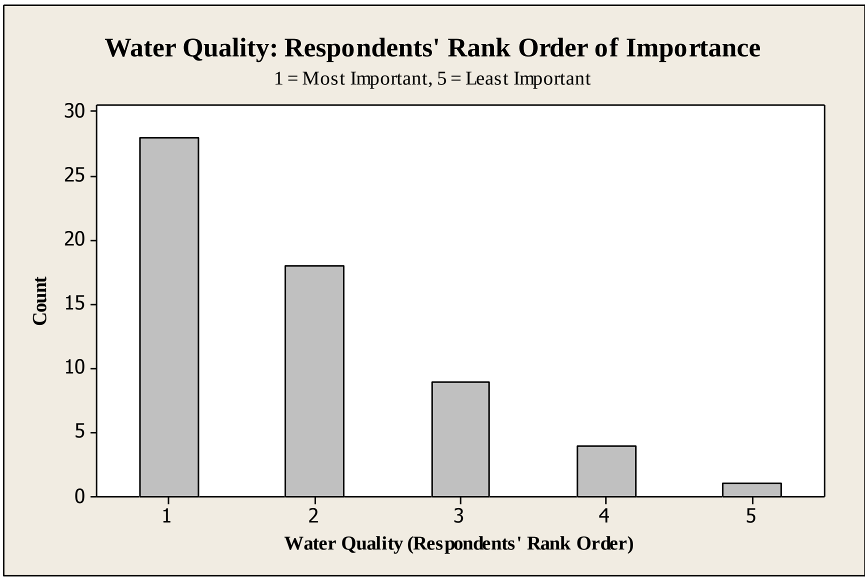


Figure 34. FES 1 Water quality: respondents' rank order of importance

'Water quality' was regarded as one of the most important characteristics for riverine environments by the respondents'. 'Water quality' scored very highly in the ranking system with 28 respondents ranking 'water quality' as the most important FES, and 18 respondents ranking 'water quality' as their second most important FES. There is a clear negative correlation in the results which indicates the decline in counts for 'water quality' in the lower ranked sections (3, 4, and 5).

FES 2: Habitat provision

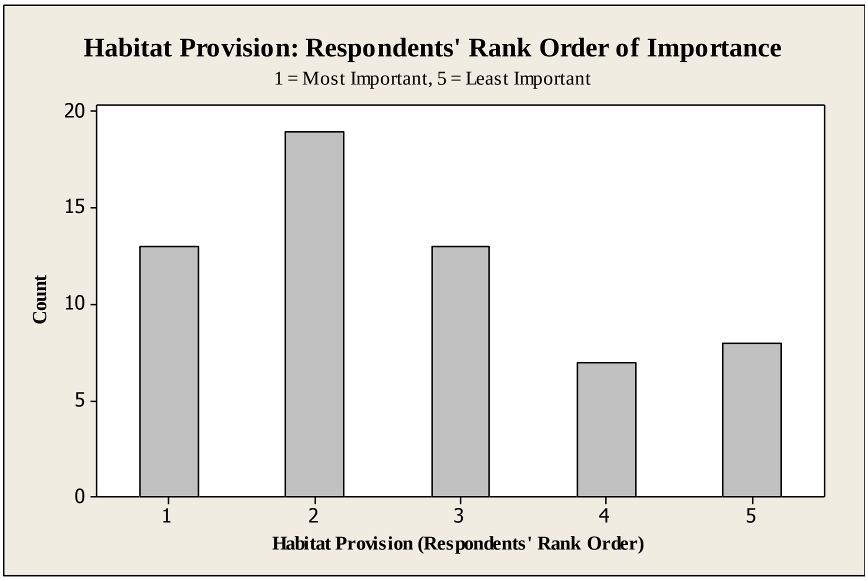


Figure 35. FES 2 Habitat provision: respondents' rank order of importance

'Habitat provision' recieved mixed reviews in terms of 'rank order' from the respondents. The main reason for this was that many respondents made the link that 'habitat provision' would be enhanced if the other FES were improved first. Respondents who made the link recognised that 'habitat provision' would be improved if 'water quality', 'erosion control' and 'flood control' were restored first. This is why 15 respondents ranked 'habitat provision' in 4 (7) and 5 (8). However, those who did not make the link scored 'habitat provision' highly in terms of importance. Thirteen respondents ranked habitat provision as the most important FES whilst 19 respondents ranked it as the second most important FES.

FES 3: Flood control

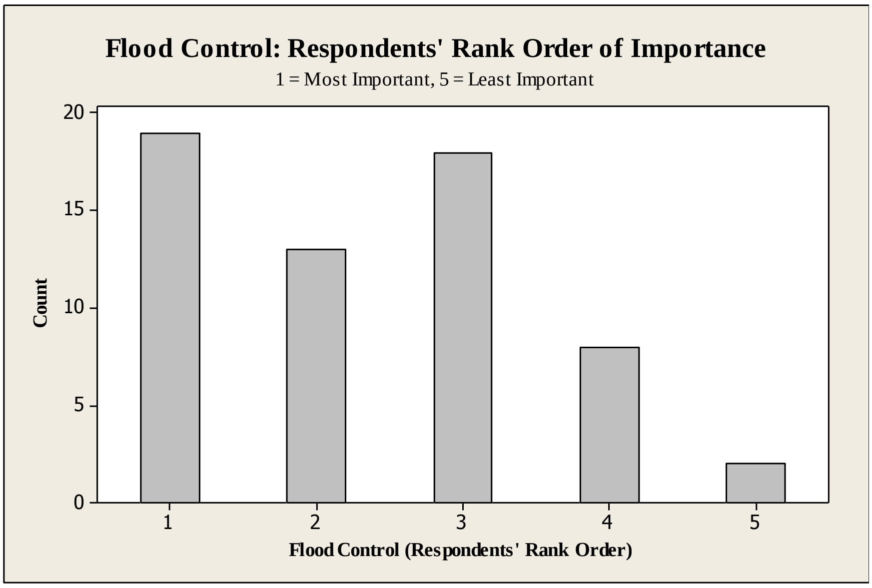


Figure 36. FES 3 Flood control: respondents' rank order of importance

'Flood control' had a mixed response from the respondents but the lowest counts were recorded in rank 4 (8) and 5 (2). The uneven spread of counts makes it difficult to state exactly which rank represents the importance of 'flood control' but the highest number of counts were recorded in rank 1 (19) followed by rank 3 (18). Rank 2 had 13 counts. However, what is clear is that the majority of respondents (50 out of 60) ranked 'flood control' in the top 3 rankings.

FES 4: Erosion control

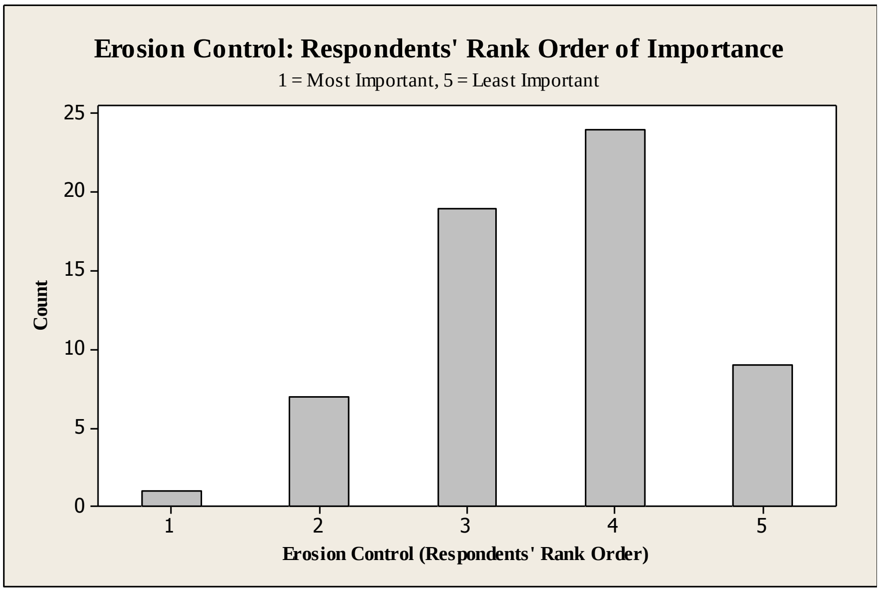


Figure 37. FES 4 Erosion control: respondents' rank order of importance

'Erosion control' was ranked quite low by respondents where the highest total of counts was recorded in rank 4 (24). Rank 3 was second highest with 19 counts and then rank 5 (9) rank 2 (7) and finally rank 1 (1). This provides evidence that respondents did not consider 'erosion control' to be as important as 'water quality', 'flood control' or 'habitat provision'. A vast proportion of the counts recorded in rank 3 are from those respondents who made the 'habitat provision' link. These respondents tended to rank 'erosion control' as the third most important FES after 'water quality' and 'flood control' as it is one of the important factors which will contribute to 'habitat provision'.

FES 5: Carbon storage

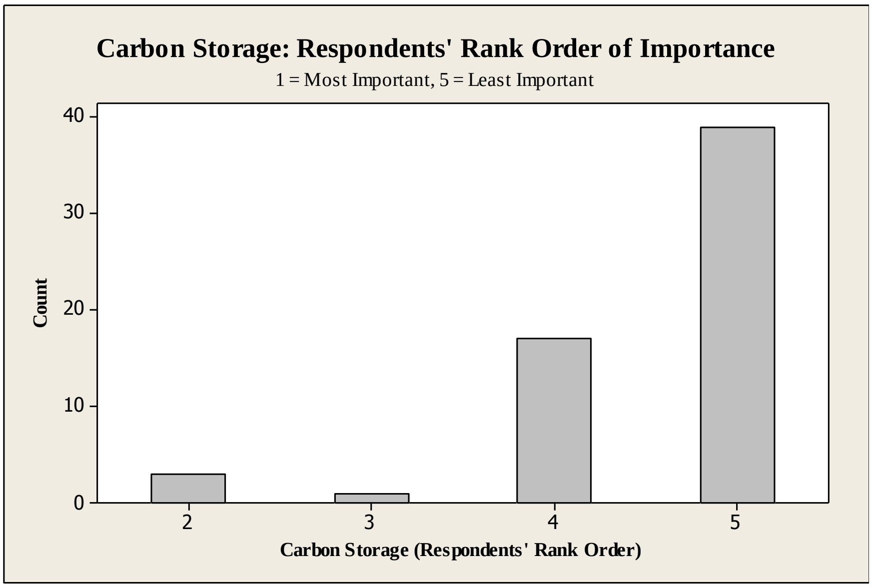


Figure 38. FES 5 Carbon storage: respondents' rank order of importance

'Carbon storage' was considered to be the least important FES by many respondents. The chart displays this trend and it is also worth noting that none of the respondents considered 'carbon storage' to be the most important FES. In fact only 4 respondents put 'carbon storage' in the top three ranks, three of which were rank 2 and one in rank 3. The majority of the respondents ranked 'carbon storage' in ranks 4 (17) and 5 (39).

	Rank 1	*Rank 2*	*Rank 3*	*Rank 4*	*Rank 5*	*Rank of Importance*
Water quality	28	18	9	4	1	*1*
Flood control	19	13	18	8	2	*2*
Habitat provision	13	19	13	7	8	*3*
Erosion control	1	7	19	24	9	*4*
Carbon storage	0	3	1	17	39	*5*

Table 22. FES rank of importance

The rank of importance was calculated by adding the counts up for each rank. The FES with the most counts in the highest rank (rank 1) is the most important and therefore is ranked at the top of the pile. 'Flood control' was ranked above 'habitat provision' because flood control has more counts in rank 3 than in 4 and 5 and less counts in ranks 4 and 5 than 'habitat provision'. However, many respondents recognised that 'habitat provision' would be enhanced if 'water quality', 'erosion control' and flood control' were restored first which may have prevented a true reflection of the relative importance of 'habitat provision' as a FES. This information was found out when respondents' were asked to justify why they ranked the FES in the order that they did.

Tabulated statistics: Water Quality, Visitor/Resident

Row: Water Quality
Column: Visitor/Resident

	Residents	*Visitors*	*All*
1	14 16.333	14 11.667	28 28.000
2	12 10.500	6 7.500	18 18.000
3	5 5.250	4 3.750	9 9.000
4	3 2.333	1 1.667	4 4.000
5	1 0.583	0 0.417	1 1.000
All	35 35.000	25 25.000	60 60.000

Cell Contents: Count
Expected count

Tabulated statistics: Flood Control, Visitor/Resident

Row: Flood Control
Column: Visitor/Resident

	Residents	*Visitors*	*All*
1	13 11.083	6 7.917	19 19.000
2	7 7.583	6 5.417	13 13.000
3	11 10.500	7 7.500	18 18.000
4	3 4.667	5 3.333	8 8.000
5	1 1.167	1 0.833	2 2.000
All	35 35.000	25 25.000	60 60.000

Cell Contents: Count
Expected count

Key:

Rows: Respondents' Rank Order

Table 23. Residents' and visitors' rank order for water quality and flood control

The individual rankings for the top two ranked FES for the New Forest ('water quality' and 'flood control') have been broken down to see if there was a difference in ranking patterns for 'residents' and 'visitors'. 'Water quality' data suggests that rankings were evenly split between 'residents' and 'visitors' alike, with the majority being ranked 1 and then 2.

However, the rankings for 'flood control' show that visitor rankings were spread out evenly between ranks '1', '2', and '3' with '3' having the most ranks. Resident rankings were more focussed in ranks '2' and '3'. However, to generate more precise conclusions between 'resident' and 'visitor' rankings, a larger data set is required. This survey was designed to identify an estimate of 'willingness to accept government funding' and respondents opinions on FES derived from riverine environments so the sample size should be adequate to make these assumptions.

4.1.4. 'Willingness to accept government funding' – percentage ratings for FES

The following charts display the total percentage breakdown of the respondents' 'willingness to accept government funding' for individual FES. For example, if a respondent is willing to accept the government/EU to pay £1,000-£5,000 per km of river restoration, the total cost is further broken down to demonstrate 'willingness to accept government funding' rating (x axis) for each of the individual FES. Therefore, if a respondent is willing to accept £1,000-£5,000 per km, then an average value of £3,500 was selected to represent its range. As part of the survey, respondents had to illustrate in a percentage breakdown for what they were willing to accept for each FES. If a respondent suggested that 30 percent of the total cost was for restoring 'water quality' that would equate to £1,050 per km.

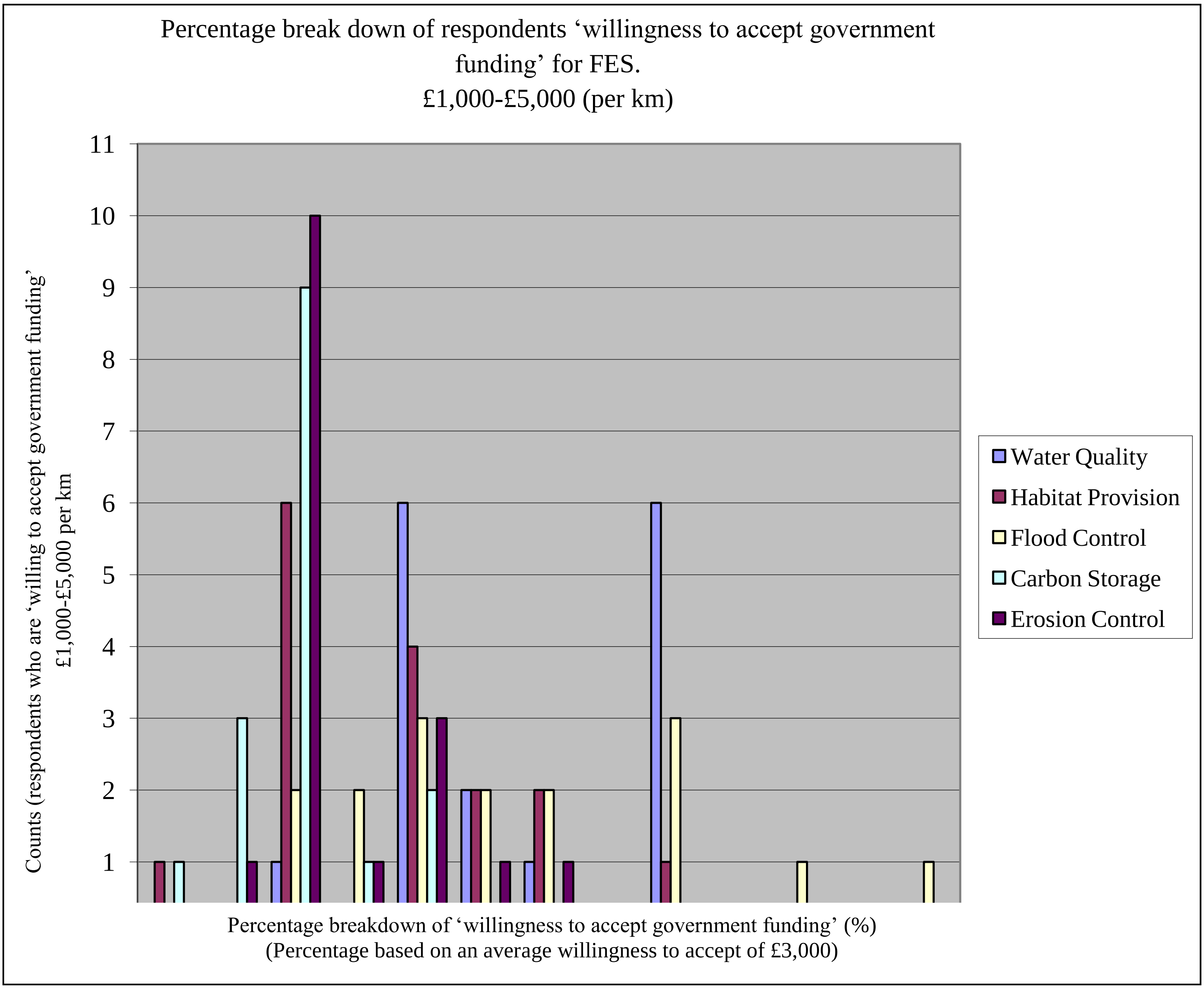


Figure 39. Percentage break down of respondents 'willingness to accept government funding' for FES.

£1,000-£5,000 (per km)

FES	Summary	Willingness to Accept (£)
Water quality	'Water quality' generally had a high percentage rating compared to other FES in the category of £1,500-£5,000. Six respondents gave it a 40 percent rating which means that they are willing to see £1,200 per km spent on enhancing or preserving 'water quality'. The other popular percentage was 20 percent which suggests people are 'willing to accept' £600.	£600-£1,200 (Average: £900 per km)
Habitat provision	'Habitat provision' percentages are spread out between 10 percent and 30 percent but the majority were recorded at 10 percent and 20 percent (10/16 respondents). The rest of the votes were split between 0, 25 percent, 30 percent and 40 percent. The 10 percent rating means that people are willing to see the government spend £300 per km on enhancing or preserving 'habitat provision'. The 20 percent rating suggests people are 'willing to accept' £600 per km to restore habitat.	£300-£600 (Average: £450 per km)
Flood control	'Flood control' is evenly spread throughout many of the percentage categories. However, some respondents gave 'flood control' the highest percentage rating (40-60 percent) of all the FES for category £1,500-£5,000. Because the percentage records have a large range, the 'willingness to accept' for 'flood control' is based on the median percentage which is 25 percent.	(Average Median: £875 per km)
Erosion control	Ten out of 16 respondents ranked 'Erosion control' at 10 percent. The remaining respondents gave 'erosion control' percentages between 5 percent and 30 percent with the second highest percentage being 20 percent (3 respondents).	(Average: £350 per km)
Carbon storage	Nine out of 16 respondents gave 'carbon storage' a percentage rating of 10 percent. The highest percentage rating for 'carbon storage' was 20 percent which suggests that respondents were not happy to allow high spending for this FES. The other percentage ratings were recorded between 0 and 20 percent with the second highest rating being 5 percent.	(Average: £350 per km)

Table 24. Summary table for 'willingness to accept government funding' £1,500-£5,000 (based on 16 respondents)

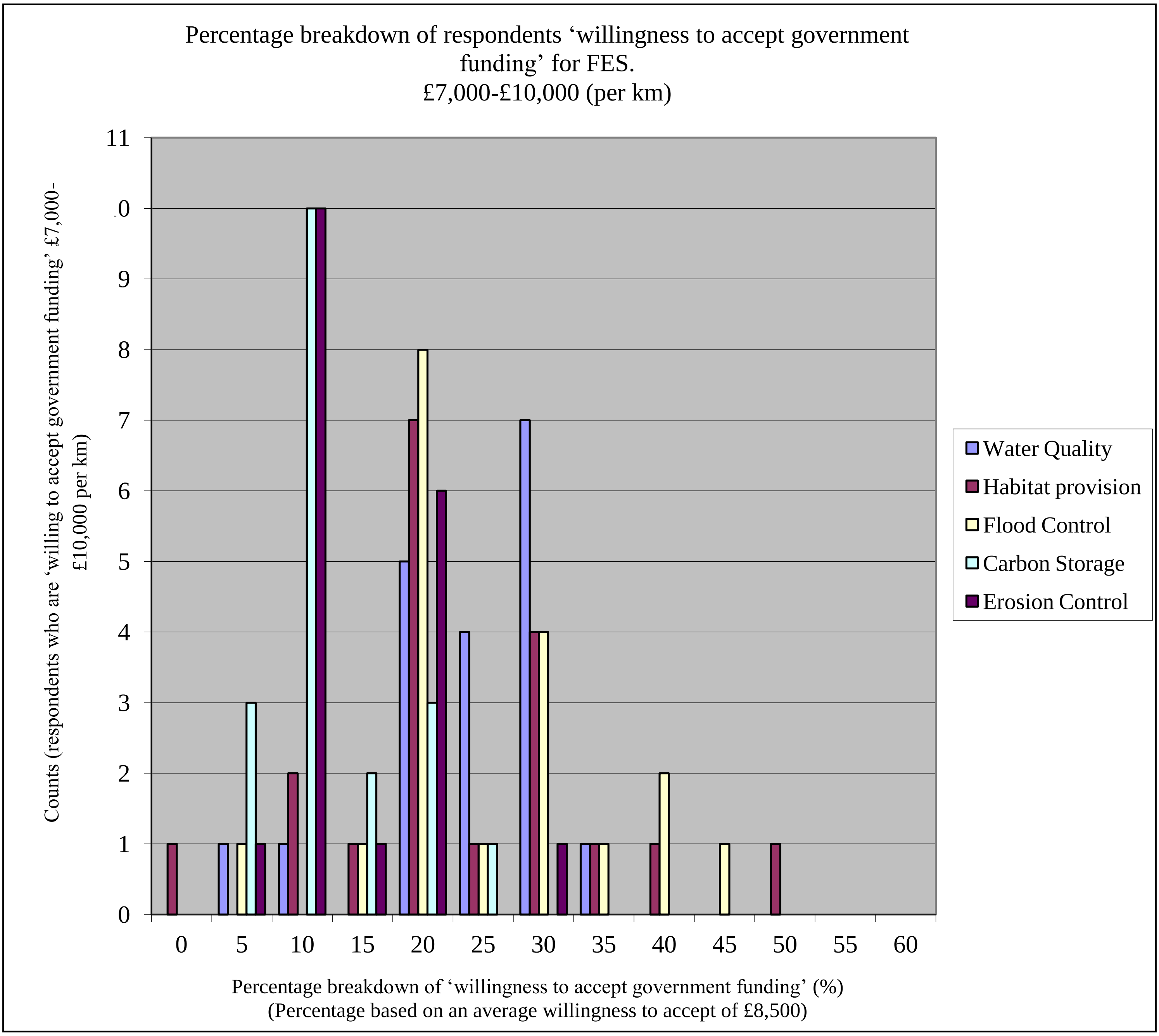


Figure 40. Percentage breakdown of respondents 'willingness to accept government funding' for FES.
£7,000-£10,000 (per km)

FES	Summary	Willingness to Accept (£)
Water quality	Many respondents (16/19) who were happy to see £7,000-£10,000 for their chosen New Forest river type gave 'water quality' a percentage of 20-30 percent with 30 percent being the most popular (7/19).	£1,700-£2,550 (Average: £2,125 per 1 km)
Habitat provision	Seven out of 19 respondents gave a percentage rating of 20 percent for 'habitat provision'. The second highest percentage rating is 30 percent (4/19). The range of percentage ratings is widespread for 'habitat provision' reflecting that some of the respondents' recognize that by restoring/enhancing the other FES, 'habitat provision' will improve as a result.	(Average: £1,700 per km)
Flood control	Eight out of 19 respondents gave 'flood control' a percentage rating of 20 percent. A single count for 5 percent, 15 percent, 25 percent, 35 percent and 45 percent was recorded and 2 counts were recorded at 40 percent with the second highest percentage rating being 30 percent (4/19).	(Average: £1,700 per km)
Erosion control	'Erosion control' has also been given quite a low percentage rating by respondents in this category. The majority of respondents (10/19) have given 'erosion control' a percentage rating of 10 percent. However, 6 respondents also have given 'erosion control' a percentage rating of 20 percent. The average 'willingness to accept' is therefore between 10 percent and 20 percent which is £1,275 per km.	£850-£1,700 (Average: £1,275 per km)
Carbon storage	'Carbon storage' has been given a low percentage rating by respondents in this category which is illustrated by just one respondent giving it a percentage rating above 20 percent. The majority of respondents (10/19) have given 'Carbon storage' a rating of 10 percent.	(Average: £850 per km)

Table 25. Summary table for 'willingness to accept government funding' £7,000-£10,000 (based on 19 respondents)

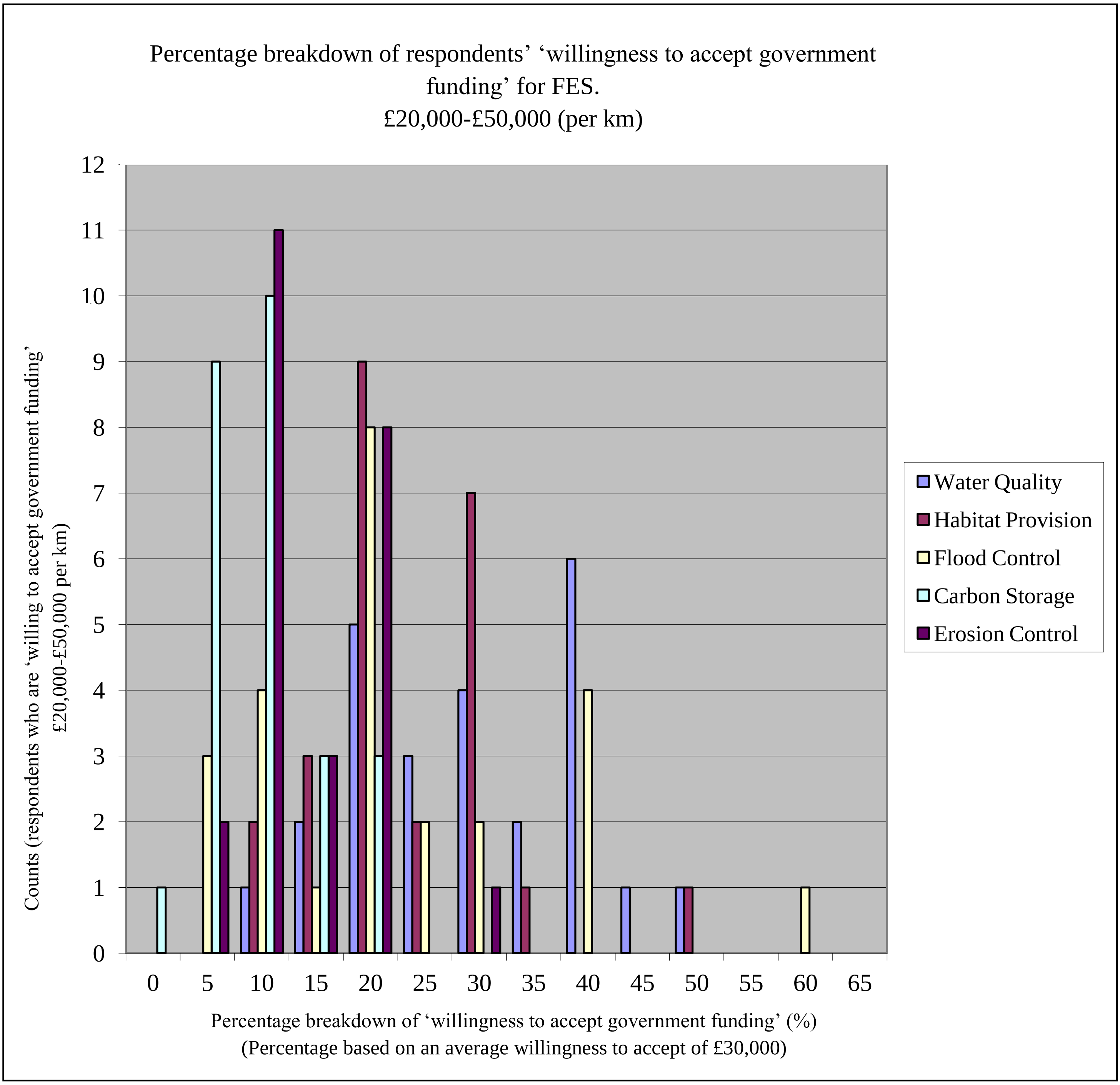


Figure 41. Percentage breakdown of respondents' 'willingness to accept government funding' for FES.
£20,000-£50,000 (per km)

FES	Summary	Willingness to Accept (£)
Water quality	The percentage ratings for 'water quality' are widespread with the majority recorded between 20 percent and 40 percent. 'Water quality' has a mean average of 30 percent. This suggests that on average respondents' are 'willing to accept' the government/EU to pay £9,000 per km for 'water quality' enhancement.	£6,000-£12,000 (Average: £9,000 per km)
Habitat provision	The majority of percentage ratings for 'habitat provision' for the category £20,000-£50,000 are 20 percent and 30 percent. Nine out of 25 respondents have given 'habitat provision' a percentage rating of 20 percent, whilst 7/25 respondents have given 'habitat provision' a percentage rating of 30 percent. Therefore, including those who have given a percentage rating of 25 percent (2/25), 18/25 respondents are 'willing to accept' payments of between £6,000 and £9,000 per km.	£6,000-£9,000 (Average: £7,500 per km)
Flood control	'Flood control' has a wide range of percentage ratings. One respondent gave it a 60 percent rating whilst 7 respondents gave it a ranking between 5 and 10 percent. The majority of respondents for the category £20,000-£50,000 have given 'flood control' a percentage rating of 20 percent (8/25) with 4 respondents giving 10 and 40 percent ratings. The percentage ratings illustrate the respondents' divide in opinions with regards to the importance of 'flood control' in the New Forest.	£3,000-£12,000 (Average: £6,000 per km)
Erosion control	'Erosion control' has been given a percentage rating of 10 percent and 20 percent by the majority of respondents (19/25). Eleven out of 25 respondents gave a percentage rating of 10 percent whilst 8/25 respondents gave a 20 percent rating. The average 'willingness to accept' is therefore calculated as £4,500.	£3,000-£6,000 (Average: £4,500 per km)
Carbon storage	'Carbon storage' has a low percentage rating for this category of respondents'. 19/25 respondents have given a percentage rating of 5-10 percent. The highest percentage rating given was 20 percent (3/25).	£1,500-3,000 (Average: £2,750 per km)

Table 26. Summary table of 'willingness to accept government funding' £20,000-£50,000 (based on 25 respondents)

		‘Willingness to accept government funding’ (average per km)		
Rank of Importance	**FES**	**£1,000-£5,000**	**£7,000-£10,000**	**£20,000-£50,000**
1	Water quality	£900	£2,125	£9,000
2	Flood control	£450	£1,700	£7,500
3	Habitat provision	£875	£1,700	£6,000
4	Erosion control	£350	£1,275	£4,500
5	Carbon storage	£350	£850	£2,750

Table 27. Summary table for respondents’ ‘willingness to accept government funding’ for New Forest FES

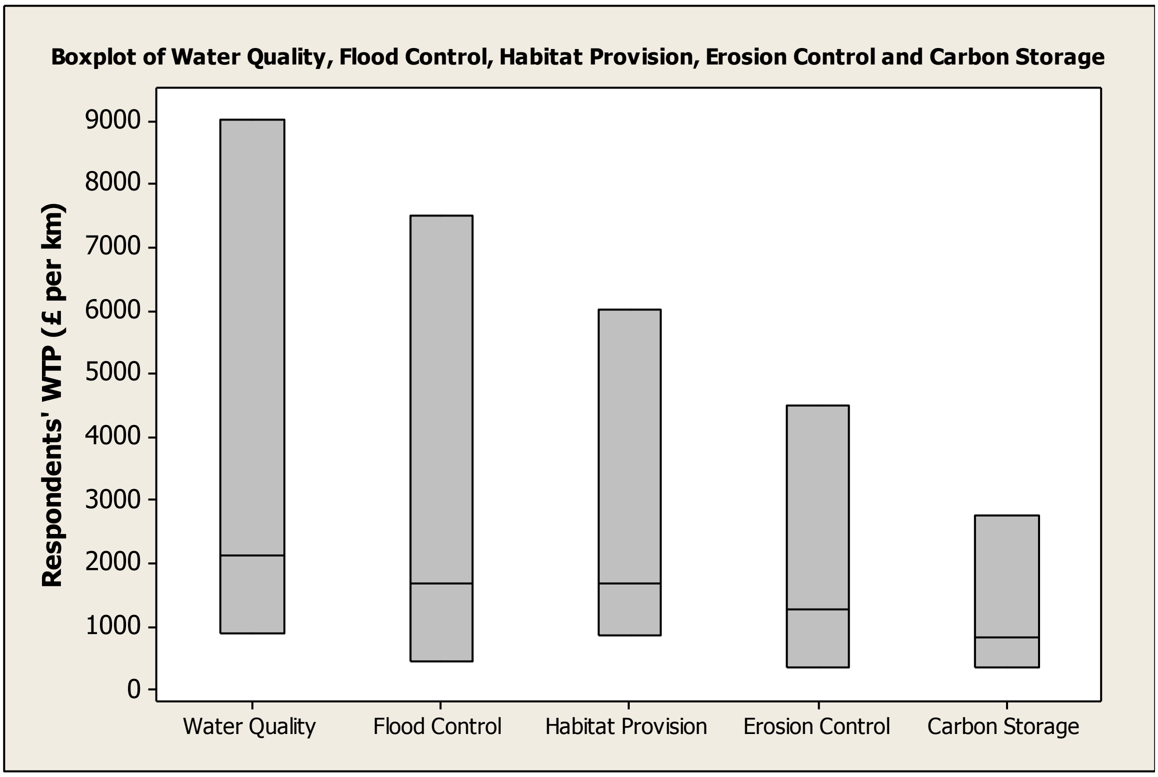


Figure 42. The ranges of capital respondents’ are willing for the Government/EU to pay to restore five FES

The summary table provides figures for the average 'willingness to accept government funding' to sustain and improve the delivery of individual FES. The results confirm that the 'willingness to accept government funding' correlates with the 'rank of importance', suggesting more people are willing for the government/EU to pay more to restore higher ranked FES such as 'water quality' and 'flood control'. However, to improve the validity of the data perhaps we should have added another 'willingness to accept government funding' column to the survey with a value of £70,000-£100,000 for example. This would enable us to see if respondents' who are 'willing to accept' £20,000-£50,000 are willing to accept higher funding.

4.1.5. A Summary of the indirect data

The indirect value survey has provided evidence that the following hypothesis number one is true:

1. The general public *do* value 'geomorphological diversity' and that they are willing to accept government/EU funding to enhance and restore GF for 'non-use' and 'option value' 'benefits' which derive from FES

This survey provides evidence that the general public in the New Forest are willing to accept the government/EU to fund and sustain naturally functioning rivers and restore the ones that are degraded. This is backed up by evidence which suggests that the majority of respondents favoured 'River Type A' and are 'willing to accept government funding' to restore this river type. The survey also provides evidence that the general public support an ecosystem service approach in riverine environments as they are 'willing to accept' funding to deliver a collection of ecosystem services. However, river aesthetics was a large factor in many of respondents' river type choice. Therefore, it is difficult to be certain that respondents' didn't just chose 'River Type A' for its aesthetic appeal, which itself is not a FES but a benefit derived from FES.

The monetary values given to the FES help represent the respondents belief that the delivery of 'water quality' and 'flood control' are the most important FES for river ecosystems to deliver. The monetary values generated through 'willingness to accept government funding' are not the values that each individual respondent would willingly pay themselves, but instead are the values that respondents think the government/EU should pay to restore GF and deliver FES. The results from this study suggest that people want naturally functioning rivers in the New Forest with a wide range of ‘geomorphological functions’ interacting to provide the platform for the delivery of a collection of ecosystem services. However, many respondents’ said that they found ‘River Type A’ more appealing as they find meanders, vegetation and riffle-pools more attractive and exciting to look at than a straightened or culvert reach that has been cleared of its natural riparian vegetation. Therefore, many ‘geomorphological functions’ were favoured by respondents’ for their aesthetic value rather than how they function.

‘River Type B’ was the most popular choice for an urban environment. The reason given by many respondents’ for choice of ‘urban river type’ was based on aesthetics (‘green areas’) rather than function of the river type, but many also suggested the most important function of the urban river is to be an efficient conveyor of floodwater. However, respondents’ who chose ‘River Type C’ assumed that ‘River Type C’ was more practical and functioned better at transporting water through an urban environment including reducing the flood potential. This survey certainly suggests that aesthetic value is a major benefit derived from ‘geomorphologically diverse’ rivers.

4.2. Restoration survey – defining the values of GF

This chapter attempts to highlight the potential monetary cost to restore and create improved natural conditions in lowland riverine environments. River restoration largely influences the ‘Geomorphological Functions’ of riverine environments and has been used to determine the value for geomorphological processes and form.

4.2.1. Direct cost of restoration

The generic charts in this section exemplify how and where capital is spent on restoration projects. The various stages of restoration are highlighted within this section along with cost estimates for individual channel restoration. The data is based on UK restoration cost estimates from the ‘River Restoration Centre’ and consider the cost for the following stages of restoration:

1. **Scoping study:** involves making decisions on how the project should be taken forward such as identifying the scale of the project, identifying stakeholders and land owners who are affected by the underlying problems, identifying appropriate techniques and devise a plan of action.

2. **Data gathering:** involves undertaking a habitat survey and/or a fluvial audit for a problematic reach so that a detailed analysis can be made. Historical data identifies changes on a temporal scale. The information from the audit will help identify the underlying factors and root causes of problematic erosion or deposition. This section is fundamental for sustainable restoration.

3. **Design and preparation:** employs the use of fluvial audit data to make decisions on how to tackle problematic reach scale problems. The restoration design will aim to work with nature, not against it like previous channelisation projects. A scientific approach is employed within the design stage of restoration. Natural conditions promote a long-term plan that creates an aesthetically pleasant environment as well as retaining the physical habitats that are central for a bio-diverse ecosystem (Sear, Newson & Thorne, 2003).

4. **Implementation:** the total cost for construction can significantly increase due to the extent of design specifications, site and contract preparation. Construction type contracts can be a lot more expensive than equipment rental contracts and the results can be less than acceptable.

5. **Measures:** is the total amount of material moved. It includes excavation of sediment as well as the augmentation of materials.

6. **Monitoring:** A detailed observation of the geomorphologic and hydraulic processes once the implementation stage of the restoration project is complete is essential in determining and testing hypothesis. As ‘applied’ fluvial geomorphology is a relatively new discipline, many restoration projects are the first of their kind and require continual detailed monitoring to highlight the effects of restoration techniques.

The cost for various restoration items in Table 28. is based on average costs for that particular item over numerous projects throughout 2004/2005. The prices are exclusive of VAT. These costs are incorporated into the generic estimates (as explained later on in this section) as part of the implementation costs.

River Restoration Works	Cost
Machine hire	
13 tonne excavator	£27 per hr/£400 per day
7 tonne excavator	£26 per hr
5 tonne excavator	£17.94 per hr
Excavator transport	£125 per move
6 tonne tracked dumper	£150 per day
8 tonne tracked dumper	£185 per day
Dumper transport	£85-90 per move
Pumps & hoses	£74 per day/£8.75 per hour
Delivery/Pick up of pumps & hoses	£40 per move
Fuel Bowser (2000L)	£60 per week
Material Costs	
Clay	£7.50 per tonne
Gravel	£7.60 per tonne £11.39 (20/40 angular)
Oversized rejects	£11.39- 14.21 per tonne
Hoggin	£7.10
Chestnut Posts	£1.50
Fuel	£0.30 per litre (plant diesel)
Labour	
Contract	£120 per day
Sundries	
Spill kit	£65
Oil absorbent booms	£85 –95 per pack
Portable toilet	£26 per week
Portable toilet transport	£20 delivery + collection
Mess cabin	£64 per month

Table 28. Average cost for items commonly required during river restoration (New Forest Life Partnership, 2006-2016b).

4.2.2. Restoration of GF; Delivering FES

The final outcome of many restoration projects will impact the 'provision', 'regulation' and 'support' of multiple FES. By adjusting the channel form to more natural conditions, many geomorphological, hydrological and ecological processes will be altered. However, the analysis for this research is focussed on the role of 'geomorphology' and how GF influence the delivery of FES on a reach scale as explained in chapter 2. The exact nature in which geomorphology can affect the delivery of FES will be explored in more detail once the framework is applied to case studies.

To demonstrate how geomorphology can impact the delivery of FES, the ‘geomorphological framework’ will be applied to a hypothetical cost restoration case study and a real life restoration case study in the New Forest. By applying the ‘geomorphological framework’ introduced in chapter 2, restoration techniques help identify the associated ‘benefits’ derived from FES once GF have been restored. Pre-restoration conditions (degraded geomorphological conditions) as well as post-restoration conditions (restored geomorphological conditions) are recorded so that we can clearly identify the impacts of GF restoration and the delivery of FES.

The restoration techniques that have been approved for this hypothetical case study have been generated through ‘data gathering’ and ‘design and preparation’ before ‘implementation’ was carried out. This is necessary if the aims are to achieve sustainability in conjunction with natural processes and form. It must also be noted that changes to FES will undoubtedly occur at various time scales once the restoration of ‘geomorphological functions’ are completed. Once the ‘implementation’ stage is completed, a lag time is going to prevent immediate economic ‘benefits’ as it will take time for the restored reach to re-establish.

Reach-scale restoration must be compatible with the geomorphological context of the catchment to ensure sustainability (Downs & Thorne, 1998). The distinction between ‘processes and ‘form’ must also be recognised. Although the cost analysis that is carried out in the ‘geomorphological framework’ is based on restoring geomorphological ‘form’, it is the restoration of geomorphological ‘processes’ that will distinguish whether the restoration design will become a success. Monitoring is essential to ensure that the restored reach can establish its potential.

4.3. Hypothetical cost example: Reconnecting a channelised reach with its floodplain

This hypothetical example aims to highlight the range of values given to GF. The natural hydromorphology of this reach has been adjusted largely through human modifications which have altered the flow regime, water flow, sediment transport and morphology of the river channel including its ability to freely migrate across its floodplain. This hypothetical example will try to help illustrate the cost of large scale restoration projects whilst indicating the variability of GF values and FES.

The hypothetical river reach under investigation is located at the middle course of the river system. Historical research has identified that the reach originally was a gravel bed river which meandered through the valley floodplain. Extensive changes in conjunction with agricultural land use has degraded the dynamic nature of the stream and impacted the morphological features you would expect to see in a 'geomorphologically diverse' river. Pre-restoration land management at this reach was arable farming with one farm occupying the floodplain of the reach.

Pre-restoration channel characteristics:

Wetted perimeter:	8 metres
Floodplain land-use:	Arable farming both sides of the channel, occupying 2km of floodplain
Sediment source:	Cultivated farmland

Table 29. provides an overview of the 'benefits' produced at the reach before restoration. Pre-restoration includes the total income based on average farm business income per £/farm 2009/2010 which is £41,000 (Defra, 2010b). It is important to note that only the fields adjacent to the river are largely influenced by stream restoration.

Pre-restoration FES	Benefit	Benefit (per annum)
Provision of food	Agricultural output.	£41,000
Irrigation	Fresh and constant water supply to crops in adjacent fields. Lower flow in stream due to water extraction.	Saved pumping costs.
Flood control (localised)	The channelised river (over-widened and over-deepened) channel prevents agricultural land from becoming flooded.	Lower localised flood risk damage costs (£ ha^{-1}) particularly crop damage.

Table 29. Relationship between FES and benefits before restoration

A systems approach has been taken so that the multiple FES that can be delivered at this reach are identified. Table 30. provides a summary of pre-restoration degraded FES for this reach and describes potentially how the problems have come about. This type of land management is unsustainable as many FES are being degraded ‘indirectly’ from the process of delivering ‘provision of food’.

Degraded FES	Problem
Water quality	Poor water quality caused by eutrophication from agricultural run-off.
Habitat provision	Loss of habitat due to agricultural practice. The removal of floodplain and riparian vegetation has occurred to maximise agricultural land use. Seasonal semi-wetlands (flooded land adjacent to the river channel during peak discharge) are no longer present due to channelisation. The straightened channel combined with substrate removal and fine sediment deposition has degraded fish habitat. The flow, substrate and sources of cover are vital for the survival and reproduction of many fish species.
Flood control	Over-widened and incised channel along with regulated flows from an upstream dam has caused a loss of floodplain

	interactions. Loss of semi-wetland habitat and flood water storage, generating a higher discharge downstream (increasing flooding risk).
Sediment dynamics (sources and sinks)	Problematic sedimentation deposition is characteristic of this straightened channel. Intense arable farming has been known to elevate sediment yields in the middle reaches of rivers such as this one (Quine & Walling, 1991). Dredging sediment to lower the bed and increase stream capacity is undertaken annually to prevent overbank flow and the flooding of arable land during winter months. The over-widened channel combined with agricultural land-use has caused a decrease in sediment size and compaction.
Erosion control	Bank slumping and in some cases bank collapse has occurred. The main reason for bank collapse is because livestock have access to the river side which when combined with the removal of riparian vegetation has slumping.
Carbon sequestration	The removal of floodplain and riparian vegetation combined with the loss of lateral floodplain interactions has reduced the land's capacity to sequester carbon as wetlands and woodlands are very efficient carbon sinks.

Table 30. A summary of the depleted FES for the generic case study

Based on the evidence so far, only a select few FES are being managed at this reach, therefore causing others to become degraded as they do not directly enhance the delivery in providing food. An 'ecosystem approach' requires a systematic approach which considers the whole system, not just a singular or a select few of the potential FES. This type of pre-restoration management is an example of exploitation economics which can result in maximising the 'benefits' of one service whilst neglecting others. A system level consideration may lead to the generation of different outcomes resulting in multiple FES and more 'benefits' as a consequence. A systems approach has been taken when exploring the relationships between restoration, geomorphology and FES during this hypothetical cost example. Pre-restoration geomorphological conditions are demonstrated using the 'geomorphological slider' concept.

Geomorphological slider: Pre-restoration

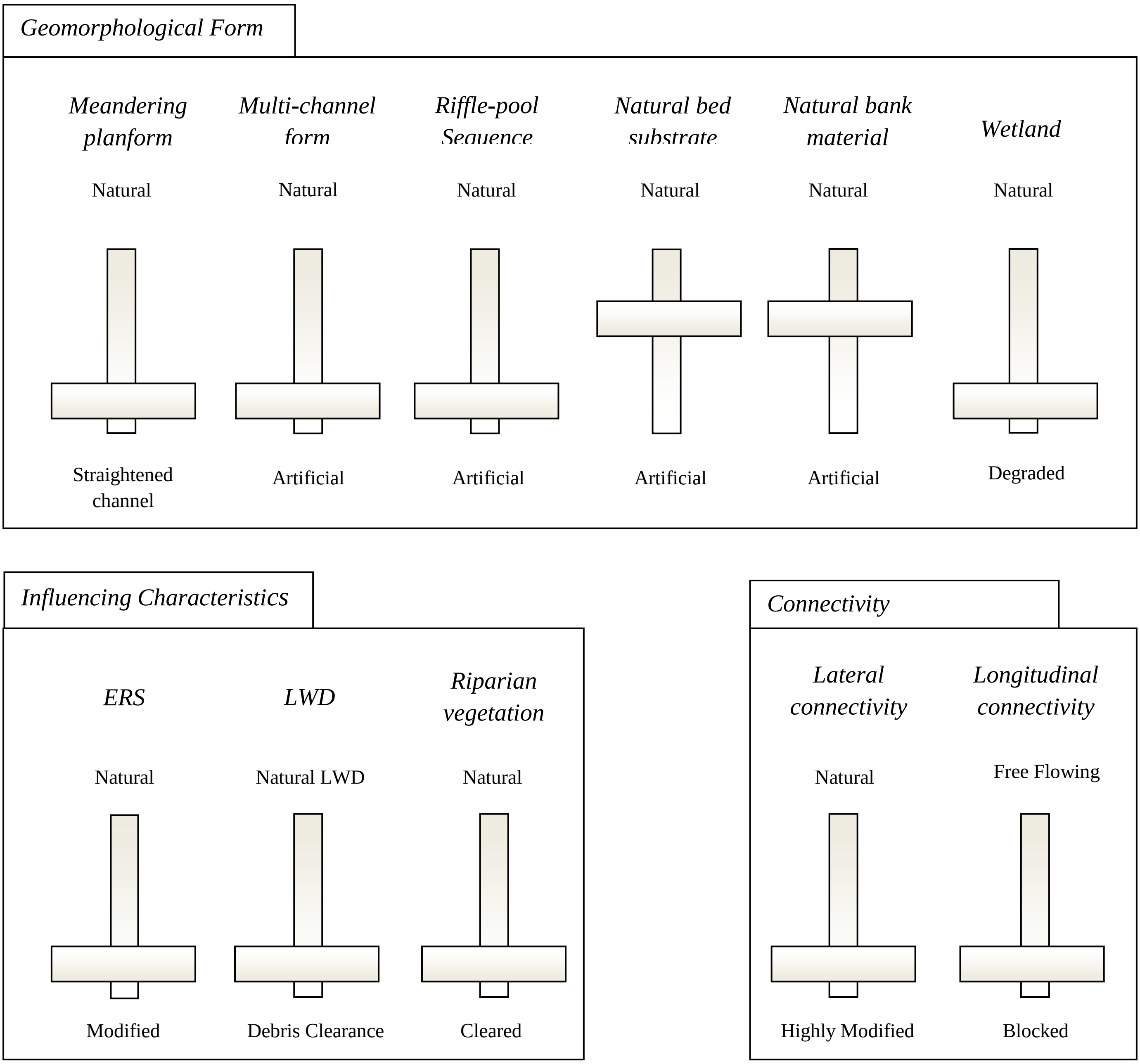


Figure 43. Geomorphological slider representing the condition of the hypothetical pre-restoration GF

Restoration:

Table 31. contains the techniques implied to restore the degraded reach. Table 31. also displays the desirable geomorphological changes for this particular reach as a result of the restoration techniques employed.

Restoration techniques	**Post-restoration geomorphological processes**
• Upstream small scale dam removal (x2) at old mill site. • Introduction of LWD. • Re-installation of a meandering planform. • Bed regrading and channel resectioning. • Introduction of riparian buffer strips between agricultural land and the channel.	Potentially desirable geomorphological process changes: • Erosion and deposition in the floodplain caused by overbank flow. • Sediment deposition altered with more sediment deposited upstream of debris dams than downstream of dam. • Formation of a semi-wetland floodplain. • Natural deposition and erosion due to natural bank and bed substrate. • Lower soil erosion rates leading to less fine suspended sediment in stream.

Table 31. Restoration techniques and their impact on geomorphological processes

Table 31. provides a general summary of how restoration impacts ‘sediment dynamics’ and ‘geomorphological processes’ for this particular reach. Table 32. provides a summary of the FES impacted by restoration. The relationship between ‘geomorphology’ and ‘ecosystem services’ will be discussed in more detail later on in the chapter.

Post-restoration FES (approximately 5-10 years after restoration due to high levels of disturbance):

GF (Post-restoration)	**Impacted FES (Post-restoration)**
Geomorphological Characteristics • Established riffle-pool • Natural bed substrate (buffer strip prevents some of the fine sediment entering the channel) *Influencing Characteristics* • LWD • Riparian vegetation (buffer strip) *Connection* • Lateral connection • Longitudinal connection	• Flood control • Habitat provision (in channel, out of channel) • Erosion control • Water quality • Carbon sequestration • Sediment dynamics

Table 32. Hypothetically impacted GF and FES.

It is clear to see that six FES are impacted by reach scale geomorphological restoration. However, the listed FES are the supporting and regulating services which are impacted by GF. Details on how the re-introduction of natural geomorphological processes and form (GF) through the aid of reach scale restoration will be explored in the following section along with delivering FES.

The ‘geomorphological slider’ (Figure 44) provides an illustrative overview of the impact from restoration on GF. It is important to note that the slider is only a visual tool used to illustrate the main impacts of restoration practices. It is noticeable that restoration moves the river to a more natural condition (for this given river context). For example, invasive vegetation species characteristic of drier soils have been cleared allowing native species to re-populate the riparian corridor (hence the large shift in the ‘riparian vegetation’ slider towards natural conditions). Vegetation succession occurs during high flows once banks are breached as a result of floodplain reconnection. Restoration has improved both lateral and longitudinal connectivity due to the removal of two dams at old mill sites along with bed raising and LWD installation in forested section of the stream.

Geomorphological slider: Post restoration

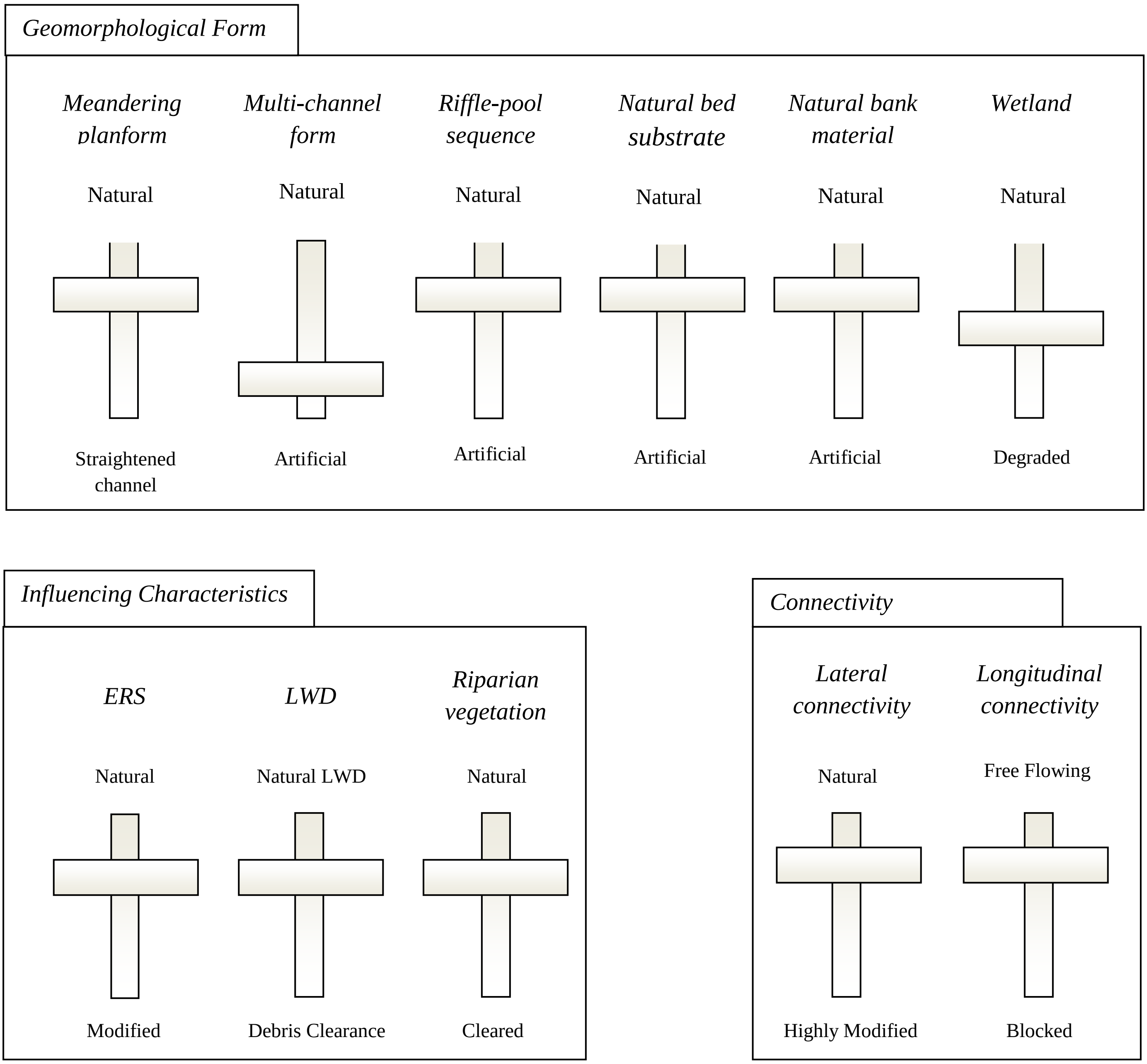


Figure 44. Geomorphological slider representing the condition of the hypothetical post-restoration GF

All but one geomorphological form is impacted by the restoration. This is because it remains a single channel river due to continued arable land use beyond the riparian buffer strip. However, fencing has provided bank stability and keeps livestock away from the river corridor. A systems approach to restoration aims to help balance ‘provision of food’ with improving the quality and delivery of multiple FES. Understanding the past allows causes of change to be identified, such that restoration practices can address these causes (e.g.

Montgomery, 2008; Spink *et al.*, 2009). In this hypothetical example, historical research has identified that a meandering planform was a distinctive feature at this reach before anthropogenic disturbance. The re-introduction of a meandering planform has generated a platform for riffle/pool sequences in slow and fast flowing sections of the channel.

Tables 34a. provides information on the restoration technique applied and the influence of restoration on the geomorphology. Table 34b. provides details on the impacted/ restored GF whilst highlighting the impact on the delivery of FES using a weighting system demonstrated in Table 33. (Defra, 2007a).

Score	Score Assessment Effect
++	Potential significant positive effect
+	Potential positive effect
O	Negligible effect
-	Potential negative effect
--	Potential significant negative effect
?	Gaps in evidence/contention

Table 33. Likelihood of impact weighting system (Defra, 2007a)

Restoration Technique	Characteristics	Geomorphological Influence on FES
Re-installation of a meandering planform	• Reforming the rivers meandering planform through its broad floodplain. • This particular river is relatively stable with little movement across the floodplain (as represented by historical data).	• The planform influences the formation of morphological features which provide valuable habitat. • An asymmetric profile with point bars (deposition) and pools (erosion). • Provides the planform and bend curvature for scour pools and riffles influencing sediment dynamics.

Table 34a. Linkages between restoration of a meandering planform and the delivery of FES

Geomorphological Function GF	Marginal FES	Score
Meandering Planform (*Geomorphological Form)*	Provision of food Water quality Flood control Habitat provision Erosion control Sediment dynamics Nutrient retention Carbon sequestration	- ++ ++ + ++ ++ +/? O/?

Table 34b. Summary table representing the FES influenced by a meandering planform

A meandering planform with a sinuosity of 1.4 has been re-introduced to this reach. The potential impacts of this particular geomorphological function and its relationship with the delivery of a collection of FES are displayed in Table 33b. The 'meandering planform' creates a positive impact to 6/8 FES at this particular reach.

Restoration Technique	Characteristics	Geomorphological Influence on FES
Installing riffle-pool sequence	• Riffles are locally raised gravel and cobble deposits that form shallow areas in the local long-profile characterised by fast flows and formed by the scour of an upstream pool (Sear *et al*., 2010). • In natural riffle-pool sediment is transported between pools over the intervening riffle (Sear *et al.*, 2010). • Riffle reconstruction involved adding gravel to the river bed from pools.	*Riffles:* • The accumulation of coarse sediment provides aeration at low flows (Sear *et al*., 2010). • The coarse substrate provides a spawning ground for fish (salmonid). • Provide habitat for fish and invertebrates *Pools:* • Backwater pools are characterised by low velocities which support fish habitats.

Table 35a. Linkages between restoration of riffle-pool sequences and the delivery of FES

Geomorphological Function GF	Marginal FES	Score
Riffle-Pool Sequence (*Geomorphological Form)*	Provision of food	O
	Water quality	+
	Flood control	+
	Habitat provision	++
	Erosion control	++
	Sediment dynamics	++
	Nutrient retention	O
	Carbon sequestration	O

Table 35b. Summary table representing the FES influenced by riffle-pool sequence

Previous land management has removed pool-riffle sequences to improve flood conveyance for agricultural land-use. The re-introduction of more natural geomorphological processes will result in changes to morphological form that will resemble these features. However, careful management is required before the implementation stage so that an understanding of the dynamic nature of features is recognised and how the two forms work in conjunction with one another as the riffle is sustained and replenished by the sediment scoured out from pools (Sear *et al*., 2010).

Habitat diversity has increased at this reach due to the regeneration of riffle-pool sequences and a diversity of hydraulic conditions that provide a variety of biological niches (Raven *et al*., 1998). Invertebrate colonisation has occurred where there is a clear distinction between species of shallow, fast flowing riffles and slow-flowing deep runs. The stabilisation of ERS has provided habitat for pioneering aquatic species leading to greater wildlife diversity within the fluvial and riparian zones (Boon *et al*., 1992; Emery *et al*., 2003). The quality of water has been enhanced since the implementation of riffles as the fast flowing turbulent water promotes aeration (Raven *et al*., 1998).

Restoration Technique	**Characteristics**	**Geomorphological Influence on FES**
Installation of LWD	• With caution, LWD is placed in the riparian zone downstream of the restoration reach. Once overbank flow occurs it will naturally position the LWD in channel. • This is a method to increase upstream flooding to reconnect the channel with its floodplain. • This technique allows the river's own dynamic processes to do the restoration.	• Helps create riffle-pool sequences within this low energy reach. • Increased the numbers and depth of backwater pools (slow-flowing, deep sections). • Increased the potential area of spawning gravel. • LWD provides an organic habitat for species colonisation (Harper *et al*., 1998). • Overbank flow has resulted in a semi-permanent wetland during winter months, creating a natural wetland habitat. • Wetlands which replace arable farm land will reduce leaching. Nitrogen, phosphorus and ochre emissions will be reduced. • Wetlands act as a carbon store.

Table 36a. Linkages between LWD and the delivery of FES

Geomorphological Function GF	Marginal FES	Score
LWD (*Influencing Characteristic*)	Provision of food Water quality Flood control Habitat provision Erosion control Sediment dynamics Nutrient retention Carbon sequestration	-- O/? ++ + + ++ +/? +?

Table 36b. Summary table representing the FES influenced by LWD

LWD helps to establish large pools which interact with the floodplain during high flows which provides flood water storage.

The simplest approximation of net carbon sequestration of a floodplain is by using the organic carbon of sediments and the flux rate under steady conditions (Brown *et al*., 2010). Pre-restoration in channel carbon storage had decreased at this reach due to deforestation and channelisation when compared with forested streams (Brown *et al*., 2010). Pre-restoration arable farming practices had changed the natural formation of peat in the riverine environment as peat was replaced by grasslands and clay-rich soils that are better for cultivation (Brown *et al*., 2010). However, since restoration the formation of peat through the accumulation of dead biomass had become a net carbon store in these more natural riverine conditions. Table 37. shows 'carbon sequestration' rates of various carbon stores.

Carbon store	Amount of carbon sequestered	Source of carbon sequestration value
Sedge fen and reed beds Alder leaves (alive) Grasslands (dependant on nitrogen availability)	20 t ha yr^{-1} 5-10 t ha yr^{-1} 2-6 t ha yr^{-1}	Lüsher *et al*., 2004 Lüsher *et al*., 2004 Hoffman and Glatzel, 2007

Table 37. Types of 'carbon stores' in riverine environments

Using the Countryside Survey (Carey *et al.,* 2007) estimates, and accounting for their land cover, acid and neutral grasslands contain 144 Tg and 149 Tg, respectively, of the UK carbon store in the top 15 cm soil layer (Chamberlain *et al.*, 2010). Grasslands can sequester large amount of carbon at a rate of 242 ± 1,990 kg/ha/yr, which is higher than slow growing forests and contrasts with a net loss from arable land (-137 ± 103 kg/ha/yr) (Janssens *et al.*, 2005). Figure 45. shows how agriculture increases the amount of soil organic carbon in England. The graph displays a negative correlation meaning that the organic carbon content of the soil decreases over time in agricultural fields under fallow.

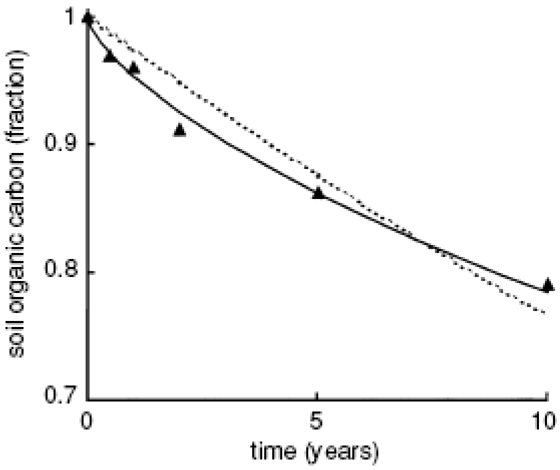


Figure 45. Decrease in the amount of soil organic matter in agriculture fields under fallow in England (Vleeshouwers & Verhagen, 2002)

Follet *et al.* (2001) imply through their research that the rate of carbon sequestration is approximately five times higher in restored wetlands compared to restored grasslands. This proposes that wetlands are very effective carbon sinks. Therefore, by restoring lateral connectivity, semi-wetland areas within the floodplain can store carbon as well as provide habitat and breeding grounds for an abundance of wildlife.

Restoration technique	Characteristics	Geomorphological influence on FES
Bed re-grading, re-introduction of natural bed substrate	• Bed raising is whereby the river bed is raised (by adding substrate) to reconnect the channel with its floodplain. • Bed substrate is dependent on the geological context of the river and its location along the watercourse .This case study is a gravel bed river (see Figure 46. for bed substrate/inorganic habitat). • Larger substrate is characteristic of upstream reaches whilst finer sediment is located downstream in the valley.	• Bed raising will largely contribute to more frequent overbank flows and the creation of a semi-wetland environment. • Frequent channel-floodplain interactions will enable the natural ability of soils to filter nutrients. • Natural substrate provides the source for riffle-pool formations which provide important habitat. • Floodplain interactions in the riparian zone will allow pioneering vegetation to flourish, but the frequency of interactions will determine the maturity of species. • Sediment dynamics will be altered. Sediment stores in the form of point bars will provide ERS which form valuable habitat.

Table 38a. Linkages between restoration of natural bed substrate and the delivery of FES

Geomorphological Function GF	Marginal FES	Score
Natural bed substrate (*Geomorphological Form)*	Provision of food	O
	Water quality	O/?
	Flood control	+
	Habitat provision	++
	Erosion control	+
	Sediment dynamics	++
	Nutrient retention	O
	Carbon sequestration	O

Table 38b. Summary table representing the FES influenced by natural bed substrate

Inorganic habitats are listed in Figure 46. Inorganic habitats are characteristic of natural bed substrate. The type of inorganic habitat is dependent on the geology of the catchment.

Inorganic habitat
Boulders (exposed rock)
Pebbles (and cobbles)
Gravel
Sand
Silt

Figure 46. List of potential ‘inorganic habitats’ for riverine environments (adapted from Harper & Everard, 1998)

Bed substrate within the river channel forms the habitat for aquatic organisms, the source of material load and the platform for the creation of morphology (Sear, 2006).

Geomorphological Function GF	**Marginal FES**	**Score**
Lateral connectivity (*Connectivity)*	Provision of food	--
	Water quality	+
	Flood control	++
	Habitat provision	++
	Erosion control	+
	Sediment dynamics	+
	Nutrient retention	+
	Carbon sequestration	++

Table 38c. Summary table representing the FES influenced by lateral connectivity

Overbank inundation patterns have been adjusted resulting in a significant increase in diversity and spatial variability of flow depths leading to a complex multi-directional flow structure that is fundamental in improving habitat diversity. These flow patterns have been significantly influenced by raising the bed of the incised channel and gravel augmentation.

The channel is re-connected with the floodplain (formerly agricultural land) creating seasonal wetlands along the river corridor. The re-connection of the river channel and its floodplain has caused a reduction in economic consequences downstream as flood risk has lowered due to the re-establishment of the natural flood regime upstream.

Estimates for flood damage can be calculated using standard estimates for flood damage costs (£ ha^{-1}) depending on the annual flood probability and the number of residences in the study site (Posthumus *et al*., 2010). The standard estimates can be calculated using Penning-Roswell (2005) flood damage to residential properties. The total flood damage costs can be divided by the size of the floodplain for specific reach scale 'benefits'.

Restoration technique	**Characteristics**	**Reach scale geomorphological influence on FES**
Riparian buffer zone	• A piece of land often having rough or semi-natural vegetation situated between agricultural land and a surface water body (Hogan *et al*. 2000). • Restoration involved planting native riparian species from the bank top extending into the floodplain with a width of 10m. • The most beneficial processes for water quality improvement occur optimally in wetland buffer strips (Hogan *et al*. 2000).	• Helps lower the amount of fine sediment entering the channel reducing turbidity. • Protects the water body from harmful impacts such as high nutrient, pesticide or sediment inputs from agriculture. • The establishment of rough or semi-natural vegetation provides important environmental benefits including extended areas of riparian habitat for wildlife conservation at this reach. • Helps stabilize river banks and limit erosion, reducing the sediment load in the river. • Provides areas of shade lowering stream temperatures which are vital for fish during warm weather. • Helps provide vegetative material to the watercourse which is a valuable food supply for aquatic organisms. • Riparian vegetation is a carbon store.

Table 39a. Linkages between restoration of natural riparian conditions and the delivery of FES

Geomorphological Function GF	**Marginal FES**	**Score**
Riparian vegetation (*Influencing Characteristic)*	Provision of food	O
	Water quality	++
	Flood control	++
	Habitat provision	++
	Erosion control	++
	Sediment dynamics	++
	Nutrient retention	++
	Carbon sequestration	+/?

Table 39b. Summary table representing the FES influenced by riparian vegetation

Prior to restoration, the absence of vegetation combined with rainfall eroded the stream banks whilst surface runoff washes soil directly into the river from the arable fields resulting in high levels of sedimentation and muddy water. Riparian vegetation has played a crucial role in providing the control of erosion. Plants and roots have helped stabilise the banks whilst grasses and plants have helped filter pollutants which are deposited in the floodplain resulting in cleaner water. Replanting riparian vegetation at this reach has resulted in clean, less turbid water which is one of the most significantly important services at this reach.

Potential organic habitats are listed in Table 40. Organic habitats will be dependent on the species of riparian vegetation as well as the size and maturity of the vegetation establishment. As riparian establishes itself on the river banks and within the riparian zone, a larger quantity of leaf litter and submerged leaved plants are present. The installation of riparian buffer strips has slowed down the rate of soil erosion via surface runoff from the arable fields lowering the quantity of fine sediment entering the channel. Tree roots will also help stabilise banks and ‘lock up’ sediment. Once riparian vegetation matures, collapsed branches may enter the channel forming debris dams. This has the potential to re-establish lateral connectivity upstream of the LWD.

Emergent plants (significant aerial portion)
Marginal plants (rooted at normal river height)
Floating-leaved plants
Leaf litter (in pools)
Mosses
Macroalgae
Submerged, broad-leaved plants
Submerged, fine-leaved plants
Trailing vegetation (tree branches or grasses breaking water surface)
Tree roots
Woody debris

Table 40. Potential organic habitat delivered from riparian vegetation and buffer strip installation (adapted from Harper & Everard, 1998).

4.3.1. Summary of GF and the delivery of reach scale FES

Although each individual GF has been given a score to highlight the impact to the delivery of FES, it is worth noting that it is through a combination of GF interactions that help deliver FES. For example, a 'meandering planform' alone is not enough to increase 'habitat provision' potential and biodiversity. It is through a collection of GF interactions such as a 'meandering planform', 'natural bed substrate' (geomorphological form), 'riparian vegetation' (influencing characteristic), 'lateral connectivity' and 'longitudinal connectivity' (connectivity) that provides the basis and potential for this reach to deliver multiple FES. Further research may be necessary to determine the full extent to which GF influence all FES as restoration of natural GF currently aim to only deliver a couple of FES such as 'habitat provision' or 'water quality'.

Table 41. displays the cost of restoring GF based on cost estimates from the River Restoration Centre (RRC). This is a hypothetical cost example to show how replacement costs can illustrate the value of natural GF.

GF (reach scale)	GF cost
Geomorphological Form	
Meandering planform	£324,000 (700m of re-alignment)
Riffle-pool sequences	£12,000 (200m of riffle creation)
Natural bed material	£108,000 (400m of gravel augmentation)
Influencing Characteristics	
LWD	£220 (4 LWD positioned in floodplain)
Riparian vegetation	£41,500 (400m of re-establishing riparian vegetation)
Connectivity	
Lateral connectivity	£175,000 (700m of embankment removal)
	£660,720 (GF combined total cost)

Table 41. Cost of reach scale GF for a 1 km reach of a lowland river in agricultural landscapes (based on average restoration costs from the River Restoration Centre, undated)

The links between 'GF', 'FES' and 'benefits' are tabulated in Table 42. The score given to 'GF' helps identify the impact restoration has had on the delivery of 'FES' on a reach scale.

4.3.2. Reach scale 'benefits'

GF	Score	Marginal FES	Marginal Benefit
Meandering planform Lateral connectivity	- --	Provision of food	The introduction of a meandering planform in conjunction with lateral connectivity has a negative impact on floodplain agricultural output and income. This is mainly due to reducing the size of arable fields to allow for lateral connectivity **(not quantified as it is a hypothetical example).**
Riparian vegetation Lateral connectivity Riffle-pool sequence Meandering planform	++ + + ++	Water quality	Improved water conditions due to lower levels of siltation. Connectivity with the floodplain is likely to enhance water purification and waste treatment. Abstraction points downstream will benefit from the protection of water quality. Savings of 0.4% to water treatment costs (based on values from Everard, 2010) **(benefit totalling £500/per annum)**.

Riparian vegetation Lateral connectivity Natural bed substrate LWD Riffle-pool sequence Meandering planform	++ ++ + ++ + ++	Flood control	It is not possible to make strong assumptions for flood risk to property as this is a small reach scale site surrounded by agricultural land **(not quantified or monetised).**
Meandering planform Riffle-pool sequence Natural bed substrate Riparian vegetation Lateral connectivity LWD	+ ++ ++ ++ ++ ++	Habitat provision	Resilience of fish stocks presents a clear benefit. Introduction of riparian vegetation and the buffer strip has lowered levels of siltation which is likely to be beneficial for bullheads and many other species of plants and animals for a considerable distance downstream. Enhanced fish stocks will have some impact on recreational angling **(monetised in recreation table).**
Riparian vegetation Lateral connectivity Natural bed substrate LWD Riffle-pool sequence Meandering planform	++ + + + ++ ++	Erosion control	It is assumed that 1 tonne of soil is lost per annum at a shadow value of £1,200. The influence of the buffer strip has considerably reduced the amount of erosion **(benefit totalling £1,200 per annum).**
Riparian vegetation Lateral connectivity LWD Riffle-pool sequence Meandering planform Natural bed substrate	++ + ++ ++ ++ ++	Sediment Dynamics	Lower levels of siltation have resulted in less fine sediment entering the channel. Resulting in channel habitat for wildlife Annual dredging is no longer necessary at this reach due to the dynamic equilibrium of erosion and deposition processes creating savings of £1,658 per annum **(benefit totalling £1,658 per annum).**
Riparian vegetation Lateral connectivity Meandering planform	++ + +/?	Nutrient Retention	The buffer strip has acted as a barrier which has resulted in lowering the amount of nutrient inputs from agriculture **(not quantified or monetised).**
Riparian vegetation Lateral connectivity LWD	+/? ++ +/?	Carbon Sequestration	Wetted margins are likely to enhance sequestration of carbon and also provide positive benefits for local microclimate (hard to quantify). Change from agricultural soils towards wetted, carbon accreting soils using a marginal cost of carbon of £27 per tonne (Everard, 2010), this yields an annual ecosystem service benefit value of £240 **(annual benefit totalling £240 per annum).**
Sediment dynamics	+	Cultural &	Angling benefits resulting from FES.

Natural bed substrate Erosion control Water quality	+ + +	Recreation	Membership prices are £230 per annum. Since restoration an increase of 3% has occurred (**annual benefit of £700 from GF restoration).** Other recreational benefits include bird watching from enhanced wildlife and river aesthetics **(not quantified or monetised)**. Additional research would have to be carried out to better understand the links between GF and this recreational benefit.

Table 42. Linkages between reach scale GF, FES and benefits

The reach scale GF contributes to monetary benefits of around £3,298 per annum. The cost to re-introduce GF seems to be unjustified if only the monetary benefits are considered. GF influence ‘habitat provision’ (annual benefits of £700 from recreation), ‘flood control’ (not monetised), and ‘sediment dynamics’ (not monetised) most significantly.

GF	Cost	Impact upon FES	Number of impacted FES
Geomorphological Form			
Meandering planform	£324,000	- = 1, ++ = 4	1 negative, 4 positive
Riffle-pool sequences	£12,000	+ = 2, ++ = 3	5 positive
Natural bed material	£108,000	+ = 2, ++ = 2	4 positive
Influencing Characteristics			
LWD	£220	+ = 1, ++ = 3	4 positive (not including +/? from carbon sequestration)
Riparian vegetation	£41,500	++ = 6	6 positive (not including +/? from carbon sequestration)
Connectivity			
Lateral connectivity	£175,000	-- = 1, + = 4, ++ = 3	1 negative, 7 positive

Table 43. The type and number of impacts on FES

GF have generated positive impacts to many FES at this reach. However, in doing so the ‘provision of food’ (agricultural output £/per annum) in the floodplain has decreased. Due to difficulties accessing cost data, restoration costs from 2004/2005 have been used. Therefore, it is important to note that the accuracy of costs relating to 2010/2011 farm business income may potentially be slightly skewed due to restoration cost fluctuations.

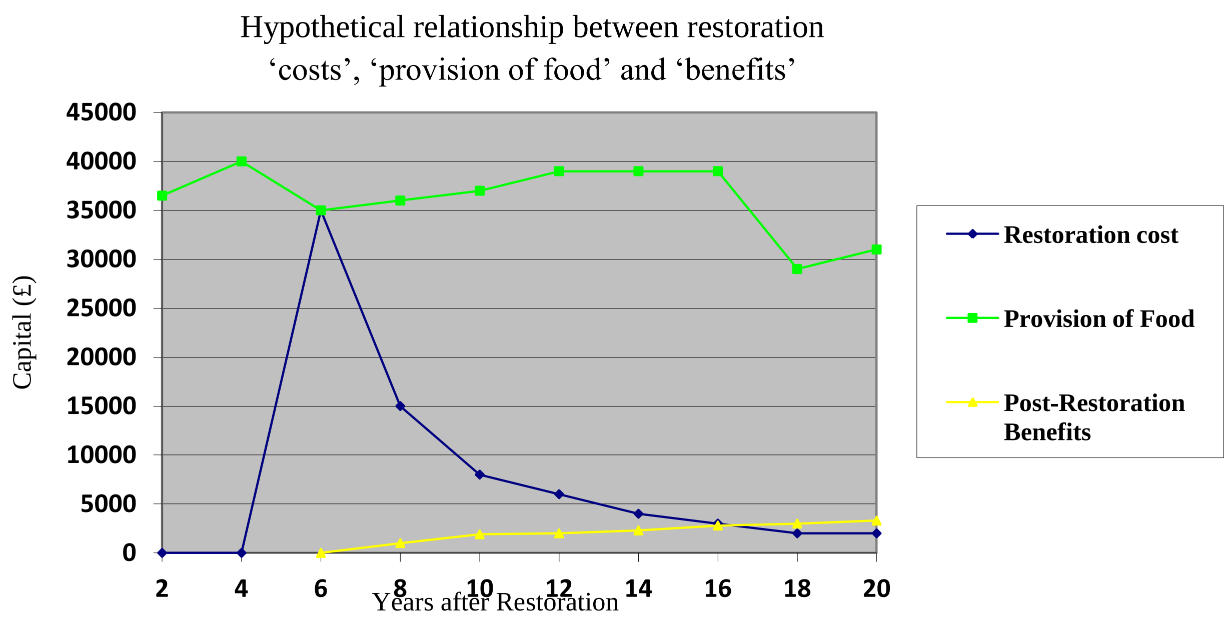


Figure 47. Graph illustrating the hypothetical relationship between restoration 'costs', 'provision of food' and 'benefits'

Restoration cost is based on the 'total cost' for the six stages of restoration that were previously explained in this chapter. The cost includes monitoring hence why the cost stretches out over a number of years after the implementation stage (year six). The agricultural output at this reach is slightly lower than before restoration (not quantified) due to the installation of the riparian buffer strip and the reconnection of the channel and floodplain. Figure 47. shows that during year 18 the output is a lot lower due to a very wet winter and flooding of agricultural land. However, the farm owner receives a bursary for setting aside land for restoration in the floodplain. This is included in the 'provision of food' value in Figure 48.

The primary focus has been on the direct monetary benefits obtained from this reach. Whilst it may seem that the cost to restore GF is a lot more expensive than the monetary benefits gained, it should be recognised that many benefits are non-monetary in nature. The non-monetary values of 'habitat provision' can be reflected through people's WTP to access or visit the site. Other 'indirect' values can be derived through a ranking system in which respondents rank the FES in order of importance. This will be explored in the following chapter as part of the New Forest case study.

The central purpose of the hypothetical case study is to highlight the importance of geomorphological processes and form in delivering FES. This has been done by comparing a degraded reach with a restored or natural reference reach. A reference reach is a blueprint that can be used to develop natural channel design criteria based upon measured morphological relations associated with the bankfull stage for a particular stable stream type (Rosgen, 2005). Although the values stated for this case study are only hypothetical, they do highlight the relationship between GF and FES. It is clear to see as a result of this case study that geomorphological processes and sedimentary features underpin morphological complexity which provides a wide range of riparian habitat vital for the delivery of high biodiversity (Sear *et al*., 2010). However, other ecosystem services are also largely influenced through geomorphological processes. These services have been highlighted through the use of a systems approach to riverine ecosystems, where the focus is on the influence of geomorphological processes in delivering a collection of potential ecosystem services. This example shows that rivers do not just provide 'in channel' services, but interactions between the channel and its floodplain contribute to the delivery of a host of other 'out of channel' services including 'carbon sequestration', 'erosion control', 'flood storage', 'sediment dynamics', and 'habitat provision'.

The cost to restore GF can be established through river restoration. However, the cost of GF fluctuates depending on the hydromorphology of the reach such as the extent to which the water flow, sediment transport and the migration of biota are impacted by artificial barriers (Sear *et al*., 2010). This case study has been constructed to include major restoration works. Therefore the cost to re-introduce GF is a lot higher than restoration of a semi-natural reach. The following section will test the framework to a semi-natural reach in the New Forest, Hampshire to highlight the changes in cost depending on the number of existing GF.

The following section will apply the geomorphological framework to a reach scale restoration project in the New Forest. This data will then be compared to the New Forest 'willingness to accept government spending' data.

4.4. New Forest case study – a semi-natural reach

This aim of this section is to provide a reach scale case study to help test the 'geomorphological framework' and highlight the values of this approach. The framework will be applied to a Life 3 project to help identify the relationship between GF restoration and the delivery of multiple FES as a result of habitat restoration.

The aims of the New Forest LIFE 3 sustainable restoration project aims are as follows (Sear, D., Kitts., D., Millington, C., (undated):

- To re-occupy former meanders whilst filling in channelised reaches.
- Generate a sinuous course where former meanders have been destroyed.
- To raise bed levels using locally scoured clay and gravels to recreate floodplain processes.
- Re-introduce LWD into the channelised reaches.

In practice, restoration of New Forest streams aims to restore riverine woodlands to favourable or more favourable conditions by re-introducing *Alnus glutinisa* and *Fraxinus excelsior* and creating appropriate conditions for the regeneration of further riverine woodlands and bog woodland. This will be achieved by:

1. Maintaining existing New Forest habitats of international and national importance for nature conservation (which includes alder woodland on floodplain, rivers and streams) in a favourable condition which sustains optimal populations of characteristic and rate plants and animals (GeoData Institute, 2003).

2. Restoring sub-optimal, or to re-create destroyed habitats, to a favourable condition where resources permit and priorities dictate. Effort will be targeted where historical evidence indicates previous cover and where prevailing conditions indicate that appropriate management would result in successful regeneration of quality habitat, or would provide a precursor to the successful regeneration of quality habitat (GeoData Institute, 2003).

Restoration within the New Forest is primarily focussed on improving ‘habitat provision’. The reach scale case study which follows this section will exemplify some of the restoration techniques applied to help enhance ‘habitat provision’. The primary focus is on geomorphological processes and form and how they are impacted by restoration. The relationships between GF and FES will be explored using the ‘geomorphological framework’ to value GF through restoration. For example, re-occupying old meanders to restore the planform and cross-section of the river will help sustain floodplain processes leading to the generation of ‘habitat provision’ and ‘sediment dynamics’, ‘erosion control’ and ‘carbon sequestration’ from bog woodlands.

4.4.1. Reach-scale case study: A background of Holmsley Inclosure restoration

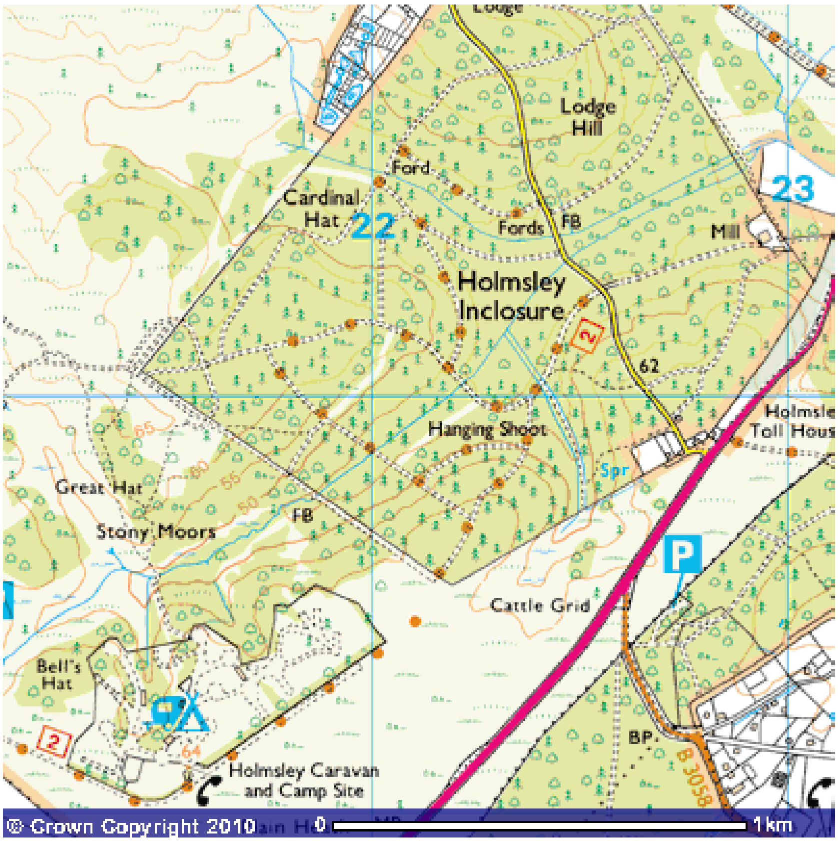


Image 1 – Pre-restoration incised channel

Image 2 – Restoration; Bed

(Images taken from New Forest Life Partnership, 2006-

Holmsley Inclosure (SU223 003) is located south-west of the New Forest approximately 2km south of Burley (SU 224 004). Holmsley Inclosure supports a wide range of woodland types and open habitats giving rise to botanical and invertebrate interest within its 345 acreages (New Forest Life Partnership, 2006-2016a). Historically, Holmsley was one continuous mire stretching through the forked valley through Holmsey bog in the east upstream to Cardinal Hat in the north and Stony Moors in the west. The wider Avon catchment is on permeable river terrace deposits and relatively permeable Headon Beds, therefore causing flows towards the mire to be quite variable. Head deposits control the nature of the mire substrate and its water regimes (Allen, 2005).

However, since the Inclosure was created, extensive drainage works have been undertaken during the 1930's-1940's. The drainage works resulted in lowering the water table and has enabled the encroachment of willow, birch and alder within previously waterlogged areas.

Mire Types, Characteristics, and Formation

Clarke and Allen (1986) characterise the mires as follows:

1. The valley mires occur as broad, shallow flush networks in the:
    - Valley bottoms
    - Valley side seepage steps that mark the junction between deposits of contrasting lithology
2. A wide range of plant communities is represented and the vegetation zonation parallel to, and along, the valley axis reflects both:
    - Water movement
    - Rate of nutrient flow
3. The current and continued existence of the valley mires depend upon groundwater supply and lateral flow is an important component of the valley mire water budget.

New Forest mires are (Forestry Commission, 2001):

- Waterlogged, acid, nutrient poor habitats occupying shallow to occasionally deep peats, representative of bogs fond in warmer, dry southern lowlands of Britain.
- Have a peat depth often as little as 30cm and usually less than 1m. Unlike northern blanket and raised bogs, deep peats are uncommon in the New Forest.

The mire which stretches through Holmsley Inclosure is an example of a valley mire which before land management and extensive drainage was permanently waterlogged. The soil structure consists of peat overlaying slowly permeable valley infill. The mires most affected by drainage were the ones flanking the Avon Water such as Holmsley Inclosure. However, whilst the mires within Holmsley Inclosure were not completely destroyed by extensive drainage, it did rupture the hydrological regime and crucially the lateral vegetation zonation which lead to the disappearance of many native plant and animal habitats.

4.4.2. Pre-restoration characteristics at Holmsley Inclosure

Pre-restoration channel characteristics:

Wetted perimeter:	Flow rarely exceeds banks
Floodplain land-use:	Plantation inclosure
Problem :	Fragmentation of native species due to lack of river-floodplain connection
Hydromorphologic condition:	Partially natural but degraded and obviously modified

Pre-Restoration FES	Benefit	Benefit Value (per annum)
Provision of fibre	The woodland enclosure provides the primary source of commercial timber within the New Forest from a combination of broadleaved and conifer woodland (New Forest Life Partnership, 2006-2016a).	Commercial timber (benefit not quantified).
Habitat provision	High conservation values. Conservation value and sites of Special Areas of Conservation (cSAC).	Non-monetary.
Flood control (localised)	The channel is over-deepened resulting in a drier floodplain beneficial for invasive vegetation species to flourish. Provides habitat for many rare and nationally scarce taxa. More dry forestry land. Flooding downstream is more frequent.	Negative impact - no benefit.
Recreation	Forestry Commission operates policy of free access on foot. Byelaws allow free access on horseback within perambulation. Forestry Commission also operates policy of encouraging cycle access on way marked tracks.	Not quantified for Holmsley Inclosure (no direct monetary benefits).

Table 44. Relationship between FES and benefits before restoration at Holmsley Inclosure

Pre-restoration, Holmsley mire habitat had become fragmented as a result of drainage and afforestation which are characteristic of previous land management. However, the enclosure provides a habitat for many rare and nationally scarce invertebrate taxa as summarised by Denton (2006).

Nationally Scarce B			
Araneae	Theridiosomatidae	*Theridiosoma gemmosum*	Ray spider
Araneae	Tetragnathidae	*Tetragnatha pinicola*	a long-jawed orb spider
Araneae	Araneidae	*Araneus alsine*	Strawberry Spider
Araneae	Araneidae	*Zilla diodia*	an orb weaver
Araneae	Salticidae	*Evarcha arcuata*	a jumping spider
Araneae	Salticidae	*Myrmerachna formicaria*	a jumping spider
Orthoptera	Gryllidae	*Nemobius sylvestris*	Wood Cricket
Orthoptera	Acridiidae	*Omocestus rufipes*	Woodland Grasshopper
Dictyoptera	Ectobiidae	*Ectobius lapponicus*	Ducky Cockroach
Lepidoptera	Sesiidae	*Synanthedon flaviventris*	Sallow Clearwing
Lepidoptera	Torticidae	*Pammene germmana*	a micro-moth
Lepidoptera	Gelechiidae	*Syncopacma cinctella*	a micro-moth
Lepidoptera	Arctiidae	*Eilema sorocuka*	Orange Footman
Lepidoptera	Geometridae	*Rheumaptera hastate*	Argent & Sable
Lepidoptera	Geometridae	*Pachycnemia hippocastanaria*	Horse Chestnut
Coleoptera	Dytiscidae	*Graptodytes granularis*	a diving beetle
Coleoptera	Hydrophilidae	*Berosus luridus*	a hydrophilid beetle
Rare (RDB3			
Araneae	Theridiidae	*Episinus maculipes*	a comb-footed spider
Vulnerable (RDB2)			
Dytiscidae		*Graptodytes flavipes*	a diving beetle
Dytiscidae		*Agabus brunneus*	a diving beetle

Table 45. Nationally scarce invertebrate taxa in New Forest enclosures (Denton, 2006)

The FES that became impacted by unsustainable management are described in Table 46. The problems are described in terms of geomorphology in the riverine environment.

Degraded FES	**Problem**
Habitat provision	Fragmentation has occurred as a result of forestry management. Semi-wetlands are no longer present due to a combination of channelisation and historical drainage. Invasive species (primarily Birch, Rhododendron, Himalayan Balsam, Japanese Knotweed) flourished in the drier floodplain conditions causing degradation of natural riparian species such as strands of alder and ash woodland and alluvial (Forestry Commission, 2008). However, pre-restoration conditions in the enclosure provide many valuable habitats for a host of scarce invertebrates. Continuing invasion of invasive species could potentially alter the biodiversity such as insect species. Channelisation has also developed an in-stream mono habitat. The loss of natural bed substrate has caused a reduction in potential trout spawning habitat (Forestry

	Commission, 2008).
Flood control	As early as the 1840's the enclosure land was modified to improve ground conditions for forestry and grazing. Large scale modifications were also carried out throughout the 1950's – 1970's (Forestry Commission, 2008). Drainage at the edge of valley mires has resulted in a loss of surface living Sphagnum layer (acrotelm) causing enhanced surface flows and rapid erosion of peat leading to hydrological disruption affecting water movement and direction (Forestry Commission, 2001). Over-widened and incised channel has caused a loss of flooding and floodplain interactions. Loss of semi-wetland habitat and flood water storage, generating a higher discharge downstream (increasing flooding risk).
Sediment dynamics (sources and sinks)	The distribution of deposited sediment is affected by the loss of overbank flows. Floodplain deposits have reduced due to less frequent overbank flows. Canalisation due to straightening, over deepening and over widening of the river channel has resulted in changes to channel morphology and width/depth ratio. As a result of changes to natural sediment dynamics ERS are affected especially as bank sediment is locked up by vegetation. Prevention of natural flooding means that more energy is focussed within the river channel itself resulting in increased erosion and transport of gravel. These gravels are deposited further downstream where the channel gradient reduces (Forestry Commission, 2008). This can result in the reduction of the channel capacity downstream, which in turn may cause drainage problems elsewhere (Forestry Commission, 2008).
Erosion control	Nick-point erosion has caused incision which threatens the mire and wet heath habitat whilst also lowering the water table in the surrounding floodplain. As the river tries to adapt to its new lowered stream bed level it creates headward erosion, often into the valley mires.

	Incised channels have occurred as a result of scour and erosion and in some places creeping headward erosion has led to deeply incised channels of 1.5m-3.0m (Forestry Commission, 2008). Human intervention alone has been found to exceed 0.5m^3 per metre of channel per year in New Forest streams (Tuckfield, 1976; 1980).
Carbon sequestration	The removal of floodplain processes has occurred due to the combination of incision and drainage installation. Lateral floodplain interactions have been reduced which has degraded and lowered the reach's capacity to sequester carbon. Drainage at the edge of valley mires has caused peat shrinkage by drying and collapse (Forestry Commission, 2001). Wetland peats are the most efficient carbon sinks so the loss of mire conditions is costly. It is also worth noting that woodland soils contain more soil carbon than most other land covers, including heathland soils. Therefore there is potential for significant CO_2 emissions if soils are managed inappropriately (Forestry Commission, 2008).
Lateral connectivity	Incision of the channel has resulted in degraded and less frequent floodplain processes. Over deepening of channel and bankside spoil reduces the opportunity for out of bank flow and flooding of the floodplain (Forestry Commission, 2008). Spoil heaps flanking the watercourse act as flood banks which prevent the water from draining back into the stream during periods of high precipitation. Spoil heaps also reduce the potential for over bank flows and therefore flooding of the floodplain (Forestry Commission, 2008).

Table 46. A summary of the depleted FES for the New Forest study

Holmsley Inclosure is partially natural but its channel-floodplain interactions have been impacted by drainage works. The restoration of this bog woodland to a more favourable condition requires the full range of fluvial processes to be allowed to function within a physically, hydrologically and geomorphologically intact natural or close to natural system. Periodic flooding of the riverine woodland stands is essential (Forestry Commission, 2008).

To restore the mire environment, rehabilitation of the reach was necessary to re-create natural GF conditions and help restore natural habitat to a reference state similar to a reach outside of the enclosure.

Geomorphological slider: Pre-restoration

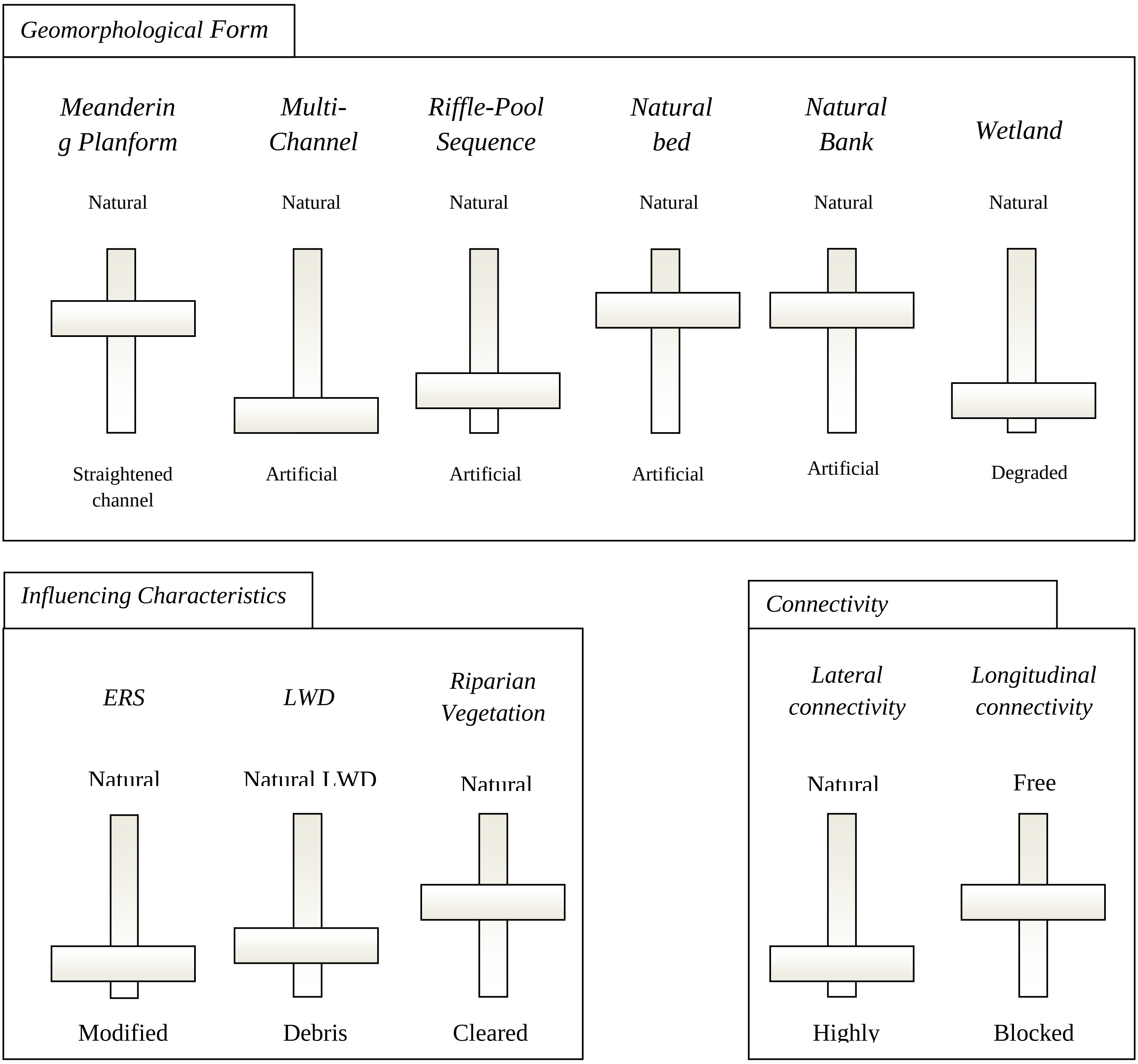


Figure 48. 'Geomorphological slider' showing the condition of pre-restoration GF at Holmsley Inclosure

4.4.3. Stream restoration at Holmsley Inclosure

Table 47. contains the techniques implied to restore the degraded reach. The table also displays the desirable geomorphological processes for this particular reach as a result of the restoration techniques employed.

Restoration techniques	**Post-restoration geomorphological processes**
• Scrub management and vegetation clearance (8.8 hectares). The process of linking native riverine woodland habitats found immediately outside Holmsley Inclosure has continued with the clearance of non native conifers from the riverine corridor (New Forest Life Partnership, 2002-2006). • Raising bed levels (500m) to within 0.4m of the surrounding floodplain to restore winter flooding on the flood plain. • Installation of log weirs. • Side drains blocked with spoil.	Potentially desirable geomorphological process changes: • Erosion and deposition in the floodplain caused by overbank flow. • Formation of a wetland floodplain and restoration of mire conditions. • Natural channel sediment dynamics (deposition and erosion) due to natural bank and bed substrate and floodplain scrub land clearance. • More natural patterns of scour and aggradation (gravel accumulation enforced by log weir).

Table 47. Holmsley Inclosure stream restoration their impact on geomorphological processes (adapted from New Forest Life Partnership, 2006-2016a)

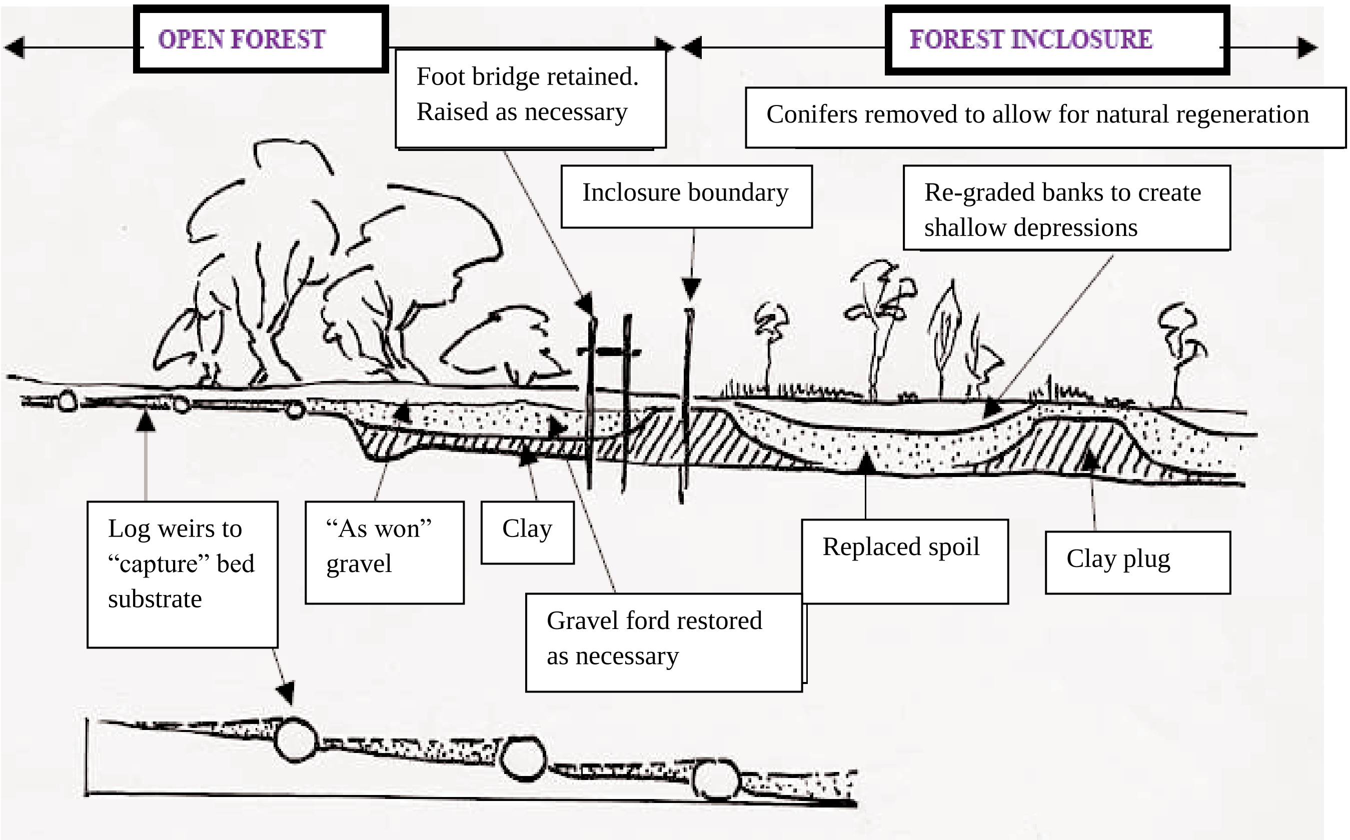


Figure 49. Restoration techniques (New Forest Life Partnership, 2006-2016a)

GF (post-restoration)	Impacted FES (post-restoration)
Geomorphological Characteristics • Natural bed substrate • Wetland generation *Influencing Characteristics* • Riparian vegetation (scrub management and vegetation clearance) *Connection* • Lateral connection (raising of bed level	• Flood Control • Habitat Provision (in channel and out of channel) • Erosion control • Carbon sequestration • Sediment Dynamics

Table 48. Impacted GF and FES at Holmsley Inclosure

Extensive restoration of the Avon Water has been undertaken during 2006/2007. The potential impacts to FES are explained in the following section.

4.4.4. Impact of GF on the delivery of FES post-restoration

This section will attempt to highlight the role of geomorphological processes and form and the relationships they have with ‘provisioning’, ‘supporting’ and ‘regulating’ riverine ecosystem services for this case study example. The Figure 50. provides an overview of restoration and the impacts upon GF. It is obvious to see that restoration moves the river to a more natural condition.

Geomorphological slider: Post-restoration

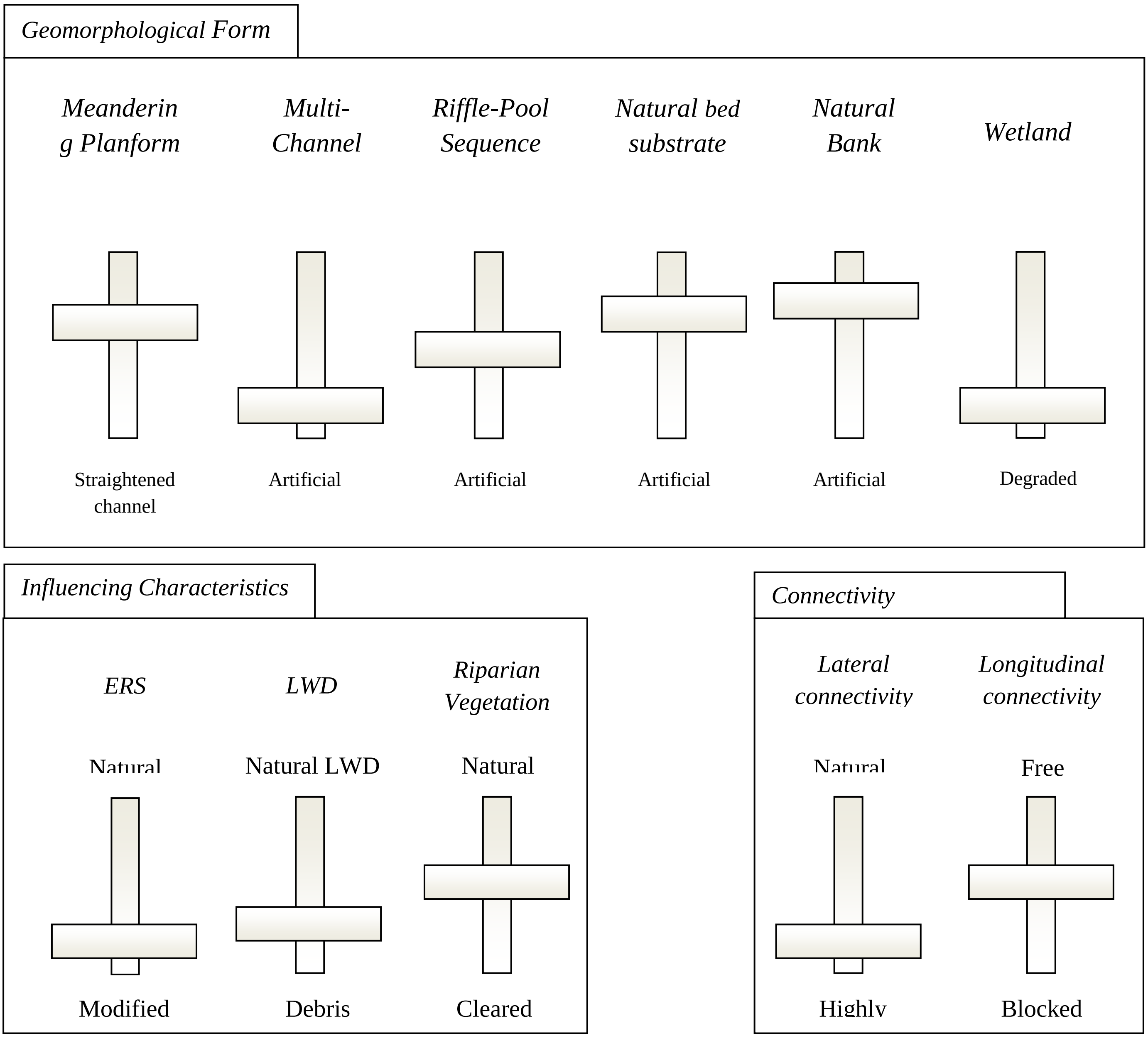


Figure 50. Geomorphological slider showing the condition of post-restoration GF of Holmsley Inclosure

The following tables will highlight the restoration techniques applied at Holmsley Inclosure and the influence restoration has on reintroducing natural GF and how GF interact to delivery of FES. The influence of GF is based on the knowledge of how geomorphological processes function from existing academic literature and reports to help assess how the various ecosystem service services are affected.

Restoration technique	Characteristics	Geomorphological influence on FES
Bed raising and gravel substrate accumulation using log weirs	• The project raised the bed level by 450mm to 600mm of the river using gravel, clay plugs and wooden steps (New Forest Life Partnership, 2002-2006). This reduces the capacity of the river, slowing down the flow whilst ensuring that floodplain processes are restored so the river regularly overtops its bank during periods of peak flow • Where bed gravels have been scoured and lost from headwater sections of a stream but where the solid geology (e.g. underlying clay) is still intact, low log weirs have been installed in the river bed to act as sediment traps • The log weirs also help to stabilise the bed and prevent erosion and scour progressing further upstream	• Bed raising will reconnect the stream with its floodplain which will contribute to more frequent overbank flows. This will sustain the wetland environment whilst helping to reduce the magnitude of flood peaks downstream as floodplain inundation will dissipate energy during floods • By reintroducing natural drainage and lateral connectivity the stream can contribute to the function and condition of SSSI habitats – notably alluvial/riverine woodland, mires, wet grassland and bog woodland (Forestry Commission, 2008) • Lateral exchanges of water and sediment are also important. Floodplain interactions and overbank flows will deposit fresh sediment in the floodplain and riparian zone building up the surface of the floodplain • Fluvial landforms, substrates, and processes define habitats for biota • Accumulation of gravel substrate from upstream will provide the source for riffle-pool formations which provide important habitat

Table 49a. Linkages between restoration of bed raising and natural bed substrate and the delivery of FES at Holmsley Inclosure

Geomorphological Function GF	Marginal FES	Score
Natural bed substrate (*Geomorphological Form)*	Provision of fibre Water quality Flood control Habitat provision Erosion control Sediment dynamics Nutrient retention Carbon sequestration	O + ++ + + ++ ? O

Table 49b. Summary table representing the FES influenced by natural bed substrate at Holmsley Inclosure

Natural substrate (gravel) has provided a valuable source of habitat at Holmsley. Due to the construction of log weirs, gravel substrate has been allowed to deposit and accumulate forming local areas of raised beds (riffles) which are characteristic of more fast turbulent flows. Over time the reach will morphologically respond to the restoration and fluvial and geomorphological processes will naturally sort and regrade the new material into a natural bed form (New Forest Life Partnership, 2002-2006). Natural bed form is essential in sustaining a diverse species community as resulting bed forms such as riffles aerate the water which helps provide a valuable habitat for invertebrates and fish in the New Forest such as bullhead and brown sea trout that are characteristic of New Forest streams. Pools will form over time due to scour with the aid of the log weirs as it is a low energy stream. Pools provide valuable habitat for species that prefer deep, slow flowing areas such as lamprey.

Geomorphological Function GF	Marginal FES	Score
Lateral connectivity (*Connectivity)*	Provision of fibre Water quality Flood control Habitat provision Erosion control Sediment dynamics Nutrient retention Carbon sequestration	O + ++ ++ + ++ + ++

Table 49c. Summary table representing the FES influenced by bed raising at Holmsley Inclosure

Seasonal flooding of the floodplain is particularly important and mires control the source and flow of water to the stream (Forestry Commission, 2008). Flooding of the forest floodplain during seasonal flooding has lowered the volume of water flowing downstream and consequently reduced the flood magnitude. The river regularly overtops its bank during periods of peak flow, restoring floodplain processes (New Forest Life Partnership, 2002-2006). Blocking the drainage channels has slowed down the erosion of peat, which was rapidly eroding back on itself leading to hydrological disruption affecting water movement and direction prior to restoration (New Forest Life Partnership, 2002-2006).

Calculating monetary values and benefits of mire, wetland and woodland carbon sequestration rates are difficult to quantify at Holmsley Inclosure. Seasonal flooding deposits fresh sediment in the floodplain which is incredibly important in sustaining bog woodland soils. Alluvial and bog woodland soils contain more carbon than the majority of most other land covers (Forestry Commission, 2008). It is therefore of great importance that these soils are managed carefully to maximise the storage capacity of CO_2 emissions. However, It has riparian and bog woodlands have been degraded by drainage engineering at Holmsley Inclosure.

Restoration Technique	Characteristics	Geomorphological Influence on FES
Clearance of invasive riparian vegetation	• Vegetation itself is in part controlled by substrate type and stability and flow conditions (Townsend *et al*., 1997). • Conifer, rhododendron and other exotics were felled and the arising burned to restore the open conditions for the recovery of transition mire. • Re-growth of willow and alder was treated with a herbicide to ensure the open conditions prevail to allow re-colonisation by mire species (New Forest Life Partnership, 2002-2006).	• The removal of invasive species (Himalayan Balsam, Japanese Knotwood) has enabled the reintroduction of native pioneering species therefore increasing biodiversity. • Scrub clearance is essential in creating natural conditions which allow the full range of fluvial processes to function within the floodplain. • The importance of riparian vegetation in controlling and defining geomorphological habitat and stream ecosystem functioning has been realised (Gurnell, 1995). • Sedimentation and spoil is deposited within the floodplain during high flows maintaining floodplain soils. • The clearance of trees will allow slender cotton-grass (*Eriophorum gracile*), a nationally rare plant in the UK species to establish itself once again in this part of the mire system (New Forest Life Partnership, 2002-2006).

Table 50a. Linkages between restoration of riparian vegetation and the delivery of FES at Holmsley Inclosure

Geomorphological Function GF	Marginal FES	Score
Riparian vegetation	Provision of food	O
	Water quality	+
	Flood control	+
	Habitat provision	+
	Erosion control	++
	Sediment dynamics	++
	Nutrient retention	+/?
	Carbon sequestration	?

Table 50b). Summary table representing the FES influenced by riparian vegetation at Holmsley Inclosure

The effect of clearing invasive vegetation species has resulted in positive impacts to the delivery of FES. In conjunction with channel-floodplain connectivity, the clearance of vegetation has allowed space for floodplain geomorphological processes to develop. This has a positive impact on water quality and flood control as peak flows which exceed bank height can be stored in the floodplain replenishing the mire, reducing the flow and potential magnitude of flooding downstream. However, what is unclear is the impact vegetation clearance will have on carbon sequestration. Quantitative research based on carbon storage of native and invasive species would be required to identify the most sufficient of carbon stores.

4.4.5. Summary of GF and the delivery of reach scale FES at Holmsley Inclosure

GF (Reach Scale)	**GF Cost**
Geomorphological Form Natural bed material and Riffle-pool Sequence	£ 11,604 (log weirs)
Influencing Characteristics Riparian vegetation	£ 4,800 (scrub clearance)
Connectivity Lateral connectivity	£ 28,560 (bed raising)
	£44,964 (Reach GF Combined Total Cost)

Table 51. The type and number of impacts on FES in Holmsley Inclosure (based on restoration cost estimations from the River Restoration Centre, undated)

Reach Scale Benefits

GF	Score	Marginal FES	Marginal Benefit
Lateral connectivity Riparian vegetation (Clearance)	-- -	Provision of fibre	Raising channel bed has caused floodplain processes to establish creating bog woodland during peak flows. Seasonality affected the timing of harvesting work. Harvesting in the spring/summer was halted because of the bird nesting season. Through wet winter periods when river levels were high it occasionally proved difficult to harvest timber, because the river and ford became impassable. **(Loss not quantified).** However, standing timber can provide a value for the provision of fibre as they have a well-established market price. **(Benefit not monetised).**
Riparian vegetation Lateral connectivity	+ +	Water quality	Better connection with the floodplain is likely to enhance natural water purification. Difficult to quantify. **(Benefit not monetised).**
Riparian vegetation Lateral connectivity Natural bed substrate	+ ++ +	Flood control	Effects of seasonal flooding and restoration of geomorphological processes on the floodplain is already noticeable (New Forest Life Partnership, 2002-2006). It is not possible to make strong assumptions for flood risk to property as the hydrological adjustments are small scale at this restored site in the New Forest. However, lateral connectivity at this reach has lowered flood magnitude downstream. Pools increase the volume for potential flood water storage. **(Benefit not quantified or monetised).**
Natural bed substrate Riparian vegetation Lateral connectivity	++ ++ ++	Habitat provision	The increased physical and hydrological diversity at the reach has stabilised some fisheries habitat (particularly spawning gravel) and has created new habitats that have yet to be fully exploited by fish populations. Species that have benefited from the restoration of GF include sea trout, brook lamprey and bullhead (New Forest Life Partnership, 2002-2006). Possible negative impact to some of the rarities recorded on the dried habitat list

			when replaced by wetland species. Further field observations are required to learn the full extent of this loss. Achieving Special Areas of Conservation (cSAC) by restoring wetland environments under the EC Habitats Directive has been achieved during the Life projects. GF have contributed to 'Good ecological status' under the EU Water Framework Directive (WFD). Post-restoration work on the New Forest streams suggests that although large numbers of juvenile fish use the river as nursery grounds, it is not yet possible to quantify the benefit. **(Benefits not monetised).**
Riparian vegetation Lateral connectivity Natural bed substrate	++ + +	Erosion control	Erosion of mire peat has been halted in the floodplain and fresh deposits from floodplain geomorphological processes are evident. Scour is prevented through installation of log weirs. Quantification is complex. **(Benefit not quantified or monetised).**
Riparian vegetation Lateral connectivity Natural bed substrate	++ + ++	Sediment dynamics	Lower levels of siltation have resulted in less fine sediment entering the channel. Resulting in channel habitat for wildlife. **(Not quantified or monetised).**
Riparian vegetation Lateral connectivity	? +	Nutrient retention	Improved habitat through scrub clearance is likely to improve nutrient cycling, but quantifying this is complex. **(Not quantified or monetised)**.
Riparian vegetation Lateral connectivity	+/? ++	Carbon sequestration	Clearance of vegetation may have an impact on the levels of carbon storage in the riparian zone. Further research is necessary to quantify the impact. Wetted margins are likely to enhance peat formation and sequestration of carbon whilst providing positive benefits for local microclimate. Erosion of mire peat has been halted in the floodplain. Difficult to quantify. **(Benefit not monetised).**
Sediment dynamics Natural bed substrate Erosion control Water quality	+ +/? +/? ++	Cultural & Recreation	Recreational benefits include bird watching, hiking and cycling. Restored GF can possibly enhance wildlife and river aesthetics. Additional research

			would have to be done to better understand the links between GF and this recreational benefit. Quality of angling may also occur due to the restored fishery habitat. **(Benefit not quantified or monetised)**.

Table 52. Linkages between reach scale GF, FES and benefits at Holmsley Inclosure

A summary of the reach scale restored GF at Holmsley Inclosure along with the impact they have contributed towards the delivery of FES is tabulated in Table 53.

GF	**Cost**	**Impact upon FES**	**Number of impacted FES**
Geomorphological Form Natural bed substrate	£11,604	+ = 2, ++ = 2	4 positive
Influencing Characteristics Riparian vegetation	£4,800	- = 1, + = 2, ++ = 3	1 negative, 5 positive (not including +/? from carbon sequestration)
Connectivity Lateral connectivity	£28,560	-- = 1, + = 4, ++ = 3	1 negative, 7 positive

Table 53. The type and number of potential impacts on FES at Holmsley Inclosure

Overall, a total of eight FES have been impacted by GF at Holmsley Inclosure. Lateral connectivity has impacted all eight FES with seven positive impacts and one negative. Riparian clearance has had five positive impacts, whilst negatively impacting the ‘provision of fibre’ due to the wetter floodplain disrupting timber harvest practices. Natural bed substrate has had a positive impact to four FES including two significant positive impacts in ‘habitat provision’ and ‘sediment dynamics’.

The restoration has met the objective of increasing floodplain ‘connectivity’ and restoring geomorphic processes on the floodplain characteristic of semi-natural reaches. However, this project was discussed in terms of ‘habitat provision’ alone. The ‘geomorphological approach’ has attempted to identify how habitat restoration can in fact impact the delivery of other FES such as ‘flood protection’ and ‘carbon sequestration’. Gaps in scientific knowledge regarding the delivery of certain FES and the inability to quantify and place monetary values to the ‘benefits’ they provide generate problems in illustrating their importance across disciplines. Everard (2010) explains that there are practical difficulties due to sparse economics literature regarding the transferable values which could be used to assess marginal improvement of existing habitat rather than gross habitat displacement or restoration. For this case study, qualitative descriptions of the ‘benefits’ derived from FES have been made. Perhaps other forms of ‘benefits’ could be derived through restoration of GF and a more detailed understanding of their relationship with FES. Further testing would be required to gain a more precise understanding of the complex relationship between GF and FES.

In terms of monetary value, timber production was the primary ‘benefit’ at Holmsley Inclosure (pre-restoration conditions), but restoration of GF along the river corridor has enhanced the delivery of multiple FES, the ‘benefits’ of which may be undervalued due to the complexity of placing monetary values to them. However, the principle aim of this thesis was to discover the links between GF and the delivery of FES and place monetary values to GF.

4.5. Restoration of GF and FES – 'willingness to accept government funding' compared with 'actual costs'

The direct cost for GF restoration in the New Forest is compared to respondents' 'willingness to accept government funding' on restoration projects. Table 54. represents other costs for similar reach scale New Forest restoration projects. The potential impacts on FES are estimations. Further quantitative data is required to accurately explain the impact of GF to the delivery of FES.

New Forest Project	Total Cost	Restored GF	Potential Impact on FES
Markway Stream	£18, 238	• Meandering planform (excavation of palaeochannel) • Lateral connectivity	• Carbon sequestration • Flood control • Habitat provision • Sediment dynamics
Holly Hatch Bottom Drainage Channel restoration	£17,692	• Bed level • Lateral connectivity • Longitudinal connectivity	• Carbon sequestration • Erosion control • Flood control • Habitat provision

Table 54. New Forest Life 3 restoration projects (adapted from Forestry Commission, 2008)

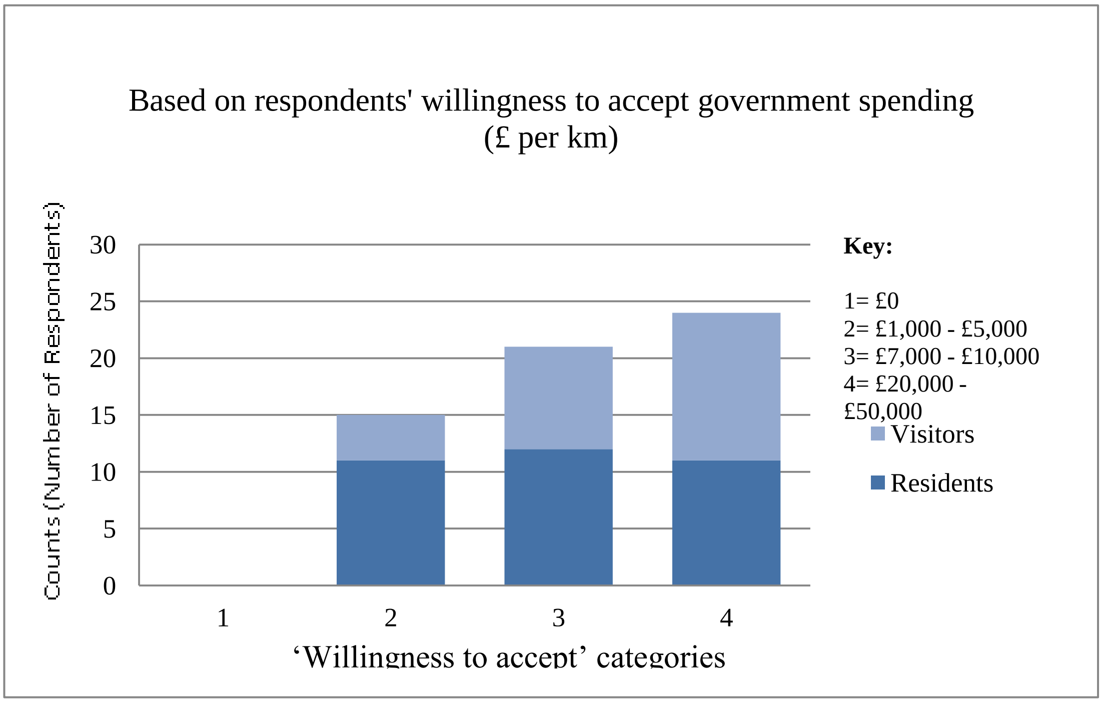


Figure 51. Respondents' 'willingness to accept government funding' for their preferred 'river type' in the New Forest

From comparing respondents 'willingness to accept government funding' for 'geomorphologically diverse' New Forest streams and actual costs to restore GF, it is clear to see that 36 out of 60 respondents' would be unwilling for the government/EU to fund the amount spent on reach scale restoration to their chosen river type. The results show that 24 respondents' are happy for the government to spend between £20,000 and £50,000 which would be required for the three Life 3 restoration projects exemplified in this section.

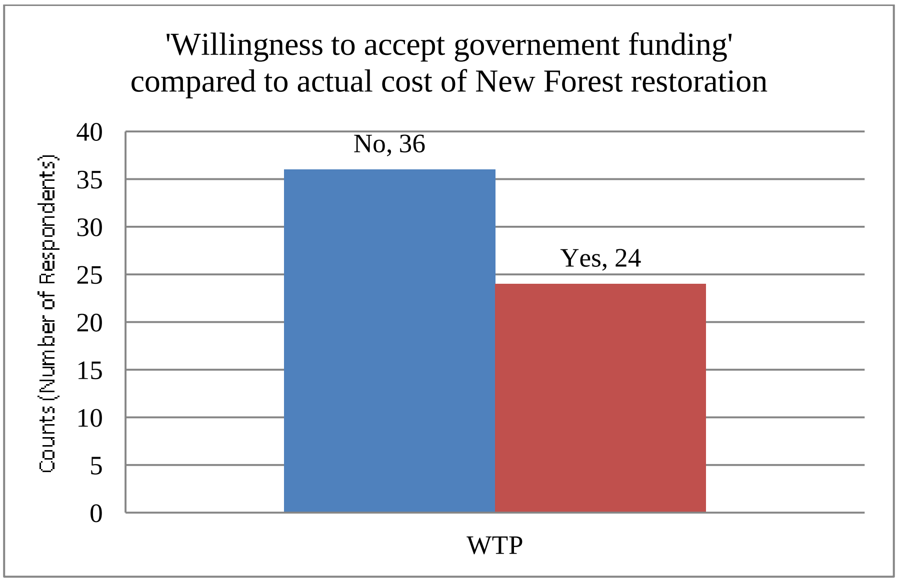


Figure 52. Respondents' 'willingness to accept government funding' compared to 'actual cost' of New Forest restoration

However, one of the drawbacks of the 'willingness to accept government funding' method was the categories used. Two of the projects came to a total of between £17,000 and £19,000 which is not covered in the 'willingness to accept government funding' categories. Therefore, it is rather difficult to assume respondents' who are happy to accept payments of £7,000 - £10,000 would not pay this amount as the option was not given. This is a problem that may skew the actual 'willingness to accept government funding' for 'geomorphologically diverse' rivers in the New Forest.

The 'willingness to accept government funding' results therefore suggest that respondents' are 'willing to accept government funding' for more 'geomorphologically diverse' rivers (between £7,000- £10,000) in the New Forest; however, less than half of respondents' find that the government/EU funding for projects at the high end of the cost range (£20,000- £50,000) is unjustified. The following hypothesis is true:

5. The general public *do* value 'geomorphological diversity' and that they are willing to accept government/EU funding to enhance and restore GF for non-use and option value benefits which derive from FES.

   But,

   The level of funding is varied. Over half of the respondents (36/60) believe government/EU funding for projects at the higher end of the cost range (£20,000-£50,000) in the New Forest is unjustified.

   And,

   'Geomorphological diversity' may be represented through respondents' appreciation of river aesthetics rather than the delivery of FES.

The total cost to restore GF in the New Forest is lower than it would be to restore a more modified reach such as the hypothetical reach discussed earlier on in this chapter. The 'geomorphological slider' provides a visual overview that the pre-restoration levels of GF are more 'geomorphologically diverse' at Holmsley Inclosure compared with the condition of the GF in the hypothetical case study. Perhaps calculating respondent's 'willingness to accept government funding' for a modified urban river would make a useful comparison for a semi-natural reach. Respondents' may accept larger funding due to the 'direct benefits' they would get from restoration (e.g. recreation, flood control).

The 'willingness to accept government funding' data also suggests respondents think 'water quality' and 'flood control' are more important than 'habitat provision' that the funding for the Life 3 projects primarily aims at restoring. Therefore, respondents' may not be willing to accept the amount of money being funded for this project as they may not feel the 'benefits' derived from the FES 'habitat provision' are justified.

5.0. Discussion

The fundamental aim of this thesis is to introduce an 'ecosystem service' approach to 'geomorphology' whilst highlighting the role of geomorphology in delivering multiple lowland riverine FES. This section explores some of the key points raised from this project along with limitations and possible ways forward.

5.1. Key points from the 'geomorphological framework'

Chapter two introduces a 'geomorphological framework' for providing ecosystem services in lowland rivers that has then been tested using the hypothetical cost estimated (highly modified) reach scale case study, and a semi-natural restoration project in the New Forest. The results have highlighted potential linkages between river functioning in terms of geomorphology and the delivery of ecosystem services. However, further testing is required to better understand linkages, natural variability of river systems and how they behave temporally. It is important to note that regional patterns of climate, geology and topography largely influence the physical and biological processes that regulate river structure and function (Edmonds *et al.,* 2003; Montgomery & Bolton, 2003).

The sensitivity of river channels to 'change' varies between and along rivers (Gilvear, 1999). The case studies explored in chapter four provide examples of where geomorphic stability of a river system can be upset by activities such as river training, removal of riparian vegetation, land use change and loss of connectivity. GF are influenced by fluxes of water or sediment and these changes can impact the delivery of many FES on a reach scale. In many cases the result of channelisation and modified river form has impacted GF and reduced the rivers ability to deliver multiple FES and in turn multiple 'benefits'. The geomorphological processes that sustain and fashion riverine morphology provide the platform in which riverine FES can flourish both in and out of channel. The application of the 'geomorphological framework' and an ecosystem services approach to riverine environments provides a clearer link between physical form, processes and the generation of FES. For example, chapter two explains that it is through a combination of GF that provides the physical habitat for biodiversity, the lateral interactions for 'flood control', and the dynamic environment for erosion and deposition which determines 'sediment dynamics' and 'erosion control' at a reach scale.

One of the project aims was to introduce existing approaches to riverine ecosystem management including river restoration. Chapter two outlines the requirement for restoration and explains that river management goals can be achieved by restoring natural geomorphologically diverse rivers. The role of restoration has played a large part in the formation of the 'geomorphological framework' and provides a method of placing monetary costs to natural GF.

Restoration projects provide us with a testing ground from which future rehabilitation of lowland rivers can benefit from. The unpredictability and complexity of riverine geomorphology and ecology make it very difficult to predict precisely how the river will respond to a particular restoration technique (Wohl *et al.,* 2005). Continual monitoring of rivers on a regular basis using fluvial audits and direct field surveys to capture variables at the correct scales of measurement is essential in generating more widespread successful restoration projects (Bruce-Burgess & Skinner, 2002; Wohl *et al.,* 2005). The use of post-project appraisals which analyse and evaluate the success of restoration schemes in relation to short-term and long-term geomorphological compatibility with the catchment hydrology, sediment processes (Downs & Kondolf, 2002) and the delivery of FES, can help provide feedback for adaptive management in which actions are treated as experiments. Adapting and emerging the post-project appraisal method with FES analysis may provide a more detailed connection between geomorphology, restoration and the delivery of FES.

An ecosystem services approach can help assess the total 'FES' and 'benefits' that can be generated via naturally 'geomorphologically diverse' riverine environments. 'Costs' and associated 'benefits' of GF have been highlighted, providing rationale for restoration. However, it is fundamental that we consider all potential FES in degraded streams before restoring a reach. This way we can better manage aquatic environments without the risk of enhancing singular services and degrading others. Equally an ecosystem service approach helps to identify and value the additional 'benefits' that restoration produces (e.g. habitat provision and carbon sequestration from flood protection restoration).

Successful restoration should generate hydrological, geomorphological, and ecological conditions that enable the river to be self-sustainable (Palmer *et al*. 2005). For example, a wild natural river may be enhanced by restoring riparian forests, increasing fishery production or by improving water quality among other functions (Wohl *et al*. 2005).

Conversely, successful restoration in an urbanised location may be largely based on aesthetic values or the minimisation of flood risk (Wohl *et al*. 2005). An ecosystem services approach can help restoration projects become more successful by identifying multiple FES that can be delivered through habitat restoration for example. An ecosystem services approach can also help uncover hidden 'benefits' so that restoration success is not only assessed using a single FES such as 'habitat provision' or 'flood control'.

'Indirect' benefits were calculated using a contingent valuation method. The approach used in this thesis differs to the methods applied in other studies that look at respondents' marginal WTP for FES such as 'water quality' by an increase in the amount respondents' would pay in their water bills (Bateman *et al*. 2010) for example. Instead of using the traditional contingent valuation method WTP, this thesis explores 'willingness to accept government funding'. This method is used because respondents' do not have to directly pay for restoration (i.e. no increase in their bills), instead it is public money that funds these projects. Therefore, this method creates a foundation for respondents' to justify whether they approve of restoration cost relating to the FES and benefits that restoration can provide.

Section 4.1. introduced a ranking system to illustrate respondents' order of importance for FES in lowland riverine ecosystems. The ranking system gave respondents' the chance to demonstrate what they thought the most important FES delivered in riverine ecosystems is. The next stage of the survey introduced a percentage rating which provides a method to quantify respondents' 'willingness to accept government funding' for individual FES. The results gained from this method illustrate how much money respondents' are happy to see the government spend on restoring GF to deliver individual FES for a given reach. This method highlights the 'indirect' monetary 'benefits' gained as people are willing to accept funding from the government to deliver for FES through restoration. However, problems' that are associated with this technique are discussed in section 5.2.

5.2. Limitations

The limitations of the 'geomorphological framework' will be explored in relation to the project aims. By integrating a relatively contemporary approach (ecosystem services) with other disciplines, there was always a risk that potential gaps in knowledge will hinder development. The following project aim will be summarised:

- To introduce existing approaches to riverine ecosystem management including river restoration

River restoration is a technique that is still in its experimental stage, therefore developments to maximise success are still under evaluation, meaning long term temporal changes in restored channels are unknown (Wohl *et al.,* 2005). Combine this with the fact that timescales for geomorphological dynamics are not adequately known, restoration success may only be short term.

Gaps in scientific understanding form a number of challenges for effective river restoration; the identification of these gaps points towards critical research requirements (Wohl *et al*. 2005). Table 55. displays key constraints of restoration. For example, benchmarks need to be calculated or else major events will be missed, so geomorphological tools need to be expanded. The system response to reach scale restoration can also vary between river systems. For example, some systems respond really quickly over a number of weeks or months, others respond much slower, over 3-5 years or longer; these temporal responses need to be considered in the scheme's design, monitoring and appraisal (Bruce-Burgess & Skinner, 2002). However, data to comprehensively characterise pre-disturbance states do not exist for many river types (Nilsson *et al.* 2007). The lack of baseline survey data on the geomorphology of rivers makes it very difficult to apply the application of geomorphology compared to hydrological or biological survey data.

A similar response variation regarding the delivery of FES is also an underlying problem. FES will undoubtedly occur at various time scales once the restoration of GF is complete. Once the implementation stage is complete, a lag time is going to prevent immediate 'benefits' as it will take time for the restored reach to re-establish. Therefore, 'benefits' should not be expected immediately after restoration. As indicated earlier in this chapter, the unpredictability and complexity of riverine geomorphology and ecology make it very difficult to predict how the river will respond to a particular restoration technique. This will impact the delivery of FES. Continual reach scale monitoring is essential for the identification and timing of benefits once restoration has been completed. However, constraints are stalling the development of successful river restoration:

Key Current Main Constraints
- Funding - Identification of the longer-term 'benefits' of river restoration - Lack of knowledge about the most appropriate techniques for different schemes - Lack of scientific/statistical understanding to undertake appropriate baseline monitoring - Lack of support from regulators - Lack of time - Lack of understanding of impacts over wider spatial areas and longer time scales - Lack of understanding of what appraisal constitutes - Learning through post-project appraisal at all sites (rather than representative sites) is limited as a result of the costs of scientific monitoring - Need for appropriate robust, cost-effective appraisal techniques - Obtaining adequate baselines is difficult, without having significant forewarning of the likelihood of a restoration project going ahead - Uncertainty attached to different approaches to river restoration - Unwillingness to publicise project failures

Table 55. Key constraints regarding restoration – understanding long term success or failure (adapted from Bruce-Burgess & Skinner, 2002)

5.2.1. Problems with generalising GF costs

One of the aims of this thesis was:

- To highlight costs and 'benefits' of geomorphology

Whilst the results suggest monetary costs have been given to GF, there has been problems' generalising the costs of GF as they vary extensively because site conditions determine the total cost of a feature. Therefore, it is extremely difficult to place a universal cost to a GF, although it will be incredibly useful for comparing the value of site specific reach scale GF with 'benefits' provided by GF. This understanding will enable economists and land use managers to appreciate what these monetary figures represent and how GF influence the delivery of FES both spatially and temporally. A more detailed and scientific understanding of processes and form will lead to more sustainable policy making in the future.

Due to the complexity, scale and variation of reach scale river restoration, total costs for restoration fluctuate. It is therefore very difficult to give a particular GF such as a meandering planform a generic monetary cost because no two restoration projects are the same which is largely reflected in the total restoration cost. Many FES derived from GF are also context and site specific as the delivery of FES is affected by catchment characteristics such as underlying geology, soil type, vegetation and level of upstream and downstream hydromorphology (Wohl *et al.*, 2005). Figures 53a., 53b. and 53c. provides a cost range for restoration techniques from internal project work carried out by the River Restoration Centre (RRC, undated) which reintroduce a meandering planform, and lateral connectivity at a 1km reach. The lowest cost estimations are calculated for a reach which has simple complexity and is easy to access (i.e. site ownership, remoteness, access route). The larger cost estimates are calculated for a reach which has simple complexity but moderate access to the site.

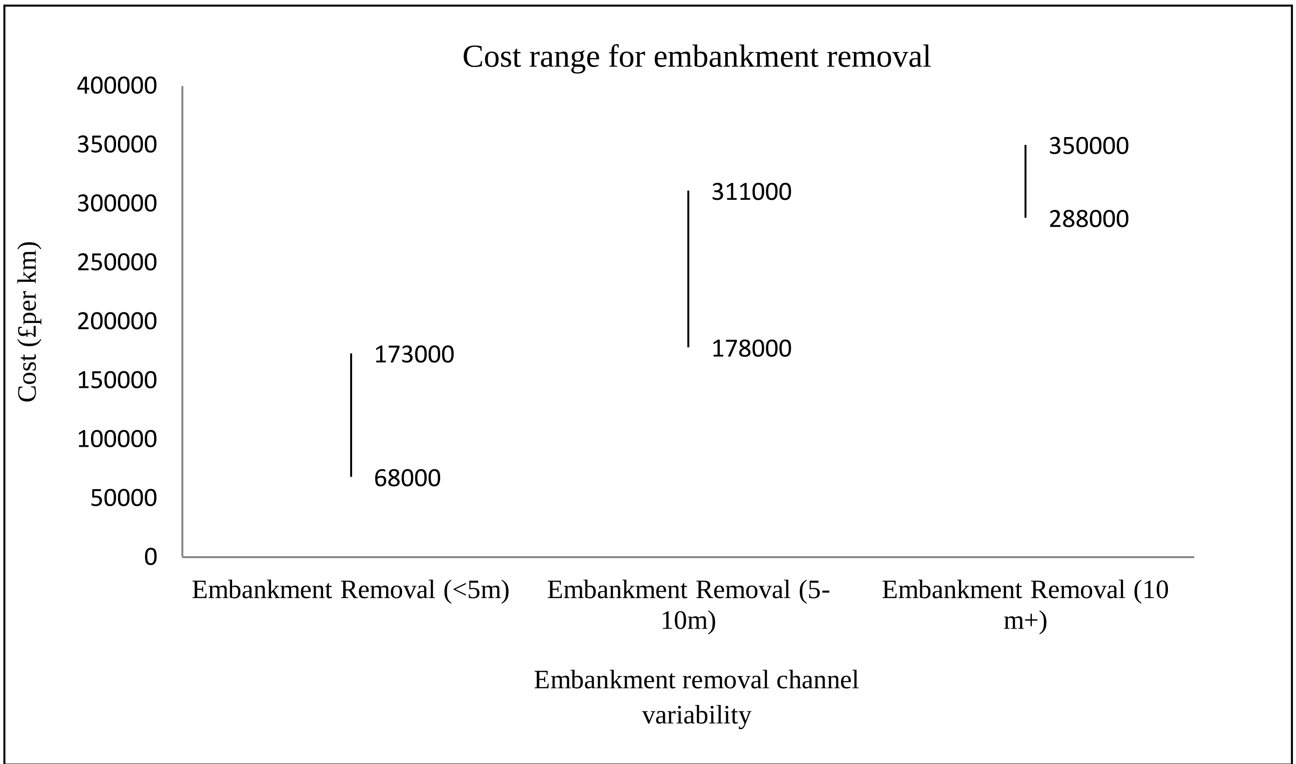


Figure 53a. Cost range for embankment removal (adapted from River Restoration Centre, undated)

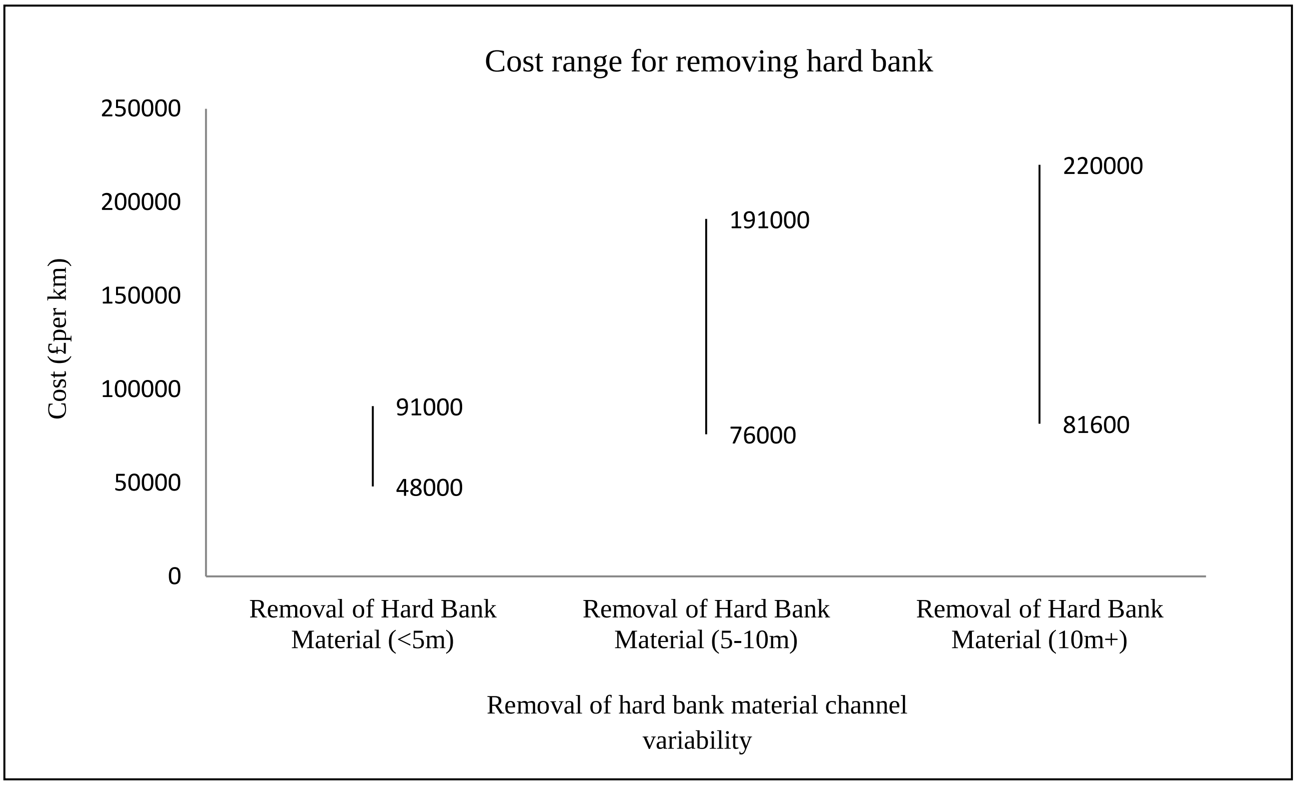


Figure 53b. Cost range for removing hard bank material (adapted from River Restoration Centre, undated)

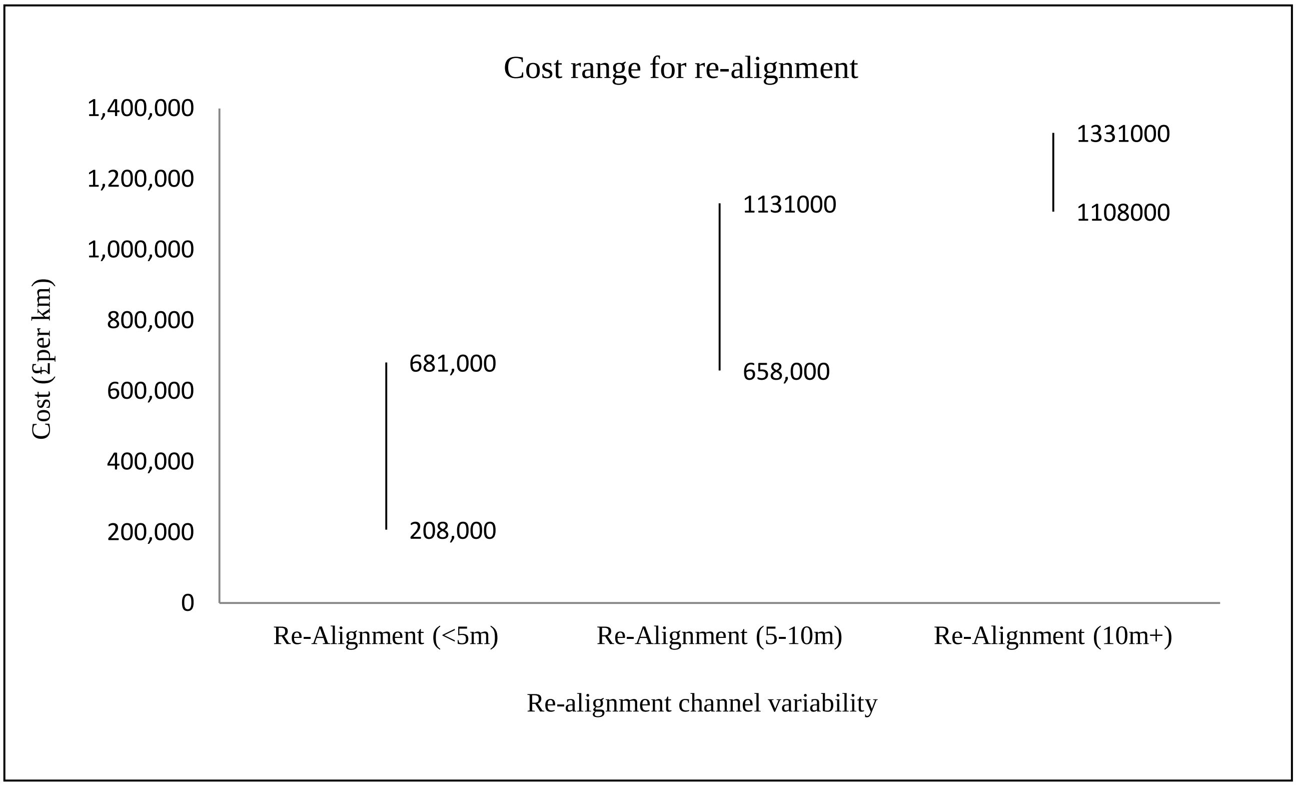


Figure 53c. Cost range for re-alignment (adapted from River Restoration Centre, undated)

Figure 54. indicates that the removal of materials can significantly influence the total cost of individual channel form restoration. It is not just the implementation of natural substrate such as gravel augmentation that costs large quantities of money, but it is the removal of materials implemented via channelisation which tend to be rather expensive. The six stages of restoration (explained in chapter two) generally remain at a similar cost for various river widths (<5m, 5-10m, 10m+) but the measures (material removal) cost fluctuates considerably depending on the amount of materials being moved/size of channel (see Figure 55.). Generally, the larger the channel width, the higher the cost for measures. However, it is also worth noting that projects with abundant on-site material cost significantly less than those which need to haul in materials from elsewhere. Labour costs also largely fluctuate because they are primarily access-driven; the highest costs are representative of restricted areas. Total restoration cost largely depends on the state of the river prior to restoration and its accessibility. It is this that prevents us saying a meander bend can be ‘x’ amount (£).

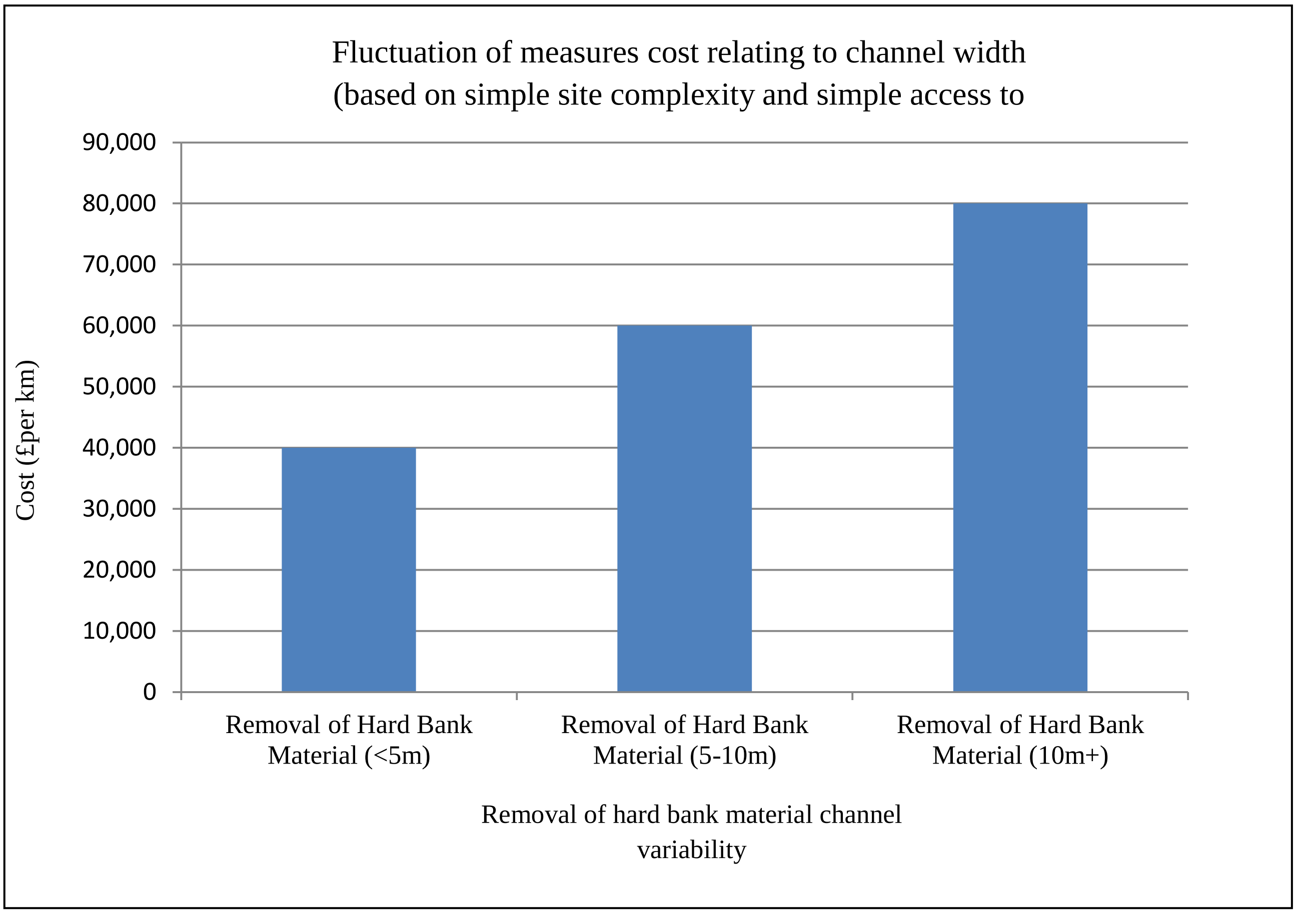


Figure 54. Fluctuation of measures cost relating to channel width (based on simple site complexity and simple access to site) (adapted from River Restoration Centre, undated)

To summarise, Figures 53a., 53b. and 53c. help conclude that location and site specifics largely influence the cost of GF. The larger the channel width, the more expensive the restoration cost. However, the hydromorphological condition of the river channel prior to restoration will impact the overall cost. This has been highlighted through the use of the hypothetical case study (channelised, high level of modification) and the New Forest, Holmsley Inclosure case study (semi-natural, low levels of modification).

Another problem identified through this framework is associated with peoples' perception of 'geomorphology'. For example, is it the 'processes' or 'form' or combinations of both that are considered 'geomorphology'? This will largely influence the data collected (Sear *et al*. 2010). The 'geomorphological framework', has given monetary values to GF based on the interaction of 'processes' and physical morphological 'form'. It includes both the static arrangement of channel features and the morphodynamics that characterise these systems.

As explained in chapter two, rivers are dynamic systems that respond differently to restoration over various time scales; therefore maintenance works carried out as a result of regular monitoring will alter from site to site. The cost to maintain 'geomorphologically dynamic' conditions was not considered in the cost of GF in this thesis. Perhaps this should be included as an indication of how degraded rivers respond to restoration, and how funding is required to maintain functioning at a reach scale. Location specifics largely influence the cost of GF so therefore, a catchment analysis is necessary for a more comprehensive understanding of how a given reach responds to restoration. By testing the framework with other river ecosystems, a cost continuum for GF conditions at various degraded reaches could be established. This will provide average values from various projects that have undergone similar restoration, helping to cost GF of a particular degraded condition.

Even with the use of modern day environmental valuation methods, research gaps still exist that thwart attempts to accurately use monetary values to value non-market goods. For example, the ability to place a monetary value on reach scale floodplain 'carbon sequestration' requires further testing and experimentation before precise values can be made. Yet the world carbon sink capacity of present day agricultural and degraded soils is 50 to 66 percent of the historic carbon loss of 42 to 78 gigatons of carbon (Lal, 2004). Carbon sequestration has the potential to offset fossilfuel emissions by 0.4 to 1.2 gigatons of carbon per year, or 5 to 15 percent of the global fossil-fuel emissions (Lal, 2004) – an extremely important global benefit associated with FES!

5.2.2. Problems associated with 'willingness to accept government funding' and ranking system

The following aim of this thesis has been summarised:

- To explore respondents' 'willingness to accept government funding' for 'geomorphologically diverse' rivers whilst highlighting the potential 'benefits' that can be gained.

To test the following hypotheses using a lowland river case study:

- The general public *do* value 'geomorphological diversity' and that they are willing to accept government/EU funding to enhance and restore GF for non-use and option value 'benefits' which derive from FES.
- The general public *do not* value 'geomorphological diversity' and feel that the current government/EU funding is unjustified in comparison to the 'benefits' derived from FES.

This thesis introduces a framework to assess how geomorphology can impact FES and help contribute towards a multidisciplinary approach to 'ecosystem service' research. River restoration provides us with a method to place a cost to riverine forms and associated processes which in turn provide FES and 'benefits'. As channelised conditions dominate many UK lowland rivers, the capacity to generate a wide array of FES is not possible as the foundation to deliver these services is absent. Restoring physical GF is essential in 'providing', 'regulating' and 'supporting' a collection of FES and 'benefits'. However, a general focus on delivering all FES is crucial for long term management to prevent less obvious services from degrading. A primary focus on one or two FES such as 'habitat provision' and 'flood control' is likely to impact the delivery of other FES.

The 'willingness to accept government funding' data suggests that there is a divide within the amount respondents are happy for the government/EU to pay for river restoration in the New Forest. The 'willingness to accept government funding' data suggests people are happy for the government to fund restoration in the New Forest; however the amount of money is divided. The 'willingness to accept government funding' data suggests that respondents are happy for the less expensive projects to be funded (£7,000 – £10,000) but are less happy with larger sums of money being spent (£20,000 – £50,000). The Life 3 restoration project at Holmsley Inclosure cost £44,964 which means only 24 of the 60 respondents are happy with that level of funding from the government/EU. However, as suggested in the chapter four, one of the drawbacks of the 'willingness to accept government funding' method was the categories used. Two of the Life 3 projects cost a total of £17,692 and £18,238 each and is not covered by the 'willingness to accept government funding' categories that are based on previous restoration project costs across urban and rural contexts (Forestry Commission, 2008; River Restoration Centre, undated). Therefore, the 'willingness to accept government funding' for 'geomorphologically diverse' rivers in the New Forest may perhaps have been skewed or misrepresented. Further testing using 'willingness to accept government funding' categories based on the costs of New Forest restoration alone could potentially be used to gather more unbiased results. Gaps in payment bands should also be avoided in the future to prevent result disparity.

Section 4.5. summarises the 'willingness to accept government funding' method and shows that respondents' are willing to pay for more 'geomorphologically diverse' rivers in the New Forest; however, less than half of respondents find that the government funding for projects at the high end of the cost range (£20,000-£50,000) is not justified. 'Geomorphological diversity' may also be represented through respondents' appreciation of river aesthetics rather than the delivery of FES. This problem could have occurred because the interview based survey used pictures to help indicate respondents' favoured river type. Rather than choosing a river type based on 'geomorphologically diversity' many respondents' have based their choice on aesthetics rather than function.

The FES 'Rank of Importance' data suggests that respondents' have ranked 'water quality' and 'flood control' highest for New Forest rivers. These two FES are both positively impacted via the restoration of riparian vegetation, lateral connectivity, and natural bed substrate at Holmsley Inclosure. Therefore suggesting 'habitat restoration' of a semi-natural reach can largely influence the delivery of multiple FES. This perspective needs to be addressed and tested through further research before any conclusions can be made.

Another problem associated with the ranking system and percentage rating method is that the monetary values given by respondents' to deliver FES are not indicative of real life restoration. The values given by the respondents' relate to the amount of money they are happy to see spent on restoring a particular FES. In reality a combination of restored GF influence the delivery of multiple FES, therefore a singular value for one FES is inappropriate at a practical level.

Contingent valuation methods have received much criticism regarding validity and reliability of data (Smith, 1993; Freeman, 1993; NOAA, 1993). This problem has also been identified by Carson *et al.* (2001) who state that 'Even if all of the survey related issues to valuing a public good can be overcome, CV (contingent valuation) is not without its limitations' (p. 197). Therefore the accuracy and consistency of the results collected using the 'willingness to accept government funding' may not reflect the true economic value of individuals' (Freeman, 1993). If ecosystem service research develops and spreads across multiple disciplines, perhaps more accurate quantified techniques will be implemented which produce agreed 'values' and 'benefits' for ecosystems. Until then, monetary value seems to work wherever possible as a universal language across multiple disciplines.

5.3 Ways forward

Integrating natural science, economics and social science is difficult, but crucial (Cornell, 2010). A greater understanding of bio-physical relationships is required to effectively understand how physical form and biological interactions deliver FES. The 'geomorphological framework' considers geomorphology as a physical characteristic that influences the delivery of FES in lowland river ecosystems. To progress our understanding of how ecosystems provide FES, more research is necessary to identify the small scale 'ecological functions' (De Groot, 2006) which help explain how natural processes and physical form interact to provide goods and services that satisfy human needs. The 'geomorphological framework' uses 'geomorphology' as a physical function in providing the platform for bio-physical interactions at a reach scale. Through understanding how 'ecosystem services' are impacted over a variety of scales, a greater scientific understanding of how to sustainably manage environments will evolve. Small scale methods are crucial in providing decision support at a local scale for stakeholders (Janssen *et al*. 2005).

Chapter one has described how many rivers require some form of restoration to enhance degraded ecosystems. Natural functioning ‘geomorphologically diverse’ lowland rivers are scarce in the UK due to spatial and temporal land use changes within river floodplains. By placing monetary costs to GF, you can begin to illustrate the importance of ‘geomorphologically diverse’ rivers to both physical and social sciences. The GF costs presented in the hypothetical and New Forest case studies help identify the amount of funding required to reintroduce GF so that the physical characteristics of lowland river ecosystems form the basis for potential bio-physical interactions which can help maximise goods and services, therefore satisfying human needs. Obtaining funding is a key step in river restoration and can alone decide on the level of intervention (ranging from emergency to preventive or enhancement actions) that is feasible for a particular project. It is therefore difficult to justify experimental restoration practices if outcomes are uncertain which suggests that public money could be more efficiently spent.

However, it is evident that continuous reach scale monitoring of GF and FES is required to better understand the complexities of lowland rivers responses to restoration projects and how this practice can affect the delivery of FES. Quantifying GF will undoubtedly contribute towards gaining further knowledge on how GF interact and help deliver FES. River ecosystem thresholds may be better understood by quantifying GF, which will help strengthen our understanding of potential regime shifts which produce large or unforeseen changes to lowland river FES.

An ‘ecosystem service’ approach should be applied across various environmental disciplines. A multi-disciplinary approach to ecosystem management will perhaps encourage the development of better ecosystem classification and valuation methods. Kondolf (1998) suggests, the main problem which hampers the development of multi-disciplinary research is that we understand the complexities of our own field, but we often reduce the set of principles for other disciplines and therefore simplify the complexities of other fields so that we can easily apply our knowledge.

The application of the ‘geomorphological framework’ has indicated that previous riverine and land management in the New Forest has degraded the natural environment. Taking this into account, instead of correcting land use practices once they have become problematic, long term goals should be prepared to help protect river ecosystems with scientists and managers communicating with urban planners so that streams can be protected during urbanisation rather than attempting to rehabilitate them afterward (Karr and Chu 1999; Cottingham *et al*., 2005). An ‘ecosystem services’ approach to ‘geomorphology’ certainly has the potential to help river restoration projects maximise ‘benefits’ whilst reducing the potential for systematic risk to lowland riverine ecosystems.

6.0. Conclusion

This thesis has introduced a framework that needs to be applied to other systems to discover its ‘usefulness’ in ecosystem research for an array of ecosystems. However, for the first time cost and associated benefits of geomorphological processes and form (GF) have been highlighted and therefore provide rationale for restoration. A ‘geomorphological approach’ also allows for a reach scale analysis which provides a useful scale to work, identifying FES at a local scale rather than a catchment or regional scale. The use of reach scale analysis can help discover underlying processes and functions that contribute towards the delivery of FES. The reach scale analysis is crucial when managing and restoring the natural environment.

The framework has been designed to prevent blinkered environmental management and single FES delivery, whilst encouraging the delivery of multiple FES specific to lowland river ecosystems. An ‘ecosystem services’ approach to geomorphology can only help enhance ecosystem management. However, the ‘geomorphological framework’ has only identified the links between ‘GF’ and ‘FES’ that are already being recorded in other frameworks (e.g. MA, 2005). A multi-objective approach will help enhance the linkages between ‘GF’ and the amount of associated ‘benefits’.

Chapter four has explored the technique of using restoration to place costs to GF and respondents ‘willingness to accept government funding’ to draw attention to the general publics’ opinions on FES. Even if ‘benefits’ that develop from FES can only be expressed in qualitative terms, recognising the links between ‘geomorphology’ and multiple ‘FES’ can help shed light on the contribution made by lowland riverine ecosystem services to society and perhaps help guide away from narrowly-framed management for single FES.

An interdisciplinary and multi-disciplinary approach that incorporates all relevant disciplines including social and natural sciences is required to help understand complex relationships between ecosystems and the services that they provide. This thesis has helped demonstrate how ‘geomorphologically diverse’ lowland riverine environments can contribute towards the delivery of multiple ‘benefits’, whilst using restoration as a technique to place monetary cost to reach scale GF. However, due to the complexity of restoration and variability of site specifics, costs for GF vary, which causes a problem when identifying the value of a specific form.

To support better decision making in the future, further communication between scientists (across different disciplines), decision holders and the general public is required. As explained by Fisher *et al*. (2009) scientific research can help inform society and decision makers on particular issues, whilst also providing a platform for scientists to learn what is deemed important by the public. A coalition of various disciplines can help develop a more detailed understanding of the links between land, water and the delivery of FES. To summarise, the 'geomorphological framework' is a method that attempts to place a cost to physical form and associated processes that are essential in providing the platform for bio-physical interactions and FES. The 'geomorphological framework' requires further testing with more field measurements in a variety of riverine environments; nonetheless it is a starting point to help place costs to natural riverine characteristics.

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