Guidebook of applied fluvial geomorphology

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Preface

Purpose of the guidebook

The primary purpose of this guidebook is to collate and summarise the results of geomorphological research and development projects performed for the Environment Agency of England and Wales and its predecessor the National Rivers Authority, and supported by Defra (R&D Project FD1914), during the period 1990–2009. During that period the use of geomorphology in river engineering, management, conservation and restoration increased dramatically. In the UK, the application of geomorphological science and practice now forms a regular part of projects involving flood risk management, fisheries, conservation, recreation, environmental protection and river restoration. The responsibilities to be placed upon the UK Environment Agency and other organisations concerned with river management by the European Union Water Framework Directive to assess the status of, and pressures on, river morphology will ensure that the uptake of geomorphology continues and expands. In this context, this guidebook is therefore intended for use by individuals involved in any area of river engineering and management. The aims of the guidebook are to:

- foster a general interest in and understanding of geomorphology in the river environment
- develop a recognition of the significance of geomorphological processes in river management applications
- give an overview of the different methods of incorporating geomorphological science into river engineering and management.

This volume is a guidebook rather than a handbook. It does not contain detailed, step-by-step instructions on how to perform geomorphological analyses and investigations. In selecting material for inclusion in the guidebook, the authors not only sought advice from relevant individuals from within the water management sector but also drew on the results of information gathered as part of training courses in geomorphology run for end users.

In drawing together this material the authors have made reference to the requests for information raised by end users as part of the questionnaires returned from training courses and from the authors' collective experience of working with the end user community both in the UK and overseas.

David Sear, Malcolm Newson, Colin Thorne
2009

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Fluvial geomorphology: its basis and methods

David Sear, *University of Southampton, UK,* ***and Malcolm Newson,*** *Tyne Rivers Trust, UK*

1.1 Introduction

Rivers are the arteries of the landscape, integrating the impacts of change in atmospheric and terrestrial systems and delivering these to the coast. En route, geomorphological processes create dynamic and diverse habitats, both in-stream and in riparian and floodplain environments (Petts and Amoros, 1996a). The dynamics of channel change have led to conflict with human resource development with the outcome that many river and riparian environments have been significantly modified and damaged (Brookes and Shields, 1996; Sear *et al*., 2000). Responses to change in driving variables (runoff regime and sediment loads) have become dampened or prevented through river maintenance (Sear *et al*., 1995), while in other circumstances, land-use and land management changes, coupled to more efficient drainage networks, may have increased system sensitivity to environmental change (Newson and Leeks, 1987; Robinson, 1990).

Nevertheless, increasing focus on the importance of the physical habitats created by geomorphological processes, and concerns raised by recent flooding, have served to highlight the importance of geomorphological processes in creating and sustaining biodiversity and flood conveyance. Thus, the recent EU Water Framework Directive (European Commission, 2000) makes 'hydromorphology' (the physical outcome of the interrelationship between flow regime and the channel perimeter) a central parameter in spatial and temporal assessment of compliance with regulations. In England and Wales, the introduction of Catchment Flood Management Plans (Evans *et al*., 2002) forces the attention of the most powerful river management function (flood defence) to evaluate channel properties and changes as a basis for sustainable asset management. Monitoring change in the geomorphology of the river environment is, therefore (and belatedly), an important measure both of river management practice and system resilience to external environmental change (Environment Agency, 1998; Raven *et al*., 1998). Fluvial geomorphology is key to understanding long-term river and floodplain processes of change and it is making an increasing contribution to environmental management of river basins.

1.2 What is geomorphology and what is it not?

Geomorphology is a natural or earth science that draws its roots from geology, hydraulic engineering and physics (Gregory, 2000). It differs from other natural sciences in that its focus is on the study of the processes of production, movement and storage of sediment within the landscape and on the characterisation of

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the features these processes produce. In its widest definition, geomorphology encompasses the study of glacial, coastal, slope, wind and fluvial processes of sediment movement across the surface of the earth. However, for the purposes of this guidebook, we shall be focusing on the movement of sediment within river catchments, and principally within the river channel and floodplain; or in other words, *fluvial geomorphology*.

Fluvial geomorphology is 'the study of sediment sources, fluxes and storage within the river catchment and channel over short, medium and longer timescales and of the resultant channel and floodplain morphology' (Newson and Sear, 1993). It is a specialist subject that usually requires outside contractors to supply the necessary levels of expertise. From the outset it is important to make clear that, like any science, a broad understanding of principles only gets you so far, and a little knowledge can be a very dangerous thing. Reading this guidebook will not make you a professional geomorphologist, but it will assist you to understand what fluvial geomorphology is and is not and help you to understand what type of contribution it can make to a range of river management issues.

The term *morphology* is also used in river management. Morphology refers to the description of the features and form of the river channel and floodplain. Morphology has significance to conservation and flood risk management interests through its links to physical habitat and conveyance respectively. Descriptions of channel morphology on their own do not provide information on the processes of sediment transfer and channel adjustment; to do this requires additional interpretation.

With the advent of the EC Water Framework Directive (European Commission, 2000) comes another term, *hydromorphology*. The hydromorphology of a river channel includes consideration of:

- 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.

Importantly hydromorphology is used within the Water Framework Directive as a biological quality element alongside water quality. In this context, therefore, hydromorphology is specifically related to the functioning of the river ecosystem and associated biological communities.

Information on both process and form are included within these broad definitions. Clearly, fluvial geomorphology is central both to the definition of hydromorphology and to the design and implementation of emerging pan-European monitoring methods (Newson, 2002; Raven *et al*., 2002).

1.3 Expertise and expectation in consulting geomorphologists

For the river manager, an important question is what skills come with what training and experience in geomorphology. For many river management problems, the geomorphologist needs first to have a good understanding of the processes of sediment transport and channel adjustment and how these are modified by changes in catchment processes or modification to the channel; and second, good field experience of interpreting river and floodplain geomorphology. Increasingly, specialist geomorphologists will come with numerical modelling experience and geographic information science skills.

Table 1.1 Guidance on the expected capability for different levels of training and experience in applied fluvial geomorphology

Experience of consultant	Expected capabilities
Specialist fluvial geomorphologist (PhD) with extensive field experience and track record of working with river management agencies and some experience of sediment and morphological/hydraulic modelling	Able to provide science-based but practical solutions to most river management issues, clearly and in terms understandable to non-specialists. Could be used on more complex projects and as specialists at public enquiries
Specialist fluvial geomorphologist (PhD) with no or limited field experience and no/limited experience of working with river management agencies and some experience of modelling fluvial processes	Sound on principles of fluvial geomorphology, but will have a steep learning curve on practical issues of river management. Advice on complex issues would be sound, and could be used as a specialist at public enquiry
First degree in geography/environmental science with Master's training in fluvial geomorphology/river management. No/limited field experience. No/limited experience of working with river management agencies; some limited modelling experience	Will understand more complex issues and should be able to identify potential causes of most problems. Limited experience of providing solutions. Best working alongside experienced practitioners
Trained non-specialist with field experience and experience of working with river management agencies (e.g. GeoRHS/RHS Geomorph. bolt-on surveyor)	Can identify potential problems and suggest solutions in straightforward cases. Able to make reliable decisions as to whether more specialised advice is required
Untrained non-specialist with field experience of working with river management agencies (e.g. RHS surveyor)	Able to recognise basic morphological features, with limited ability to interpret their significance or judge the need for specialised advice
Undergraduate trained geographer/environmental scientist	Able to recognise basic morphological features and identify potential problems, but would have a steep learning curve on practical issues. Best working alongside experienced practitioners

At present, no formal industry accreditation currently exists for geomorphologists such as the chartered status available to civil engineers and landscape architects. Instead, fluvial geomorphology is generally taught as part of an undergraduate or Master's degree in geography (physical geography). There is no training in geomorphology within existing taught courses in civil engineering or biology. Industry training in applied fluvial geomorphology for river management is available although tends to be organised locally and according to demand. This situation places river managers in a difficult position when attempting to identify the appropriate level of expertise for a particular task. Table 1.1 provides guidance for assessing the level of expertise that can be expected for a given qualification and experience. The daily rates for the different levels of experience and training should fall within normal commercial ranges.

1.4 What is the contribution of fluvial geomorphology to river management?

> 'It should be possible to persuade decision-makers that incorporating historical or empirical (field based) geomorphic information into river management strategies is at least as valuable as basing decisions on precise, yet fallible mechanistic models.'
>
> (Rhoads and Thorn, 1996)

Geomorphology needs to be considered in river management practice/policy if the answers to any of the following questions are YES: 1. Has/will the proposal/work alter the river discharge or sediment load? 2. Has/will the proposal/work alter the river channel or floodplain morphology or dimensions? 3. Has/will the proposal/work alter the channel boundary materials? If the answer to more than one question is YES then it is likely that the functioning of the geomorphology of the river system will be significantly impacted and some form of assessment will be required (see Chapter 2 for rationale behind these questions).

Fig. 1.1 When to consider geomorphology in river management

Since the early 1990s, applied fluvial geomorphology has risen up the operational and policy agendas of river management authorities (Sear *et al.*, 1995; Brookes and Shields, 1996; Thorne *et al.*, 1997; Downs and Gregory, 2004). It is now firmly established within the river management policy and practice of government and non-government agencies within Europe, North America, South Africa, Australia and New Zealand, where it is seen as vital and necessary for sustainable river channel and catchment management. The growth in the application of geomorphology has been driven by the recognition of the cost, both financial and environmental, of ignoring natural system processes and structure in river channel management (Evans *et al.*, 2004; Pitt, 2007). More slowly, a sense has emerged that geomorphology also brings direct benefits rather than simply reducing costs; its role in achieving sustainable channel management is a case in point. Figure 1.1 provides a simple framework for assessing whether or not a proposed or existing river management practice requires any knowledge of geomorphology in order to improve its performance or sustainability.

At its core, the fundamental philosophy of applied fluvial geomorphology is to understand, through interdisciplinary science, the causes of river management problems arising from river channel sediment transport processes, and to consider the implications of any proposed activity to address the problem on the local and regional sediment system. In concept this simplifies to answering the following three questions:

1. How is the problem linked to the catchment sediment system?
2. What are the local geomorphological factors that contribute to the problem?
3. What is the impact of any proposed/existing solutions on channel geomorphology (which includes physical habitat and sediment transfer processes)?

This concept is not alien to river management. The clearest analogy is in flood protection. A flooding problem may be viewed at two scales. First, the localised problem of the flooding itself, the cause of which may be a low point in a flood embankment. Second, the flooding problem may be viewed in terms of the wider catchment processes that generate the flood, such as changes in the infiltration capacity of the land surface and the efficiency of flood routing through the river network. The solution to this problem may be tackled locally (e.g. raising the flood embankment) or holistically (e.g. creating upstream flood storage areas, improving urban runoff management). The former is time efficient, the latter is more sustainable. The same approach applies to problems arising from processes of fluvial sediment transport, except that here, river managers are only just beginning to appreciate that you need additional specialist input, namely fluvial geomorphology, to identify the cause of the problem. Similarly, when designing river rehabilitation projects or flood alleviation works, the river manager is used to considering the effects on water conveyance (usually applied through 1-D hydraulic modelling of a proposal), but rarely considers the effects on sediment conveyance.

A review of the scientific literature and R&D reports highlights the following major problems facing the river environment and river management bodies that would benefit from the application of fluvial geomorphology:

- *Problems of excessive levels of fine sediments* or pollutant/toxin association with fine sediments (including metaliferous mine waste).
- *Channel instability* – river maintenance, habitat change (pool infilling), loss or gain of conveyance, land/infrastructure loss or damage.
- *Design and strategic planning* of river rehabilitation, flood channels, and river maintenance and flood protection programmes.
- *Mitigation through restoration* of the legacy of past river management where this has led to (currently) unacceptable damage to the river environment.

Some of the above relate to relatively local problems arising from sediment transport through a reach, but others clearly have a wider catchment basis. Fluvial geomorphology links these scales and, when working alongside other relevant disciplines, can make meaningful and significant contributions to the improvement of river system management.

Not all river management issues require the input of geomorphological advice, however those that influence the conveyance of sediment, or the modification of channel features and form, most likely require some level of input. Common or typical river management problems that benefit from understanding the fluvial geomorphology of the river system include:

- sedimentation of river beds, in particular spawning gravels
- contamination of floodplain soils through overbank sedimentation and floodplain evolution
- influence of channel adjustment on flood conveyance
- bank erosion management
- desilting/shoal removal arising from deposition of sediments that increase flood frequency
- rehabilitation of rivers and floodplains for habitat improvement
- design of environmentally acceptable flood/drainage channels
- strategic assessment of catchment issues including Catchment Flood Management Planning and designation of conservation status
- Environmental Impact Assessment.

The forgoing list makes clear that fluvial geomorphology contributes naturally to issues of flood risk management and biodiversity. This is a strong asset, since its application can help rationalise the issues surrounding channel maintenance or rehabilitation by focusing on the implications of proposed operations on river channel form and stability. Since river channel form encompasses attributes of both physical habitat and channel stability, the use of fluvial geomorphology is pivotal to planning projects that are sustainable. Table 1.2 sets out some of the main generic procedures undertaken in support of river management in the UK, together with their main national and European policy drivers. The geomorphological input to these management procedures is given in broad terms. What is clear is that the impact of any proposal/policy on the form, function and sediment system of a river channel and surrounding catchment should be among the issues considered at the inception and evaluation phase.

Table 1.2 The role of fluvial geomorphology in UK river management procedures

Management procedure	Policy driver	Fluvial geomorphological input
Development control/land drainage consent	UK Biodiversity Action Plan/European Habitats Directive/Water Framework Directive/Wildlife and Countryside Act (WCA), Natural Heritage (Scotland) Act	Will the proposal influence the channel morphology/function/sediment system?
Planning applications	UK Biodiversity Action Plan/European Habitats Directive/Water Framework Directive	Will the proposal influence channel morphology/function/sediment system?
Habitat improvement/restoration/rehabilitation Includes fisheries enhancement projects	Environment Agency responsibilities and works/UK Biodiversity Action Plan/European Habitats Directive/Water Framework Directive/WCA	Geomorphological input to the design of such works to ensure appropriate form and function is retained/restored
Physical quality objectives	Environment Agency corporate targets/Water Framework Directive	Identification for management of geomorphological reaches within river systems. Setting of appropriate targets for improvement of geomorphology of river reaches
Habitat protection	Environment Agency responsibilities and works/UK Biodiversity Action Plan/European Habitats Directive/Water Framework Directive	Appraisal of form and function and significance/rarity of morphological features/processes to support local or national protective designation (SSSi, RIGS etc.)
Catchment abstraction management	Environment Agency corporate targets	Input to geomorphological aspects of ecological impact assessments for CAMS
Flood protection – capital schemes	Environment Agency responsibilities and works	Will proposed works adversely impact form/function/sediment system? Conversely, will geomorphological features/process adversely impact on proposed works?
Flood protection – maintenance schemes	Environment Agency responsibilities and works/ 1997 Flood Prevention and Land Drainage Act (Scotland)/WCA	Will proposed works adversely impact form/function/sediment system? Conversely, will geomorphological features/process adversely impact on proposed works?

Catchment flood management planning	Environment Agency flood defence management tools	Identification of broadscale geomorphological characteristics to inform understanding of catchment processes. Inform where further strategic studies are required
Post project appraisal (flood defence capital schemes)	Environment Agency responsibilities and works/ 1997 Flood Prevention and Land Drainage Act (Scotland)/WCA	Have works performed as expected in terms of interaction with form/function/sediment system?
Post project appraisal (Habitat improvement, etc. works)	Environment Agency responsibilities and works/WCA	Has design worked as intended in terms of form/function/ sediment system?
Environmental impact assessment	Environment Agency responsibilities and works	Will proposed works adversely impact form/function/sediment system?

Note: *Morphology* is the set of features and dimensions of a river channel. *Function* refers to whether the reach is supplying sediment, storing sediment, transferring sediment or a combination of these. The *sediment system* refers to the set of processes that supply, transfer and store sediment in the river catchment and therefore includes actions that occur on the catchment land surface that may increase or decrease sediment delivery to the channel.

1.5 Costs and benefits of using fluvial geomorphology in river management

Sear *et al.* (2000) have demonstrated that the costs of erosion and deposition in England and Wales, as managed using standard engineering approaches, are more extensive and expensive than previously thought. Moreover, the costs to the environment in terms of modified hydromorphology resulting from past engineering practice are likely to be immense based on the substantial lengths of modified channels revealed in national river habitat surveys (Raven *et al.*, 1998; Sear *et al.*, 2000). At the same time the number of projects that have used river geomorphology is increasing. A review of over 40 river management projects reveals the following benefits of using fluvial geomorphology:

1. Geomorphological approaches differ from existing conservation-led approaches, in providing a clear link between catchment processes and management and the management of river processes.
2. In a *strategic role*, fluvial geomorphology may be used to predict the outcome of operations for inclusion in environmental assessment procedures and the planning of improvements in river morphology and habitats.
3. In a *proactive role*, fluvial geomorphology may be used as a decision support tool for managing flood risk management capital and maintenance programmes; providing reasons for the preservation or restoration of morphological features and creating designs for channels that seek to minimise or accommodate erosion and deposition over short, medium and longer terms.
4. In a *regulatory role*, geomorphology is used to assess and consider development control/land drainage consents and planning applications in terms of the likely impacts of proposals on morphological change and sediment load.
5. In a *reactive role*, geomorphology may be used to assess the cause of channel changes, and provide practical guidance directly applicable to a wide range of functional users.
6. The outcome of incorporating geomorphological approaches is always beneficial to the hydromorphology and wider river environment.

Before moving further into the detail of geomorphology as a science and source of useful information and assistance in the decision making of river management, it is important to emphasise that rivers (particularly mountain streams and those rivers conveying gravel loads in steeper areas of the country) often behave quite unpredictably during flooding. Thus just like other disciplines associated with rivers, while in general it may be possible to explain or even predict how a river and reach function, there will always be ‘surprises’. These should not be seen as failures of the science, but rather, as that great engineer Sir Isembard Kingdom Brunel realised on the collapse of his first railway bridge on the Great Western Line, such occurrences are in fact the greatest opportunity to learn.

At a national level, it has been argued that a significant proportion of the costs of protecting against bank erosion and maintaining river channel capacity could be recovered by applying fluvial geomorphology (Environment Agency, 1998). This can be achieved through efficiently targeting best-practice solutions based on identifying the cause(s) of erosion/siltation problems. This has been the independent conclusion of all the reports reviewed to date. These reports specifically identify cost savings from fluvial geomorphology in the following key areas:

- a reduction in maintenance frequency
- more efficient targeting of resources for treatment of the cause of an erosion/siltation problem

- improved design performance (e.g. self-cleansing low-flow channels)
- designs that enhance the aquatic environment and *which need no future restoration*.

Intangible costs such as those associated with the impoverished aquatic environment inherited from past practices can be redressed through their rehabilitation – a process that requires knowledge of how the river creates and sustains an appropriate river morphology that can only be found in the science of fluvial geomorphology.

In terms of the additional cost component, it is clear that of the schemes reviewed to date, *incorporating fluvial geomorphology in standard project areas amounts to between 0.1% and 15% of total project costs*. Using fluvial geomorphology at a project level is therefore *not* cost prohibitive, while the potential benefits, though sometimes intangible, are considerable.

The value-added factor of geomorphology over current river management practice is based on its ability to predict the nature and cause of river channel evolution, which provides the information needed to answer questions about intervention and enhancement. In addition, because geomorphology actively promotes understanding of the complex form and processes in river channels, designs that include a geomorphological component are generally more likely to be sustainable in terms of long-term maintenance, aesthetically pleasing, and to retain physical habitat that is essential for preserving or enhancing biodiversity. Chapter 6 provides examples of how geomorphology has been applied to real river management issues.

1.6 Geomorphology and sustainability

While there is little agreement on reaching a unified definition of sustainable development, the concept embodies at its core an understanding of natural, ecosystem processes and their incorporation within practical (river) management (e.g. Clark, 2002). The following dimensions of sustainable management are well understood by fluvial geomorphologists and are a feature of the advice and outcome of its use in river management:

- longer planning timescales
- an understanding of natural processes over such long periods
- separating natural and artificially induced change in natural systems
- threshold behaviour of a system under certain conditions of stress
- reaction and recovery of natural systems.

Graf (2001) concludes that "The primary consideration in establishing policy for river restoration is to address the problem of 'what is natural'." Similarly, the Water Framework Directive uses the concept of 'natural rivers' to define reference conditions for defining good ecological status. Geomorphology has much to contribute to this discussion and the broader debate around deciding how far towards the natural reference state society will go and what is possible to achieve in terms of ecological status under different conditions of restoration (see the journal *Earth Surface Processes and Landforms*, Vol. 31, 2006). Clearly the role of geomorphology in developing sustainable river management practice is not isolated and requires improved dialogue with other disciplines (e.g. ecology/engineering – Chapter 6).

1.7 What are geomorphological timescales?

One of the least understood aspects of the practice of fluvial geomorphology is the apparent obsession with longer timescales. Why this misunderstanding occurs is

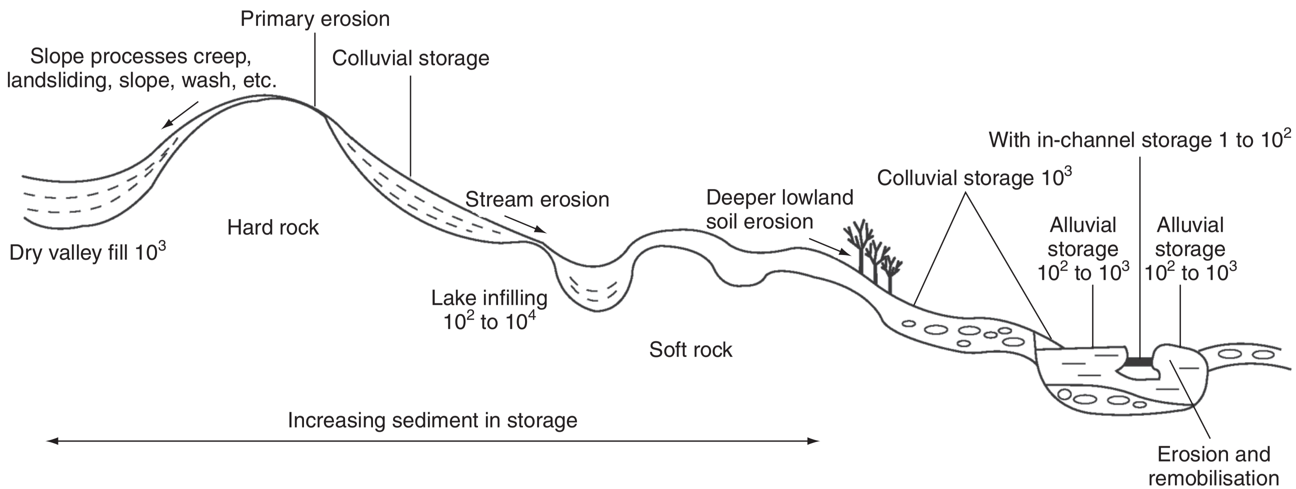

Fig. 1.2 Indicative sediment storage time in the river landscape. Reproduced, with permission, from Brown, 1987. © 1987 John Wiley & Sons Limited

unclear, since anyone involved in flood risk management is familiar with the value of historical documents for extending the flood record; and ecological surveyors often lament the lack of longer-term datasets. The main reason for including a longer-term perspective in geomorphological studies is simply that the processes that create the features observed in a river landscape often work slowly, or are responding to events that happened in the past. A full understanding of current river processes and forms must therefore logically extend investigation back in time. Among the main processes that introduce the need to consider longer timescales in geomorphological studies is the storage of sediment in the catchment and channel network and the role of past events in producing long-term phases of channel adjustment. A good example of both is the continued incision of upland streams into their valley floors following increased flood frequency in the 18th and 19th centuries and the deposition and reworking of the sediments evacuated from these valleys that occurs within the main trunk streams (Macklin and Rumsby, 1994; Passmore and Macklin, 2000).

The movement of sediment across the landscape is often punctuated by periods of storage. For example, up to 30% of fine sediment loads are stored in floodplain soils for periods of up to thousands of years, while coarse sediments may be stored in different types of in-channel deposit (Fig. 1.2). As a result, the time taken for a release of sediment from the land surface to be detectable within the river network, varies according to the intervening opportunities for storage. This has the effect of increasing the timescales necessary for the understanding of the sediment system, from single events (a flood, landslip, etc.) up to thousands of years. To many, the notion of exploring river behaviour over such long timescales seems irrelevant to the operation of normal river management, that typically considers action at event to a 50-year timescale. However, the value of having a longer-term perspective is fundamental to understanding the functioning of certain river channel processes, such as planform change and floodplain evolution. Similarly, because of sediment storage, it is often necessary to look much further back in time for the cause of a recent change in the river sediment system. An example of this might be the reactivation of former alluvial deposits arising from recent channel migration.

A feature of working with longer timescales in river management is that, as one looks back in time, the quantity and accuracy of information declines, and the degree of specialism required for reliable interpretation increases (Sear and Arnell, 2006). Significantly, as one begins to view a river system from increasingly longer timescales, there is a shift in emphasis from local to catchment scale processes. Here the significance of a single event reduces as the timescale of investigation extends. Leys (1998) provides an example based on the cut-off of a single meander bend (Table 1.3). In this example, what appears to be a drastic change in river planform (and usefulness of riparian land) is shown to be not only typical of the behaviour of the reach but broadly explicable in terms of the adjustment of the River Endrick to long-term reduction in sediment supply after glaciation. The channel response is both natural and typical; the decision to intervene is not straightforward but now involves judgement based on the potential longer-term commitment to erosion control in this reach.

The significance of applying a longer and wider view of river channel form and process helps the river manager understand not only the role of other processes in the creation of the river landscape but also the significance of environmental change in driving river channel behaviour.

Identifying the appropriate timescale for the development of river channel morphology is particularly relevant to the management of lowland river systems in the UK. Like many low-energy river systems, there is increasing evidence that

Table 1.3 The significance of timescale in applying fluvial geomorphology to river channel management; meander cut-off processes on the River Endrick

Timescale	Source of evidence	Interpretation	Management guidance
Event/year	Measurement, observation	The process of cut-off development is an isolated problem for one riparian owner	Fix problem (channel reprofiling or bank erosion control) or check if problem is really isolated
Decade	Measurement, observation, air photography	The neck of the meander bend has been reducing in width over the past decade through active bank erosion processes	This is part of a general trend, but does it have a recent artificial cause?
Century/ historical time	Historic maps, records, observations, air photographs, field-based landform interpretation	Historical analysis shows that the cut-off is part of the meander migration process characterising this reach. Rates of migration are variable over these timescales	The cut-off is part of the long-term behaviour of this reach. Other bends have behaved similarly, and there is evidence for floodplain development through this process
Post-glacial	Field-based landform interpretation, sedimentological analysis of floodplain Landform analysis from air photos	The site is set within an alluvial basin that has at first filled with post-glacial sediments, and then incised following a reduction in catchment sediment supply. The meander migration processes are part of this long-term response to de-glaciation in this alluvial basin	The whole reach behaviour and channel typology owes its existence to glacial and post-glacial processes. It is part of the natural processes of adjustment. Do not intervene. To do so would be expensive and involve long-term commitment

what semi-natural morphology exists today is largely relict (Sear *et al.*, 1999). Restoration of features that were possibly uncommon, or randomly distributed in these systems (e.g. riffle–pool sequences), may provide abundant habitat for certain species, but does not restore the natural level of ecological diversity or physical functioning to the river system (German *et al.*, 2003; Kondolf *et al.*, 2003b).

1.7.1 Timescales and threshold behaviour in river channels: implications for river management

The longer timescales used by geomorphologists have led many to consider river behaviour in terms of a dynamic but steady system, one in which short-term changes occur, but do not alter the general state of the river system (Fig. 1.4). The routine observation of a river confirms this dynamic stability; day to day the river looks the same, has the same dimensions and form and is in the same location. Some river types, maintain the same dimensions, form and location over long periods of time, up to many hundreds of years – these are considered to be in equilibrium with the inputs of water and sediment. Others may outwardly maintain size and form, but progressively change location, displaying dynamic equilibrium. Still other river types may switch rapidly from one set of dimensions and form to another in response to either external drivers (a recent flood or modification) or as a result of internal change (the meander cut-off that drastically alters the planform of a channel). These latter river types display threshold behaviour; a term drawn from physics where, for example, thresholds occur between solid, liquid and gaseous states of a material (Fig. 1.3).

Threshold behaviour in river channels is well documented (Newson, 1992; Church, 2002) and presents river managers with potentially challenging scenarios.

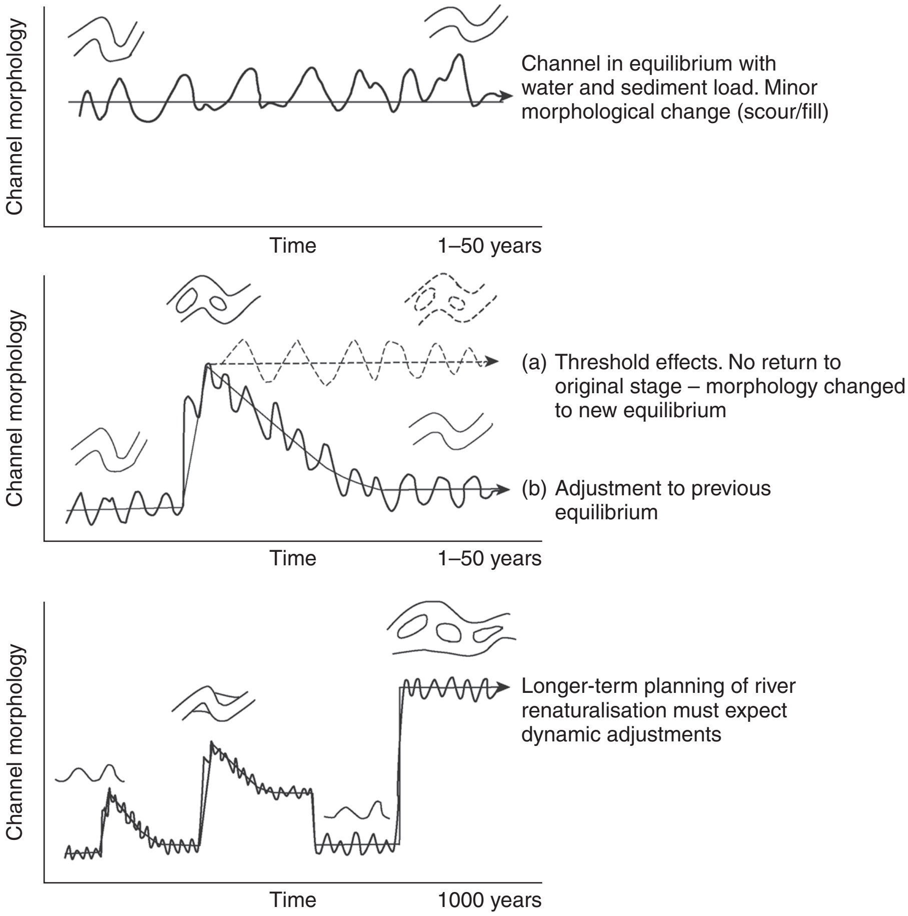

Fig. 1.3 The concept of equilibrium in fluvial geomorphology. Reproduced, with permission, from Sear, 1996. © 1996 John Wiley & Sons Limited

For example, rivers close to a threshold state are said to be sensitive to external pressures; they can exhibit large changes in form, location and scale in response to a relatively limited change in controlling variable (e.g. change in sediment load, grazing of vegetation from banks). Equally, knowledge of the threshold behaviour of a river reach can provide river managers with the confidence not to intervene due to the sensitive nature of a reach close to a threshold. The recent MImAS morphological assessment tool incorporates the sensitivity of a channel into the evaluation of the impacts of an engineering activity (SNIFFER, 2006).

Models of channel sensitivity incorporate notions of resistance to change and resilience to change. Resistance to change describes the ability of a channel (or morphological feature) to remain essentially unchanged in the presence of a disturbance (or pressure). Resilience describes the ability of a channel to recover (return to its original state) after a disturbance. Within this resistance/resilience framework, channels (or ecological communities) of increasing resistance and resilience are described as less sensitive to disturbances, whereas channels (or ecology) of decreasing resistance or resilience are described as more sensitive. Resistance/resilience has been linked to channel type (Table 1.4) within the MImAS morphological assessment (SNIFFER, 2006).

The valley floor and floodplain often contain clear evidence of former channel morphology, and can, along with historical information, provide very clear guidance as to the typical morphological response of a reach/channel network. In contrast,

Table 1.4 Linking channel types to geomorphic resistance and resilience to external pressures (e.g. engineering works or rehabilitation) (after SNIFFER, 2006)

Resistance/resilience classes	Channel types	Terminology
High resistance (bed and bank) Low resilience (bed and bank)	Bedrock, cascade	A
High resistance (bank) Medium resistance (bed) Low resilience (bank and bed)	Step-pool, plane bed	B
Medium resistance (bed and banks) Low resilience (bed and banks)	Low-gradient passive meandering	F
Low resistance (bed and bank) Medium resilience (bed and bank)	Plane-riffle, pool-riffle, braided, wandering	C
Medium resistance (bank) Low resistance (bed) Low resilience (bed and banks)	Groundwater dominate (chalk)	E
Low resistance (bed and bank) Low resilience (bed and bank)	Low-gradient active meandering	D

recent channel response to the 'millennium floods' of autumn 2000, resulted in little channel response in lowland Britain despite high magnitude and prolonged flows (Sear *et al.*, 2002). In lowland systems, the combination of low slopes and resistant channel boundaries makes these systems relatively insensitive to changes in water and sediment regime, with the notable exception that fine sediments tend to accumulate within the channel.

Differences in channel dynamics have a significant impact on the development of ecological communities (Petts and Amoros, 1996b). Highly dynamic and stable river morphologies are both characterised by relatively low species diversity, the former arising due to the lack of perturbation in the system, the latter due to too much perturbation (Beechie *et al.*, 2006; Yarnell *et al.*, 2006). Diverse ecological communities in river channel/floodplain systems require some morphological adjustment. This strongly suggests that if we increase or remove the dynamism within a river environment, we will not only influence the geomorphology but will also impact the ecology. This principle is incorporated within the EU Water Framework Directive (European Commission, 2000) that recognises the importance of hydromorphology for maintaining ecological status.

1.8 What are geomorphological data?

Many people assume that geomorphology requires data that are in some way non-standard. In some respects this is correct, but in fact an increasing amount of the data needed for the geomorphological assessment of a river system can be derived from existing, standard datasets. Where the data needs differ is usually in the demand for information on sediments. Geomorphology differs too in terms of its focus on the spatial arrangement of features and material. The detailed location and sequencing of features is common to all geographical science, but is uncommon to most others. The reason behind it lies in the need to establish the sequence of source, and storage of sediments and to build up the longer-term picture of how these have changed over time. Most other field surveys (RHS, RIVPACS, Flood

Defence Asset Surveys, etc.) are concerned with defining the status of features at fixed locations, rather than the sequence of movement of those features (dynamics) over time.

Most geomorphological studies require data on three areas of information:

1. *The morphology or form of the river* which may involve a variety of scales including the catchment, river network, valley form, river channel size, shape and features.
2. *The materials associated with the morphology* – including measures of the sediment size range, vegetation composition, geology. In more detailed studies the strength of the materials may be needed since these influence the production and transport of sediment.
3. *The processes associated with the functioning of the fluvial system* – these may include slope processes (e.g. soil erosion, land sliding), bank erosion processes, processes of deposition and transport of sediment.

In turn, information on these factors is often required at a range of space and timescales, ranging from cross-section to whole catchment, and from short duration event to millennia (Fig. 1.4). In addition to these main factors, information is required to help understand the rates of change in a catchment sediment system. These involve data collection on the change in driver variables of river geomorphology. One of the main challenges for applying geomorphology in the UK is the lack of data on sediment transport rates either suspended or bedload. Unlike the US, where at least 9000 sediment gauging stations exist, the UK has none. Thus, changes in one of the two main drivers of channel behaviour must be inferred from a mixture of empirical (field-based) data, theoretical or numerical modelling, and interpretation of the river and landscape. Problems with the application of existing empirical and numerical models of sediment transport lie in the need to calibrate them to the local conditions, and the availability/expense of data and suitably skilled modellers. However, even when calibrated and performed by specialists, the output from sediment transport models is usually indicative rather than absolute. Interpretation of the river and landscape is a cheaper approach which, although semi-quantitative, provides more information than the other methods on the important control of sediment supply on the rates of sediment transfer in UK rivers. Ideally, acquisition of sediment transport data should be seen as a goal for future investment in the UK gauging station network, particularly when in the case of fine suspended sediments it is relatively inexpensive to monitor, and is essential in order to validate expensive catchment management programmes aimed at reducing fine sediment yields.

1.8.1 Data on morphology and form

Data on river morphology includes information that defines the planform, cross-section form and the long profile of the river channel. It also includes information on the floodplain such as width, slope and features such as terraces and floodplain channels. Data on the valley form may also be important to consider, particularly the presence or absence of connectivity between the valley sides and channel. At a larger scale, morphological information extends into definitions of the river network and drainage basin. An increasing number of UK catchments have been surveyed by geomorphologists, and information on the detailed morphology of the river network is available (see Chapter 6).

Much morphological data is derived from existing topographic surveys (see review in Gurnell *et al.*, 2003), aerial photography and increasingly remote sensed data such

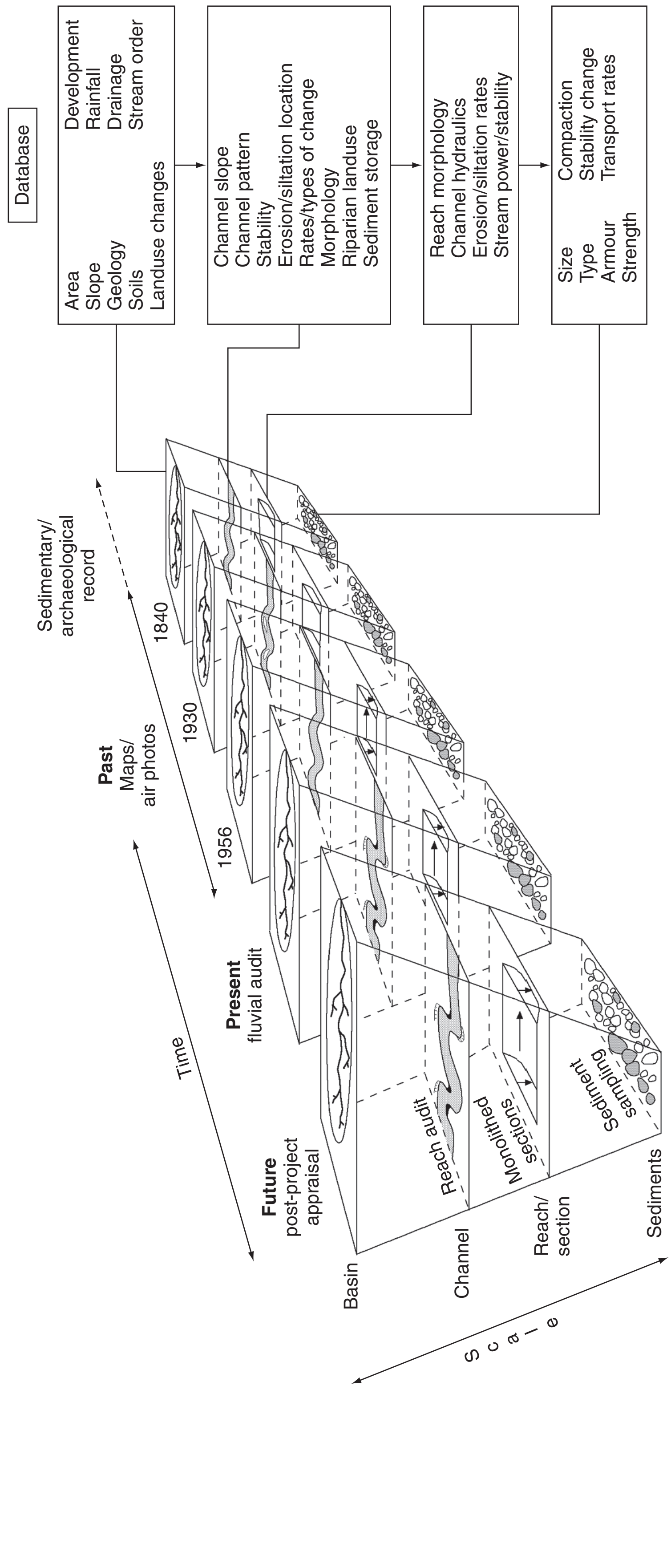

Fig. 1.4 Types and scales of data used in fluvial geomorphological assessment. Reproduced, with permission, from Sear et al.*, 1995. © 1995 John Wiley & Sons Limited*

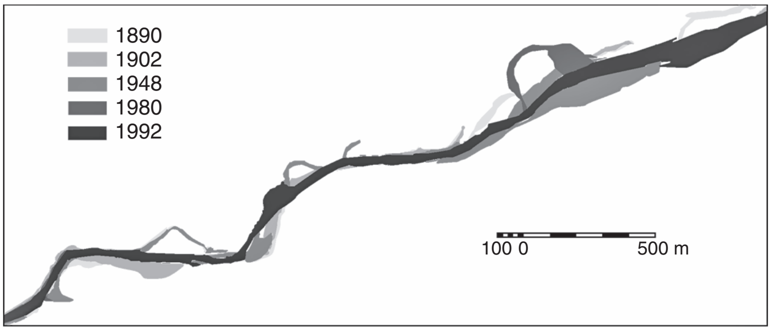

Fig. 1.5 Information on historical river planform change derived from overlaying large-scale maps (Afon Dyfi, i.e. River Dovey)

as LiDAR and Multispectral imagery mounted on aircraft or satellites (see review in Gilvear and Bryant, 2003). In the case of existing topographic maps and air photographs, these provide the opportunity to record changes in channel morphology (e.g. planform, channel width, meander dimensions) over periods of up to 200 years in some cases. Figure 1.5 illustrates how the use of historical map overlay can provide information on the changing planform morphology of a river channel, set within the context of the floodplain. Such data may be useful for establishing the presence of change in a system, or for reconstructing channel dimensions for restoration or for evaluating erosion zones (Rapp and Abbe, 2003).

One of the main problems with using existing topographic maps for deriving absolute values of channel dimensions, or for reconstructing channel change, is the degree of accuracy and error within the data. Gurnell *et al.* (1994) and Gurnell (1997) have shown that of those errors that can be quantified, the resulting channel change must be larger than 10 m in order to have confidence that the movement recorded on the maps is real. A similar analysis for the estimation of channel width from maps by Sear *et al.* (2001) gives an error of ± 4 m, which for smaller channels may represent a complete or multiple channel width.

An increasingly valuable source of information for geomorphology lies in the interpretation of remotely sensed data flown for government agencies and others. Remotely sensed data takes the form of multi-spectral scanning (CASI) or laser altimetry (LiDAR). The two datasets can be combined to generate 3-D thematic maps of water depths in the floodplain, vegetation classifications, detailed floodplain and channel topography (see Fig. 1.6). The topographic data recorded from LiDAR can be used, when processed, as input data to hydraulic modelling, and enables much higher resolution to be achieved than is currently possible through field surveying. Further improvements in resolution are becoming available through low-level laser scanning of the river and floodplain through helicopter-mounted platforms (e.g. FLIMAP). Even higher spatial resolutions (sub-centimetre) are possible for short reaches (1–2 km) using terrestrial-based laser scanning. At these resolutions, it is possible to measure the roughness characteristics of flooplain and bar surfaces.

One of the most important data sources for morphological information is the field survey. Field reconnaissance is a key tool for geomorphology (Downs and Thorne, 1996). Recording the spatial arrangement (both downstream, across the valley floor and vertically), provides the geomorphologist with a dataset from which inferences can be made as to the adjustment processes and impacts of former management activity on a river system. Two methods of data collection are used: the walk-through survey, that records in mapped form the distribution of geomorphologically relevant

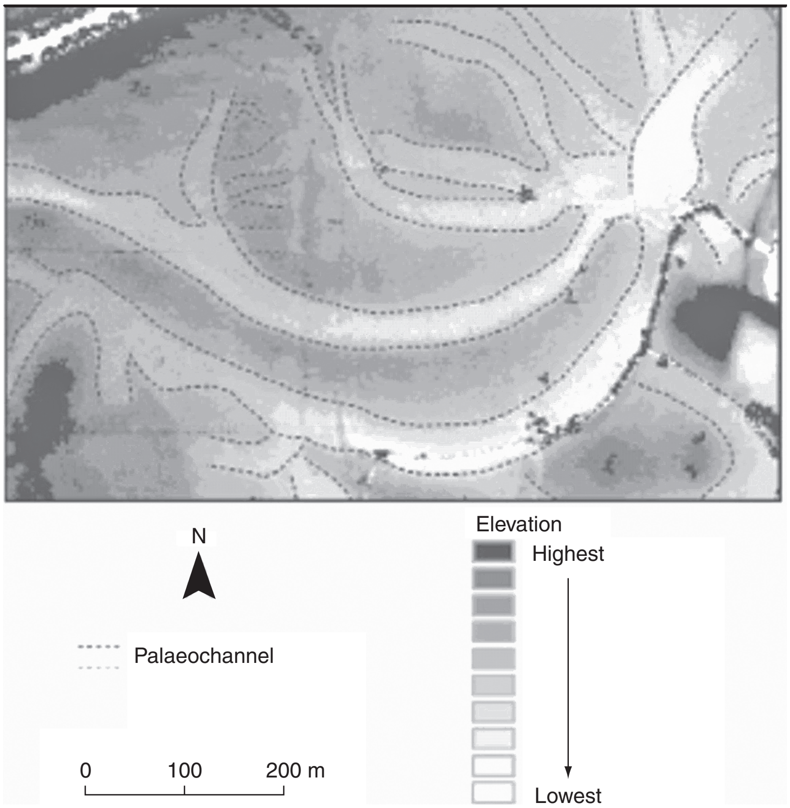

Fig. 1.6 Example of geomorphological data extraction from a LiDAR raster dataset. Reproduced, with permission, from Jones et al., *2007. © 2007 John Wiley & Sons Limited*

features (Fig. 1.7a); and the geomorphological map (Fig. 1.7b). The former often simplifies the detail but covers scales up to the river network, while the latter is typically used for detailed interpretation of a river and valley floor. With the advent of global positioning systems, accuracy in positioning features in space has improved, increasing the value of such mapping and surveys as baseline data sources.

Cross-section surveys generally exist for those reaches of a river network that have been subject to flood modelling or for the design of land drainage or flood protection schemes, where embankment levels and bed elevations have been required. In the latter case, only long profiles may be available. In some cases such surveys may date back to early 'river works' of the 1930s, but in the majority of cases information will be more recent. The geomorphological data found in such surveys take the form of cross-section morphology and dimensions, some estimation of bed slope, information on bank angles that might be important for bank stability analysis, and of course location of the bed elevation and channel. The opportunity to resurvey former cross-sections can provide important quantitative data on channel change in three dimensions – planform, width adjustment through bank erosion of deposition, and depth adjustment through incision into the river bed or aggradation of the bed as a result of sedimentation (Downward, 1995). The accuracy of these data depends on the ability to relocate cross-sections, and the degree of change relative to the measurement errors in the survey technique (Downward, 1995; Gurnell *et al.*, 2003).

The main problem with the use of existing cross-section survey data for geomorphological interpretation lies in the coarse resolution of the cross-sections. In

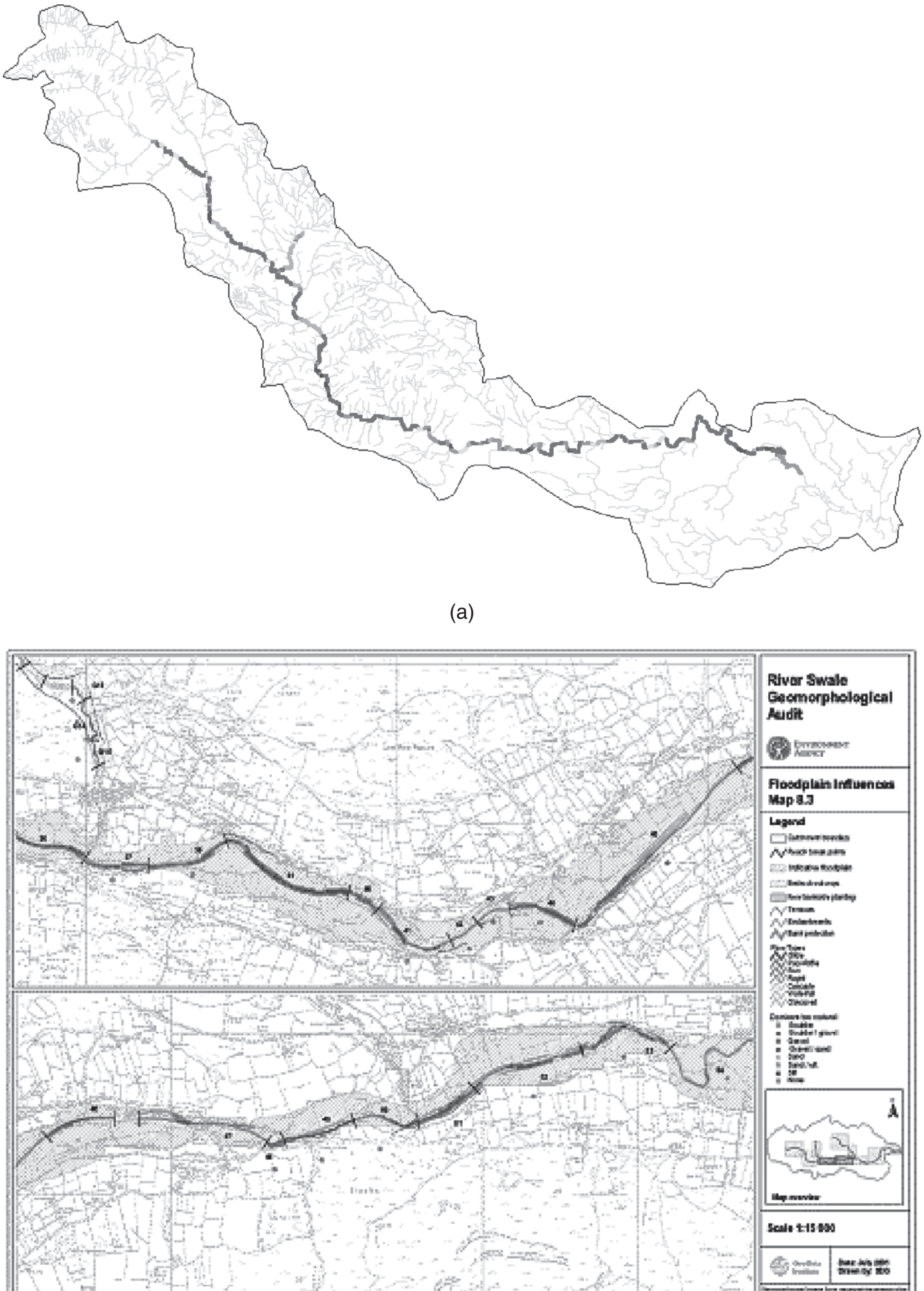

Fig. 1.7 Example of fluvial geomorphologial data capture (a) in a catchment scale survey (GeoData Institute, 2000); and (b) at the reach scale (GeoData Institute, 2001a)

general, most cross-sections are surveyed at regular intervals of multiple channel widths and do not attempt to pick out geomorphological features such as riffle crests, height of bar surfaces, etc. Omission of these features from a long profile can lead to erroneous estimates of bed slope, a term often used in the calculation of sediment transport where a measure of water surface slope or energy grade line is unavailable.

Table 1.5 Data and information used for the management of bank erosion and siltation in a small lowland catchment: River Sence, Leicestershire

Data source	Information
Historical records from the Land Drainage/Flood Defence Committee	Dates and location of land drainage scheme, maintenance programmes. Earliest date for bank erosion and siltation problem
Historical maps dating back to 1898 at 1:10560 scale	Location and type of channel planform change through time. Estimates of bankfull width. Information of erosion rate (1878–1965)
Cross-section surveys along the reach made in 1968, 1976, 1992	Location and type of cross-section change. Information on change in channel dimensions. Evidence for incision/siltation between surveys. Bank erosion rates (1967–1992)
Suspended solids data from records of water quality 1970–1992	Magnitude and date of changes in fine sediment loads
Field reconnaissance survey to record location, extent and type of bank erosion and sedimentation	Current location, extent and type of bank erosion and sedimentation. Network scale evidence for incision/aggradation of river bed

Case study. Using cross-section surveys to understand bank erosion processes in support of river maintenance: River Sence, Midlands Region, Environment Agency

The River Sence is a small low-gradient stream draining a catchment area of 133 km^2 to the south of Leicester. The river suffers severe bank instability throughout much of the river network, resulting in the accumulation of fine sediments within the channel, and loss of riparian land. A geomorphological approach to the problem of maintaining bank stability and reducing siltation of the channel was based on identifying the causes of both management problems. A suite of data was used to build up a picture of the historical channel adjustment, as well as comparing this to contemporary evidence of bank erosion processes. Specific datasets used together with the information they provided are given in Table 1.5.

The interpretation of these data showed how the erosion and sedimentation were linked to the impact of a land drainage scheme that over-deepened the channel and steepened the river banks to a point where they became geotechnically unstable. Field evidence confirmed the presence of incision of the river bed and rotational slips in the banks, indicative of a geotechnical basis for the erosion. Using estimates of bank erosion rates derived from repeat cross-sections, together with reconnaissance survey estimates of eroding bank length, provided evidence for the contribution of bank erosion products as the main sources of the sedimentation in the channel. In addition, it was possible to identify a threshold of bank height and bank angle above which the channel banks were geotechnically unstable (see Chapter 4, Fig. 4.14).

1.8.2 Data on materials

Material properties are necessary as they provide information on the resistance of the bed and bank material to erosion, and the particle size characteristics of sediment supply and sediment storage (Kondolf *et al.*, 2003b). The data used to define the materials of a river bank, river bed and floodplain are again contingent on the needs of the investigation. Clearly, at a catchment scale, it is unreasonable (except in research projects) to expect detailed particle size information to be

Table 1.6 Indicative types of sediment analysis required for different scales and types of geomorphological investigation

Type of study	Sediment analysis
Asset Register, strategic geomorphological survey	Visual estimation of dominant particle size where this changes along the river network
Fluvial auditing of sedimentation problem	Pebble counting (100 clasts) at points where size changes in the network if budget/time allows
Sediment survey for salmonid habitat assessment	Freeze coring of spawning gravels to retain fine sediments and vertical splitting of frozen sediment cores. Particle size analysis undertaken on each layer
Bank erosion study	Record of bank stratigraphy (layers of sediment). Borehole shear test for sediment cohesion/friction angle. Particle size analysis undertaken on individual layers. Record of vegetation and root density/type
Sediment transport modelling	Surface and subsurface particle size estimation of a representative sample size required within study reach

collected except where this is the primary focus of a project (e.g. a catchment-wide assessment of salmon spawning habitat). Similarly, in a project that seeks to model sediment flux through a flood scheme, or one that needs to understand the processes of bank erosion in detail, then descriptive estimates of bed and bank materials are inappropriate (Table 1.6).

In addition to the description of the materials themselves, important information on the vertical adjustment of the river channel, and past river channel forms can be obtained from the vertical changes in river bank materials. Recording and understanding the arrangement of sediments is called stratigraphic interpretation, and should only be attempted by trained specialists (Jacobson *et al*., 2003). Nevertheless, relatively simple diagnostic indicators of whether the river bed has been lowered artificially or cut down naturally may be found where former river bed sediments are now perched above the level of the river bank (Fig. 1.8). Valuable historical

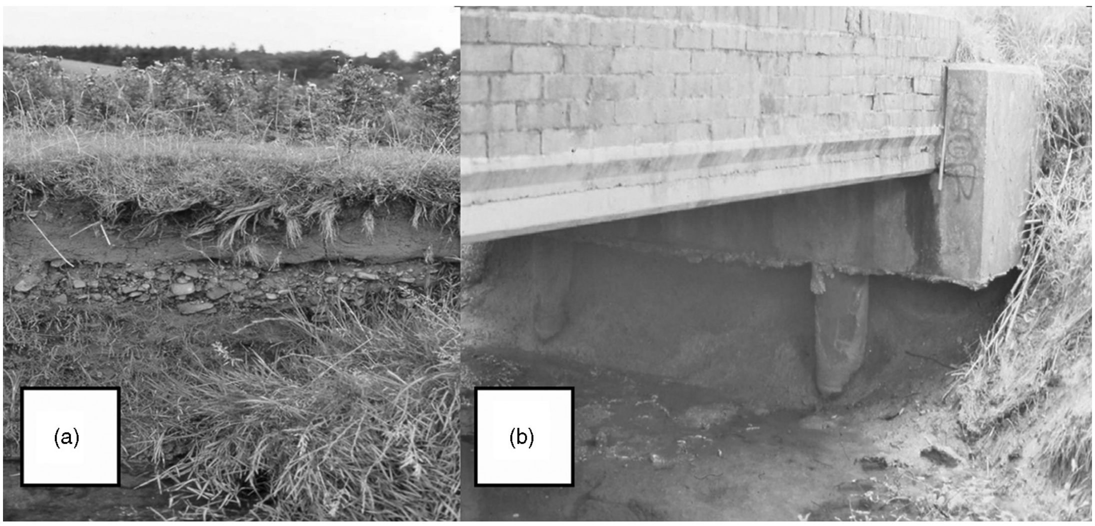

Fig. 1.8 An example of channel incision revealed by exposure of (a) a former bed level in the bank material. (b) Incision in this instance was a result of a land drainage scheme

information on the plant communities present in the past may be interpreted from analysis of the plant remains and pollen found in buried soils and peat surfaces (Brown, 2002). These may be relevant where river managers are attempting to recreate past river and floodplain environments (Sear and Arnell, 2006).

For detailed assessments of bank erosion or sediment transport calculations, additional information is required to account for the strength of the materials present and the vertical arrangement of sediments.

1.8.3 Data on erosion and deposition processes

Data on the processes of erosion and deposition are generally unavailable for most catchments. Therefore these processes must be measured (typically restricted to short reaches <1 km) inferred from field observation of bed and bank features, through interpretation of historical channel change (Downward, 1995; Gurnell *et al.*, 2003) or from morphological modelling studies (Mosselman, 1998; Darby and van de Weil, 2003). Process information draws on the datasets discussed in the preceding sections.

Typical geomorphological process interpretation in a river management project might include the following:

- estimation of bed mobilising or fine sediment flushing flows (Wilcock, 1998)
- identification of the cause of bank erosion, i.e. fluvial scour, geotechnical instability or weathering (e.g. Simon and Downs, 1995)
- identification of the role of vertical downcutting (incision) in the instability of a river reach or undermining of a structure (Darby and Simon, 1999)
- interpretation of the process of lateral river movement (type of meander migration) (Hooke and Redmond, 1992)
- classification of the river network into sediment storage, sediment supply and sediment transfer reaches (Sear *et al.*, 1995; Brierley and Fryirs, 2000)
- interpretation of the historical behaviour of a river and floodplain system over timescales up to thousands of years (Macklin and Lewin, 1989; Brown, 2002)
- identification of the role of past management versus natural adjustment processes in the creation of habitat and channel morphology (Kondolf *et al.*, 2003a; Large and Newson, 2006)
- identifying the role of long-term versus short-term river processes in the creation of protected river habitat (Sear *et al.*, 2006, 2009).

Interpretation of geomorphological process data requires a trained geomorphologist. Direct process monitoring should ideally extend over a range of flows and seasons to incorporate some measure of natural variability.

1.8.4 Problems with geomorphological data collection

The lack of baseline data on the geomorphology of UK rivers makes the task of applying geomorphology more difficult than an equivalent hydrological or biological survey. In most instances data are fragmentary or non-existent. The client effectively has to specify a baseline survey in order to get to the point where interpretation of the sediment system can begin. Such surveys may be difficult for a non-specialist to write, so increasingly, standard specifications are being adopted for baseline geomorphological data (e.g. Environment Agency, 1998; Natural England, 2007).

The widespread availability of River Habitat Survey data and Fluvial Audit data is starting to ease the situation within the UK. However, neither datasets are comprehensive and in the latter case has no central data repository. Another constraint already mentioned is the lack of long-term monitoring of sediment yields, or any systematic approach to the recording of geomorphological change – for example, bank erosion or channel deposition.

A further problem arises from the different perceptions of what constitutes geomorphology and, therefore, what its role and data needs are likely to be. For example, in conservation and rehabilitation projects, geomorphology is often interpreted in terms of static features – the physical habitat elements – whereas in flood risk management projects, there is more emphasis on the processes and dynamics of erosion and sedimentation, in addition to consideration of morphology in so far as it determines conveyance. Since 2000, the advent of the term hydromorphology is often taken to mean the static arrangement of channel features or types, contrasting with the morphodynamics that characterise fluvial geomorphic systems; hence, river managers need to be quite specific in defining what they require in terms of geomorphology.

1.9 Procedures for the collection and interpretation of geomorphological data

This section introduces the range of survey procedures developed under the research and development (R&D) programme of the National Rivers Authority (NRA), Environment Agency (EA), Scottish National Heritage (SNH) and Scottish Environment Protection Agency (SEPA). Methodological details on each approach can be found in Chapter 4, with some examples of the application of the methods in Chapter 6. While practice in applied geomorphology has progressed to the point where some elements of geomorphological data acquisition and investigation can justifiably be termed 'standard procedures', it is not the case that methods and approaches are applied uniformly. Usage varies both between geomorphologists in different regions of the UK and across agencies and consultancy groups depending on the context of the application and pedigree of the investigator.

Variation in the application of 'standard' approaches is, in any case, inevitable as collection and interpretation of geomorphological data is dependent on the type of question that is being addressed.

Typically, a geomorphological project will include some of the following elements; ideally, a geomorphological study should include all of them:

1. desk-study to collate historical/documentary evidence on river channel change, land management and channel management practices, hydrology, water quality and geomorphological datasets (river corridor surveys, river habitat surveys, geomophological surveys, etc.)
2. field reconnaissance to audit the current river system in terms of materials, forms and processes
3. detailed survey of sediments and topography at specific reaches in order to calculate sediment transport, critical flows for sediment movement, sediment population available for transport
4. quantitative measures of morphological change using combinations of items 1 and 2 above
5. interpretation of the geomorphological functioning of the river/reach
6. detailed channel design incorporating sediment transport issues
7. post-project appraisal of existing works in terms of channel stability, appropriateness of channel dimensions and morphology, and sediment conveyance.

Methodologies appropriate to these elements have been developed through regional and national R&D programmes of the EA (formerly NRA) of England and Wales (Environment Agency, 1998) and, in Scotland, through SNH (Leys, 1998) and SEPA (SNIFFER, 2006). In addition, there has been considerable ad hoc input from academic and professional geomorphologists working as consultants on river management projects (see Thorne *et al.*, 1997). In addition to these UK-based methodologies, there are also an increasing number of geomorphic assessment approaches available from the United States and Australia; principal among these are the classification of watercourses developed and employed by the US Forest Service (Rosgen, 1996), the Watershed Assessment process developed by Montgomery and Buffington (1998) and the River Styles© geomorphic classification system developed for the New South Wales water management agencies (Brierley and Fryirs, 2000). However, though interesting methods in themselves, application of methods outside the strict physiographic environments in which they were developed needs to be treated with caution.

Arguably, the most comprehensive and widely applied system for guiding clients on the application of fluvial geomorphology to river management within the UK is that developed under a series of R&D contracts for the NRA/EA, SNH, English Nature (now Natural England) and SEPA (Table 1.6). The different methods were synthesised into a single set of procedures (Environment Agency, 1998) which is now widely applied across a range of river management activities. The suite of methods developed through NRA/EA R&D during the 1990s and summarised in R&D Guidance Note 18 (Environment Agency, 1998) are dealt with in detail in Chapter 4. Since then, an over-arching framework for the procedures and expected outputs from a comprehensive geomorphological investigation have been drawn together under the title Geomorphological Assessment Procedure (GAP). Guidance literature supporting each level of the GAP is specified in Table 1.7. Copies of the relevant reports are available from the R&D publications office in each agency, while publication details are given in the references to this guidance document.

The bases of the GAP are scale and level of detail. The entry level into the procedure is the *Geomorphological Assessment*. Depending on the type of information needed, a river manager can commission a detailed *Catchment Baseline Survey (CBS)* that focuses on the distribution of reaches with similar morphology, geomorphological conservation value and sensitivity to disturbance within the river network (see Chapter 4, Section 4.1.3 for more on these terms). These reaches are mapped in the field and their broad physical attributes are recorded.

Alternatively, a river manager may be more interested in the sediment system, specifically the location of reaches that supply and store sediment within the river network and adjacent catchment. In this case a *Fluvial Audit (FA)* is more appropriate, so named because it literally seeks to check for the credit (sources), debit (storage) and transfer routes of sediment in a river catchment (see Chapter 4, section 4.1.4 for more on these terms). A Fluvial Audit is often commissioned in response to a specific sediment-related problem such as the sedimentation of a flood channel, or the progressive erosion of a reach of river. However, it may also be used as a strategic decision support tool, performed following a CBS as part of a comprehensive Geomorphic Assessment (GA). Data on bank erosion, sediment deposits, physical features (pools, riffles, bars) and processes within the channel network and adjacent floodplain are mapped in detail and a geographic information system (GIS) may be used to store results, perform spatial analysis and generate derivative maps. These data are integrated with information on historical channel change and channel

Table 1.7 GAP framework for geomorphological investigations

Stage	Planning/project		Project	Project	Project
Procedure	Geomorphological assessment		Geomorphological dynamic assessment	Geomorphological channel design	Geomorphological post project appraisal
	Catchment baseline study	Fluvial audit			
Aims	Overview of the river channel morphology and classification of geomorphological conservation value	Overview of the river basin sediment system typically aimed at addressing specific sediment-related management problems and identifying sediment source, transfer and storage reaches within the river network	To provide quantitative guidance on stream power, sediment transport and bank stability processes through a specific reach with the aim of understanding the relationships between reach dynamics and channel morphology	To design channels within the context of the basin sediment system and local processes	To assess the degree of compliance between design expectations and outcomes in terms of geomorphological processes, dimensions and morphology
Scale	Catchment (size 25–300 km^2)	Catchment (size 10–300 km^2) to channel segment	Project and adjacent reach	Project reach	Project reach
Methods	Data collation, inc. RHS/GeoRHS. Reconnaissance fieldwork at key points throughout catchment	Detailed field studies of sediment sources, sinks, transport processes, floods and land-use impacts on sediment system. Historical and contemporary datasets	Field survey of channel form and flows; hydrological and hydraulic data, bank materials, bed sediments (GA/FA if not available)	Quantitative description of channel dimensions and location of features, substrates, revetments etc. (GDA/FA/GA if not available)	Review of project aims/ expectations. Re-survey of project data sets. Field survey
Core information	*Characterisation* of river lengths on basis of morphology and sensitivity to management intervention	Identifies *range of options* and 'potentially destabilising phenomena' (PDPs) for sediment-related river management problems	Sediment transport *rates* and morphological *stability/trends*. 'Regime' approach where appropriate	The 'appropriate' *features* and their *dimensions* within a functionally designed channel	*Extent of changes or conformity* to original project design and recommendations for mitigation options
Outputs	15–30-page report; GIS including photographs	GIS; time chart of potentially destabilising phenomena; 25–50-page report including recommendations for further geomorphological input (GDA)	Quantitative guidance to intervention (or not) and predicted impacts on reach and beyond	Plans, drawings, tables and 15–50-page report suitable as input to quantity surveying and engineering costings	Plans, tables, 10–30-page report

Table 1.7 Continued

Stage	Planning/project		Project	Project	Project
Destination	Feasibility studies for rehab/restoration, Input to Catchment Flood Management Plans (CFMPs), candidate Special Areas of Conservation (cSACs)	Investment/management staff, engineering managers or policy forums, project steering groups, cSACs	Engineering managers and project steering groups	Engineering managers and project steering groups	Engineering managers and project steering groups
Reference material	Environment Agency (1998) *Sediment and gravel transportation in rivers: a geomorphological approach to river maintenance*. EA National Centre for Risk Analysis and Options Appraisal, Steel House, London	Environment Agency (1998) *Sediment and gravel transportation in rivers: a geomorphological approach to river maintenance*. EA National Centre for Risk Analysis and Options Appraisal, Steel House, London. Natural England *Guide to Specifying Geomorphological Audits* (2007), Northminster House, Peterborough, UK	Leys (1998) *Engineering methods for Scottish gravel-bed rivers*, Report No. 47, SNH, Edinburgh. Environment Agency (1998) *Sediment and gravel transportation in rivers: a geomorphological approach to river maintenance*. EA National Centre for Risk Analysis and Options Appraisal, Steel House, London	NRA (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. NRA (1994) *Sediment and gravel transport in rivers: a procedure for incorporating geomorphology in river maintenance*. NRA, Bristol, Project Record 384, prepared by Sear, D.A. and Newson, M.D.	Environment Agency (1998) *Sediment and gravel transportation in rivers: a geomorphological approach to river maintenance*. EA National Centre for Risk Analysis and Options Appraisal, Steel House, London. Briggs, A.R. (1999) *The geomorphological performance of restored and rehabilitated rivers*, PhD thesis, University of Southampton

management. Data collection may be undertaken by surveyors with training in the identification of geomorphological features, but a specialist, postdoctoral-level field geomorphologist should at least review the river network, and should have an overview and input to the interpretation.

A GA combines CBS and FA components to yield information on both conservation value/sensitivity to disturbance and sediment dynamics. This not only maps the current distribution of sediment stores and supplies but also links these to physical habitat and channel morphology. An important element of the fluvial auditing element of a GA is the desk study of past catchment and channel changes that may have impacted the delivery of sediment and routing of sediment through the river network. The fluvial audit requires interpretation of the sediment system and the identification of geomorphologically distinct reaches. It therefore requires a trained field geomorphologist to undertake the procedure. A specification for the application of geomorphological assessment for catchment-scale strategic river restoration planning in support of the Habitats Directive is available from Natural England (Natural England, 2007).

Recently, the River Habitat Survey (RHS) database has been used to provide basic geomorphological data for a range of projects. The development of an enhanced geomorphological methodology for the standard RHS (termed GeoRHS) has further improved the level of geomorphological data available through this approach (EA 200x GEORHS reference). GeoRHS data are sampled on a 500 m reach and are suitable when undertaken 'back-to-back', for Detailed Catchment Baseline Survey. GeoRHS therefore fails to provide the level of spatial data or interpretation necessary for the more detailed investigations of cause and effect such as Fluvial Audit, Geomophological Assessment, Geomorphological Dynamics Assessment, Environmental Channel Design or Geomorphological Post Project Appraisal. Nevertheless, GeoRHS and RHS remain valuable datasets for national- and network-scale reconnaissance and strategic decision support.

The remaining three elements of the Geomorphological Assessment Procedure focus on a selected or 'project' reach (rather than the whole system) and demand more detailed analysis of the geomorphic processes and boundary conditions present within that reach. All three require the services of specialist geomorphologists trained to at least doctoral level, and preferably with experience of working in applied geomorphology with river management agencies. Chapter 4 provides more details.

At present many geomorphological assessments concern Land Drainage Consent applications and increasingly these will need to be screened for hydromorphological impacts to determine their impact on Ecological Status. To support river managers, SNIFFER (a consortium of river management agencies within the UK) has developed a geomorphological screening tool for engineering activity in watercourses termed MImAS (Morphological Impact Assessment System; SNIFFER, 2006). MImAS is and Oracle-based application based on a geomorphic typology of rivers that was derived from the watershed assessment typology of Montgomery and Buffington (1997). MImAS works by determining the likely impact resulting from a single or multiple combinations of specific engineering activity within a given length of channel. Impacts are measured in terms of a river's capacity to absorb/sustain engineering pressures. This capacity relates to the channel type, and information on both engineering activity and channel type is needed before the system can predict how much capacity is likely to be lost and what impact it will have on Water Framework Directive status. The MImAS assessment tool is currently used by SEPA for Scotland.

Two cautionary notes must be recorded concerning the value of the various elements of geomorphological assessment. First, like any specialised investigation, the work should be undertaken by trained and experienced professionals. While the collection of some field data may be undertaken by field survey specialists with some geomorphological training (e.g. mapping and identification of features, collection of historical datasets), professional fluvial geomorphologists should, wherever possible, undertake the more difficult interpretation of datasets generated by the GAP. Second, no amount of geomorphological assessment can predict precisely the location, severity and extent of morphological impacts on a river system that are generated by rare events. However, it should be possible to highlight reaches and locations in a river network that are most sensitive to disturbance and even to identify the most likely forms of channel response to rare events.

Further details and specific examples of the geomorphological methods making up the GA and GAP are given in Chapters 4 and 6. These highlight the components, techniques and outputs expected to be performed and demonstrate how the information from such surveys can be used in a variety of management and engineering contexts.

References

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S. and Davies, J.R. (2006) Channel pattern and river-floodplain dynamics in forested mountain river systems. *Geomorphology*, **78**(1–2), 124–141.

Brierley, G.J. and Fryirs, K. (2000) River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management*, **25**, 661–679.

Briggs, A.R. (1999) *The geomorphological performance of restored and rehabilitated river channels*. Unpublished PhD thesis, University of Southampton, 380 pp.

Brookes, A. and Shields, F.D. Jr (eds) (1996) *River restoration: guiding principles for sustainable projects*. Wiley, Chichester.

Brown, A.G. (1987) Long-term sediment storage in the Wye and Severn catchments. In Gregory, K.J., Lewin, J. and Thomas, J.B. (eds) *Palaeohydrology in practice*. Wiley, Chichester, pp. 307–332.

Brown, A.G. (2002) Learning from the past. *Freashwater Biology*, **47**, 817–829.

Church (2002) Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, **47**, 541–557.

Darby, S.E. and Simon, A. (1999) *Incised river channels: processes, forms, engineering and management*. Wiley, Chichester, 424 pp.

Darby, S.E. and Van de Weil, M.J. (2003) Models in fluvial geomorphology. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 503–537.

Downs, P.W. and Gregory, K.J. (2004) *River channel management. Towards sustainable catchment hydrosystems*. Arnold, London.

Downs, P.W. and Thorne, C.R. (1996) The utility and justification of river reconnaissance surveys. *Transactions of the Institute of British Geographers*, New Series, **21**, 455–468.

Downward, S.R. (1995) Information from topographic survey. In Gurnell, A.M. and Petts, G.E. (eds) *Changing river channels*. Wiley, Chichester, pp. 303–323.

Environment Agency (1998) *River geomorphology: a practical guide*. EA, London, Guidance Note 18, prepared by Thorne, C.R., Downs, P.W., Newson, M.G., Sear, D. and Clarke, M.

European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23rd October 2000: Establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, **L327**, 1– 72.

Evans, E.P., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Foresight. Future flooding. Scientific summary: Volume 1 – Future risks and their drivers*. DTI, Office of Science and Technology, London, DTI/pub 7183/2k/04/04/NP, URN 04/939.

Evans, E.P., Ramsbottom, D.M., Wicks, J.M., Packman, J.C. and Penning-Rowsell, E.C. (2002) Catchment flood management plans and the modelling and decision support framework. *Civil Engineering*, **150**(1), 43–48.

GeoData Institute (2000) *River Ure geomorphological audit*. GeoData Institute, Southampton, Report UC446/1.

German, S.E. and Sear, D.A. (2003) *Geomorphological Audit of the River Wylye*. Conserving Natura 2000 Rivers, Conservation Techniques Series No. 9, Peterborough, English Nature, 89 pp. Accessed via http://www.english-nature. org.uk/lifeinukrivers/publications/Wylye%20 audit.pdf.

Gilvear, D.J. and Bryant, R. (2003) Analysis of aerial photography and other remotely sensed data. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 135–170.

Gregory, K.J. (2000) *The changing nature of physical geography*. Arnold, London, 368 pp.

Gurnell, A.M. (1997) Channel change on the River Dee, 1946–1992, from the analysis of aerial photographs. *Regulated Rivers, Research and Management*, **13**, 13–26.

Gurnell, A.M., Downward, S.R. and Jones, R. (1994) Channel planform change on the River Dee meanders, Holt to Worthenbury, 1876–1992. *Regulated Rivers, Research and Management*, **9**, 187–204.

Gurnell, A.M., Piery, J. and Petts, G.E. (2003) Using historical data in fluvial geomorphology. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 77–101.

Hooke, J. and Redmond, C. (1992) Channel planform change in England and Wales. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (eds) *Dynamics of gravel-bed rivers*. Wiley, Chichester.

Jacobson, R.B., O'Connor, J.E. and Oguichi, T. (2003) Surficial geologic tools in fluvial geomorphology. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 25–57.

Kondolf, G.M., Lisle, T.E. and Wolman, G.M. (2003a) Bed sediment measurement. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 347–395.

Kondolf, G.M., Montgomery, D.R., Piegay, H. and Schmidt, L. (2003b) Geomorphic classification of rivers and streams. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 171–204.

Large, A.R.G. and Newson, M.D. (2006) Hydromorphological quality – a policy template for channel design in river restoration. In Anderson, M.J. (ed.) *Encyclopedia of hydrological sciences*. Wiley, Chichester.

Leys, K. (1998) *Engineering methods for Scottish gravel-bed rivers*. Scottish Natural Heritage, Edinburgh, Report 47.

Macklin, M.G. and Lewin, J. (1989) Sediment transfer and transformation of an alluvial valley floor: the River South Tyne, Northumbria. *Earth Surface Processes and Landforms*, **14**, 233–246.

Montgomery, D.R. and Buffington, J.M. (1998) Channel processes, classification and response. In Naiman, R. and Bilby, R. (eds) *River ecology and management: lessons from the Pacific coastal ecoregion*. Springer-Verlag, New York, pp. 122–135.

Mosselman, E. (1998) Morphological modelling of rivers with erodible banks. *Hydrological Processes*, **12**, 1357–1370.

National Rivers Authority (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. NRA, R&D Note 154, prepared by R.D. Hey and G.L. Heritage.

National Rivers Authority (1994) *Sediment and gravel transport in rivers: a procedure for incorporating geomorphology in river maintenance*. NRA, Bristol, Project Record 384, prepared by Sear, D.A. and Newson, M.D.

Newson, M.D. (1992) River conservation and catchment management: a UK perspective. In Boon, P., Petts, G.E. and Calow, P. (eds) *River Conservation and Management*. Wiley, Chichester, pp. 385–396.

Newson, M.D. (2002) Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**, 365–379.

Newson, M.D. and Leeks, G.J.L. (1987) Transport processes at the catchment scale – a regional study of increasing sediment yields and its effects in mid-Wales. In Thorne, C.R., Bathurst, J.C. and Hey, R.D. (eds) *Sediment transport in gravel-bed rivers*. Wiley, Chichester, pp. 187–223.

Newson, M.D. and Sear, D.A. (1993) River conservation, river dynamics, river maintenance: contradictions? In White, S., Green, J. and Macklin, M.G. (eds) *Conserving our landscape*. Joint Nature Conservancy, Peterborough, pp. 139–146.

Passmore, D.G. and Macklin, M.G. (2000) Late Holocene channel and floodplain development in a wandering gravel-bed river: the River South Tyne at Lambley, northern England. *Earth Surface Processes and Landforms*, **25**, 1237–1256.

Petts, G.E. and Amoros, C. (1996a) *Fluvial hydrosystems*. Chapman and Hall, London.

Petts, G.E. and Amoros, C. (1996b) The fluvial hydrosystem. In Petts, G.E. and Amoros, C. (eds) *Fluvial hydrosystems*. Chapman and Hall, London, pp. 1–12.

Pitt, Sir M. (2007) *The Pitt Review: learning lessons from the floods of 2007*. Cabinet Office, London, 503 pp.

Rapp, C.F. and Abbe, T.B. (2003) *A framework for delineating channel migration zones*. Washington State Department of Ecology, Report 03-06-027.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J., Everard, M., Fozzard, I. and Rouen, K.J. (1998) *River habitat quality: the physical character of rivers and streams in the UK and Isle of Man*. National Rivers Authority.

Raven, P.J., Holmes, N.T.H., Charrier, P., Dawson, F.H., Naura, M. and Boon, P.J. (2002) Towards a harmonised approach for hydromorphological assessment of rivers in Europe: a qualitative comparison of three survey methods. *Aquatic Conservation*, **12**(4), 405–424.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J., Everard, M., Fozzard, I. and Rouen, K.J. (1998) *River habitat quality: the physical character of rivers and streams in the UK and Isle of Man*. NRA, Bristol.

Rhoads, B.L. and Thorn, C.E. (1996) *The scientific nature of geomorphology*. Wiley, New York.

Robinson, M. (1990) *Impact of improved land drainage on river flows*. I.H. Wallingford, Institute of Hydrology Report No. 113, 226 pp.

Rosgen, D. (1996) *Applied river morphology*. Wildland Hydrology, Pagosa Springs, CO.

Rumsby, B.T. and Macklin, M.G. (1994) Channel and floodplain response to recent abrupt climate change: the Tyne basin, northern England. *Earth Surface Processes and Landforms*, **19**, 499–515.

Sear, D.A. (1996) Sediment transport in pool-riffle sequences. *Earth Surface Processes and Landforms*, **21**, 147–164.

Sear, D.A. and Arnell, N.W. (2006) The application of palaeohydrology in river management. *Catena*, **66**(1), 164–187.

Sear, D.A., Armitage, P.D. and Dawson, F.D.H. (1999) Groundwater dominated rivers. *Hydrological Processes*, **11**(14), 255–276.

Sear, D.A., Darby, S.E. and Scaife, R. (2001) *Wise use of floodplains: River Cherwell pre-engineering scenario*. RSPB Report, Sandy.

Sear, D.A., German, S.E., Hill, C.T. and Branson, J. (2002) *Impact of recent floods on channel morphology and physical habitat using RHS re-survey*. Environment Agency, Bristol, R&D Report W5A-064.

Sear, D.A., Hill, C.T., Newson, M.D., Emery, J. and Branson, J. (2009) Applying geomorphology for assessing the physical condition of riverine habitats in support of the Habitats Directive. *Aquatic Conservation: Marine and Freshwater Ecosystems* (in press).

Sear, D.A., Kitts, D.R. and Millington, C.E. (2006) *The geomorphic and hydrological response of New Forest streams to river restoration*. Hampshire County Council.

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment-related river maintenance: the role of fluvial geomorphology. *Earth Surface Processes and Landforms*, **20**, 629–647.

Sear, D.A., Wilcock, D., Robinson, M.R. and Fisher, K.R. (2000) Channel modifications and impacts. In Acreman, M. (ed.) *The changing hydrology of the UK*. Routledge, London.

Simon, A. and Downs, P.D. (1995) An interdisciplinary approach to evaluation of potential instability in alluvial channels. *Geomorphology*, **12**, 215–232.

Skinner, K.S. (1999) *Geomorphological post-project appraisal of river rehabilitation schemes in England*. Unpublished PhD thesis, University of Nottingham.

SNIFFER (2006) *A new impact assessment tool to support river engineering regulatory decisions*. SNIFFER, Edinburgh, Technical Report WFD49 (Rivers).

Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) (1997) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester.

Wilcock, P. (1998) Sediment maintenance flows: feasibility and basis for prescription. In Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B. (eds) *Gravel-bed rivers in the environment*. Water Resources Centers, Colorado, USA, pp. 609–638.

Yarnell, S.F. Mount, J.F. and Larsen, E.W. (2006) The influence of relative sediment supply on riverine habitat heterogeneity. *Geomorphology*, **80**(3–4), 310–324.

2

River processes and channel geomorphology

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2.1 Introduction to the chapter

This chapter is intended to provide an overview of the wider catchment sediment system, and how the range of depositional and erosion features reflect the processes operating within it. As part of this overview the chapter introduces some of the more important concepts of fluvial geomorphology that are necessary in order to understand how a river system works. The final section describes the main features of UK river geomorphology using a sliding scale from the river catchment to smaller-scale habitat features such as pools and riffles.

2.2 River channel form: the basic drivers

The driving variables of the fluvial system are the inputs of water and sediment, represented in Fig. 2.1 as water and sediment hydrographs. Although these variables are often considered to be independent of channel form at timescales greater than a year, this is not necessarily the case. Reach scale adjustment of channel form may control water and sediment flux downstream through changes in available storage, thereby controlling the form of the downstream channel, independent of catchment scale processes (Lane and Richards, 1997).

According to this conceptual model of driving variables, inputs of water and sediment generated from upstream catchment and channel processes interact with the boundary characteristics to form the channel. These characteristics may be considered as independent variables, inherited by past geomorphological processes, for example the valley slope, and bank materials. The nature of the valley form is significant in that it determines the degree of coupling that exists between the channel system and the valley slopes (Harvey, 2002). In incised, confined valleys the channel may be frequently coupled with the slopes. Channel form will then be influenced as much by slope processes as by channel processes.

As a floodplain evolves, alluvial sediments increasingly form the dominant boundary material, and the river channel becomes increasingly 'self-formed'. Self-formed alluvial channels have a morphology that results from erosion/deposition processes generated by stream flow. This is complicated, however, by the presence of vegetation communities that may significantly influence channel form, and the rates and location of erosion/deposition along an alluvial reach.

The interaction of these variables is further conceptualised in Fig. 2.2 (Ashworth and Ferguson, 1986). This figure displays the process–form interactions in a manner

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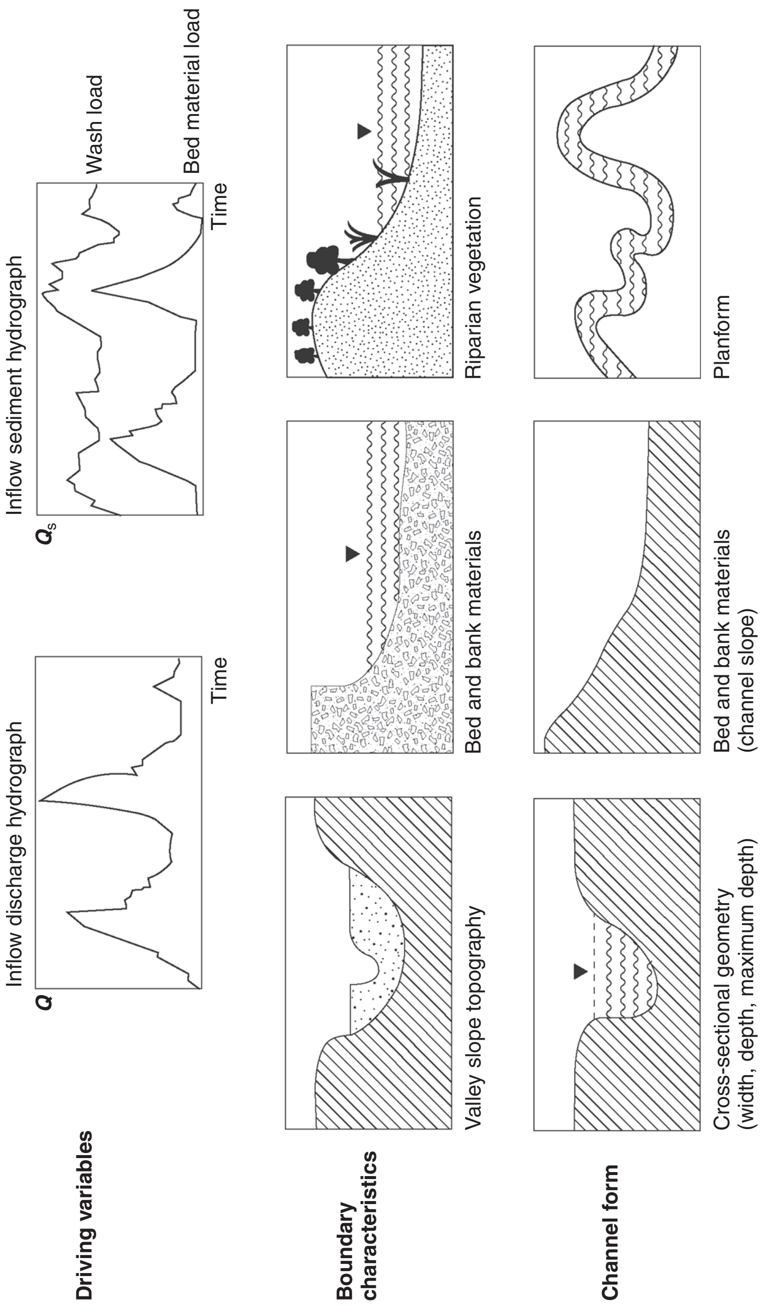


Fig. 2.1 Independent and dependent controls on channel form. Reproduced, with permission, from Thorne, 1997. © 1997 John Wiley & Sons Limited

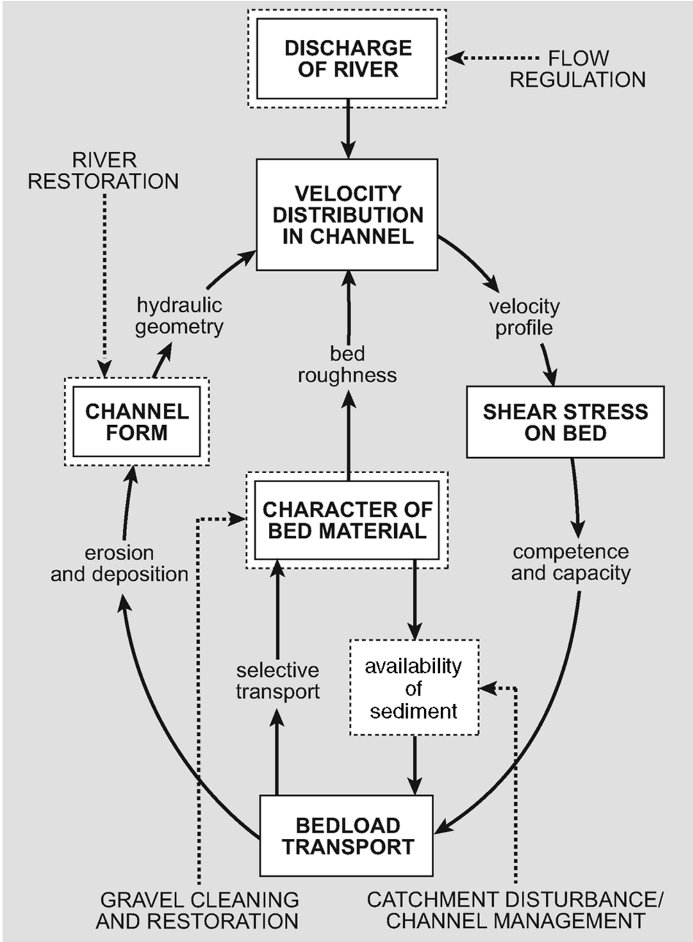


Fig. 2.2 A conceptual model of the feedback between channel form, flow, sediment transport and grain size. Modified, with permission, from Ashworth and Ferguson, 1986. © Swedish Society for Anthropology and Geography. Courtesy of Wiley-Blackwell

that could be represented in numerical or analytical models. The model is four-dimensional, in that channel form and flow are three-dimensional in nature, while the fourth dimension, time, defines change in the system. Very few geomorphological studies have determined all of the parameters and processes operating in this diagram and even theoretical treatments are only partial. The figure therefore serves to illustrate both the complexity of even one type of fluvial system (alluvial), together with the extent of interaction between variables that describe the processes found in such rivers. Figure 2.2 may also be used to indicate the potential effects of given treatments on the fluvial system of alluvial river channels. For example, changes in channel geometry arising from rehabilitation or flood channel design, are seen to feedback into the three-dimensional distribution of velocity and, through shear stress, to sediment transport and thus back to channel geometry through erosion and deposition. Such an understanding warns us against oversimplification when designing new channels.

Table 2.1 recognises that the relative importance of the local controls discussed above, vary between river types; in this instance between higher-energy rivers and those lowland channels that are confined by structures, cohesive valley fills and low-gradient long profiles.

Table 2.1 Variations in the controls on river channel form in upland and lowland river channels

Channel controls	Upland river	Lowland river
Inflow hydrograph	Flashy; steep flood frequency curve; snowmelt effects	Longer-duration floods; moderate flood frequency curve; often regulated by structures
Inflow sediment	Bed material dominates; local sediment sources; forest and reservoir effects	Suspended load dominates; bank erosion or general catchment sources. Quality problems of sediments
Valley slope	Steep, narrow	Gentle, wide. Floodplain effects on secondary flows and stream power
Bed/bank materials	Coarse, cohesive but also loose gravels	Fine, cohesive, plus engineering
In-stream vegetation	Little morphological role	Large seasonal impact on sediment transport
Riparian vegetation	Sparse or short in headwaters; semi-natural woodland in undeveloped areas	Often farmed – arable and heavy stocking destabilises banks; cattle access to bars
Section geometry	Extremes of width/depth ratio (gorge-braided)	Low width/depth in cohesive alluvium. Engineering changes width/depth ratios
Long profile	Steep, stepped; frequent instability zones and flood impacts often local	Gentle, often controlled by structures of seasonal vegetation growth
Planform	Full range present; most dynamic unless confined by cohesive/rock/engineering	Confined/engineered but generally sinuous, even if stable

A useful framework that integrates the issues developed in this section, is to consider river catchments and the river network in terms of possessing a sensitivity or resilience to changes in discharge or sediment supply. Identification of factors that contribute to this resilience becomes important both strategically in terms of assessing catchment/channel status, and operationally in terms of specifying systems that may need treatments to increase or decrease this resilience. To understand these principles requires knowledge of how the sediment system of rivers operates.

2.3 The river catchment sediment system

In many cases the river manager is concerned with the prediction of appropriate morphology (what shape of river should be created?), the likely type and rates of change to expect (where and how dynamic will this design be?) and the sustainability of the design (will it need maintenance to preserve its intended function?). These concerns can be expressed in basic terms where:

sediment supply > sediment transport = sediment storage
(or creation/maintenance of depositional morphology)
sediment transport > sediment supply = sediment removal
(scouring or incising channel)

However, in order to understand rates of change and styles of morphological adjustment, the preferred approach should include an assessment of sediment loads and, more importantly, the cause and magnitude of changes in sediment load at the design location. From this information the river manager must also be able to assess the appropriate morphology associated with a given change in sediment load. To accomplish these formidable tasks the river manager must be able to quantify and interpret the sediment system of the river upstream of the point of

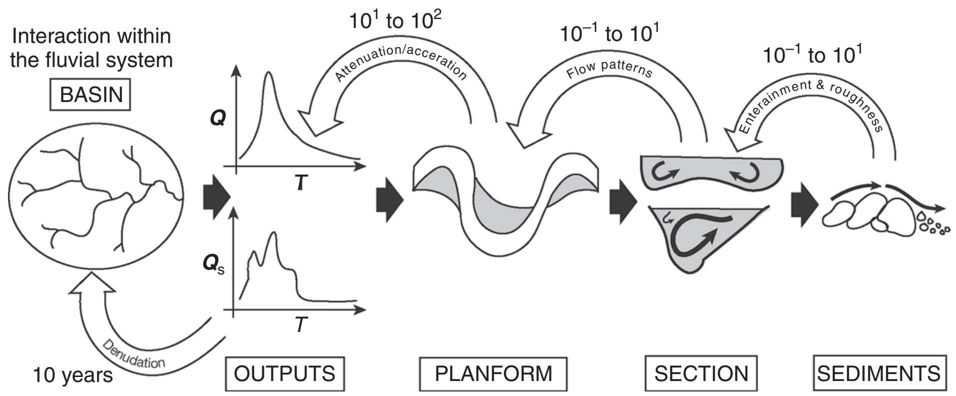


Fig. 2.3 Links between the different scales of river geomorphology. Reproduced, with permission, from Sear, 1995. © 1995 John Wiley & Sons Limited

interest (sediment supply to the reach in question) and the impact of the reach on downstream transmission of sediment.

The sediment system in a river is a continuum of sediment supply, transport and storage operating at a range of scales in space and time and incorporating the terrestrial and aquatic components of the river catchment (Sear *et al*., 1995). The catchment is perhaps the largest scale at which this system operates, while particles can be supplied, transported and stored within the river channel over areas of a few square metres.

The relative role of internal and external controls on water and sediment movement within the basin mean that predictions based solely on external variables such as runoff will be of little use to river managers. Instead as Newson (1993) suggests '*the sediment system of each river basin deserves its own detailed environmental assessment before any new development begins*'. Figure 2.3 illustrates the linkages between form and process within the catchment sediment system. Clearly, from the point of managing river reaches, it is important to place those of interest within the wider catchment context, which inevitably must involve an appreciation of the timescales over which channel change is driven.

2.4 Coupling and connectivity in river basin sediment systems

Geomorphologists conceptualise river basin sediment systems in terms of sediment stores that are more or less coupled to transport networks (hillslope gullies, the river network). Coupling refers to the degree of linkage between hillslope sediment systems and the river network (Harvey, 2002). Connectivity has been explicitly used to describe the physical linkage within the channel network, and expresses the potential for a given particle of sediment to move through the system (Hooke, 2003). The concept of sediment coupling and connectivity is increasingly being used within geomorphological assessment tools such as Fluvial Audit (Sear *et al*., 1995) and River Styles© (Brieley and Fryirs, 2000). Harvey (2002) identifies temporal and spatial variability in the degree of coupling, and associates this with adjustments in channel morphology. For example, in a long-term study of gully-channel coupling driven by a 1:100-year flood, Harvey (2001) demonstrates how local transmission of sediment from gullies resulted in abrupt (event scale) change in channel morphology. Two decades later, it was possible to observe changes in channel morphology where gully sediment systems had become disconnected from the river network, and others where the coupling remained (Harvey, 2001).

Coupling within the catchment sediment system operates downstream in terms of the transmission of sediment from hill slope and through the river network, and upstream in terms of the propagation of the effects of changes in base level (e.g. creation of knick-points that can erode upstream and destabilise river banks and slopes). Upstream coupling tends to operate over longer timescales (100–100 000 years) while downstream coupling can locally operate at the event scale, or for medium-sized catchments (e.g. the Tyne; see Macklin and Rumsby, 1994) over decades. Harvey (2002) identifies the degree of coupling as a fundamental geomorphic control over landform development and as such represents an important system state for river managers to define. Well-coupled systems transmit the effects of change in sediment production throughout the system, whereas in buffered (poorly coupled sediment systems) the effects of such change may only be expressed locally (Harvey, 1997). The degree to which a catchment sediment system is well coupled with highly connected sediment stores is important for determining how sensitive that system is to environmental change and river management.

Both geomorphic coupling and connectivity are influenced by opportunities for sediment storage. Storage of sediment within the river catchment depends on:

- the nature of the materials stored (how easily they are transported)
- the degree of storage available at a given site (it is possible for sediment stores to be 'over-filled' and to become suppliers of sediment)
- the type of store; either *active* such as a dune where particles are concentrated but in motion, or *passive* where sediments are immobile, e.g. a floodplain or infrequently inundated bar surface
- cover of vegetation (that influences erosivity of the store)
- distance from channel (as opportunity for subsequent storage is increased with distance).

Timescales of sediment storage are not commonly available to the river manager, but may be inferred for portions of the valley floor and river channel from historical surveys and map information (Kondolf and Larson, 1995), or field work. Although values for sediment storage have been estimated theoretically and empirically for relatively few river basins, evidence suggests that the capacity for river systems to store sediments may lead to both self-regulation of sediment loads and rapid changes in sediment loads as stores of sediment become unstable (Trimble, 1992; Harvey, 2002).

The effect of storage within the channel network may be enhanced or reduced depending on river management practices. Revetment of channel boundaries may act to increase the residence time of sediments stored in floodplains and therefore to increase the adjustment period between cause and effect. Similarly, artificial protection of sediment storages effectively reduces the sediment supply in a channel, which can cause erosion of other stores within the river. The activity of sediment storage elements can vary naturally over time, with periods when storage is released resulting in episodes of relatively high sediment yield and dynamic river channel change (Passmore *et al*., 1993). This activity may also vary spatially within a catchment, resulting in the complex response of a river catchment to a given change in boundary conditions (e.g. a large flood event). Mapping sediment storage features and, where possible, quantifying their sensitivity to flooding and management practice, therefore becomes an important contribution to catchment-based river management.

A useful tool for quantifying the sediment system of rivers is the sediment budget (Trimble, 1995; Hooke, 2003). Sediment budgets use combinations of field data and historical data to quantify the available stores, sediment fluxes and processes. In some cases sediment budgets can be extended to cover relatively long time periods using lake or floodplain sediment stores. In these cases it is possible to identify climatic and land-use change impacts on sediment budgets, or the significance of high-magnitude events.

2.5 Channel adjustment: concepts of change

Adjustment to a change in the external independent variables of water and/or sediment discharge has been the focus of much geomorphological research (Schumm, 1991; Gurnell and Petts, 1995; Werrity, 1997). Predicting adjustments is problematic, not least because multiple variables may respond to any given change, but also since the rates of change in variables differ in space and time (Hey, 1979). To conceptualise this problem, geomorphologists have viewed river channel adjustment in terms of a series of ‘equilibrium states’, often characterised by a given morphology. The transition between these states has significant management relevance. The path of adjustment of a given channel state to another may involve rapid change or threshold response. Other changes may be more gradual.

The existence of river reaches that although morphologically similar may have different responses to a given change in discharge or sediment flux is referred to by Schumm (1977) as *complex response*. Complex response makes it difficult to predict where in a channel network (or catchment) a given adjustment will occur. This places strong emphasis on being able to identify the attributes of sensitive or resilient channel geomorphology that can guide the river manager, and identify those that are most likely to respond to climate change. One way in which this has been achieved has been to examine the historical record of channel adjustment, in order to discern threshold behaviour (or not) and landform robustness. This approach may also be used to define system resilience. Palaeohydrology and historical geomorphology have been used successfully to reconstruct channel response to climatic and catchment changes over the past 15 000 years (Sear and Arnell, 2006). The advice is first, that it is often increasingly difficult to establish what the driving cause of a given change actually is, and second, that adjustment time (reaction time to perturbation plus relaxation time after perturbation) is often longer than the frequency of environmental change. The implication is that rivers are seldom in equilibrium (dynamic or otherwise) with prevailing sediment and hydrological regimes. The corollary of this view is that we must expect adjustment and a suite of responsive landforms over geomorphologically relevant timescales (10+ years). This is self-evidently not the case for all rivers. In the lowlands of central and southern England, for example, channel incision and aggradation are minimal at present, and channel planform has remained morphologically stable for (in management terms) long periods. In these systems, the absence of coarse woody debris in the river channel, and the low ratio of stream power to boundary resistance may mitigate against large-scale erosional adjustment, though there is evidence that depositional adjustment processes do operate (Brookes, 1984; Downs, 1994). However, over longer timescales (centuries to millennia), these channels are shown to respond to phases of land-use change and climatic instability, through aggradation and incision into floodplain sediments (Macklin and Lewin, 1994; Brown, 2002). In effect, many lowland river systems are poorly coupled and disconnected in terms of coarse sediment transport, but are more frequently coupled and connected in terms of finer sediment sizes.

Channel adjustment processes vary in accordance to the resistance to lateral and vertical erosion and the ability of a reach to transport the sediment load supplied from upstream. These factors determine the general tendency of a reach to incise over time or aggrade, but within these there are specific processes of adjustment that determine the form and evolution of bend geometry, bar size and location and bank erosion mechanics. Table 2.2 links the style of adjustment to the channel type and makes the point that adjustment processes can be expected to vary within a catchment as boundary conditions controlling channel form vary spatially.

2.6 River channel geomorphology

The classification and description of channel features is perhaps the most common aspect of fluvial geomorphology known to non-specialists. Thus ecologists and engineers are familiar with descriptions of channel planform (meandering, braided etc.) or specific features (pools, riffles, bars) but are often less familiar with their function and formation.

The product or output of the operation of the catchment sediment system over time is a river morphology and associated substrates, that interact with the biological and geochemical systems to produce a suite of physical and biological habitats, and at the largest scales, a river landscape. Fluvial geomorphologists also recognise that the channel and floodplain morphology help regulate the storage and transfer of sediment through the river network. For example, the loss of a meandering planform through river straightening and the storage of sediment this provides, results in a more rapid transfer of incoming sediment load to the downstream reach and an expensive maintenance bill (Sear *et al.*, 1994).

An understanding of the link between form and process is essential for the re-creation of channel features in river systems that have been physically modified. In the UK, most of the channel network is in some way modified, either through regulation of the flow regime, modification of the sediment regime, or direct modification of the channel morphology (Raven *et al.*, 1998; Sear *et al.*, 2000). In many cases all of these impacts occur in one catchment. The result is a river morphology and physical habitat that is unrelated to the natural processes currently operating, or a transitional morphology that reflects the change in catchment processes. In lowland UK rivers, much of the morphology has been removed by centuries of management and modification. Recognition that much of this morphology arose from past processes that no longer exist (e.g. woody debris or post-glacial flow and sediment regimes) helps to explain the lack of adjustment and natural re-creation of past features (Dury, 1984; Sear *et al.*, 1999). It also suggests that a sustainable morphology based on current processes may be different to that expected or desired. Features and physical habitat diversity are reintroduced by non-specialists in an attempt to improve physical habitat diversity and thus biodiversity. Often this involves re-creation of mimics of natural features such as riffles, but it may involve creation of totally new features that provide the desired habitat (introduction of large stone deflectors in sand bed rivers etc.). The process impacts of such features are seldom considered (Skinner, 1999).

Recently, the interaction between ecology and geomorphology has led to the creation of much more complex physical descriptions of channel form via the need to define physical habitat. For example, to the pool-riffle sequence is now added the *run*, *glide* and *cascade* (Church, 1992; Newson and Newson, 2000). The precise significance of these features in terms of geomorphological processes is not clear, but glides and runs may represent areas of sediment-filled pools or conditions where pool formation is imminent. Similarly, there has been an increasing recognition of the role that vegetation and other biological components of the catchment play in moderating processes and creating channel form (Hupp *et al.*,1995; Brummer *et al.*, 2006). Furthermore, it is becoming clear that past channel processes have been

Table 2.2 Styles of channel adjustment associated with different channel types

Channel type	Morphological description	Style of adjustment
Steep headwater channels (0–2 order)	Cascades, step-pool, poorly sorted grain size with boulders and exposed bedrock. Confined by valley sides resulting in strong coupling. Absence of floodplain. Steep slopes (>0.03)	Limited lateral movement – commonly the result of avulsion. Channel bed elevations periodically aggrade and incise in response to slope–channel connecting events often in association with generation of a sediment wave. Bed morphology can be destroyed by high-magnitude events but reform step-pools. Woody debris contributes to aggradation and sediment accumulation creating steps in long profile
Pool-riffle and plane bed channels	Can exist in meandering partially confined and unconfined states. Characterised by lateral oscillating sequences of bars, pools and riffles. The gradient of such channels is low to moderate and the width/depth ratio high. The bed is predominantly gravel, with occasional patches of cobbles and sand. Interactions between the stream and the riparian zone result in overbank flood flows and wetland areas	The banks are typically resistant to erosion, and lateral migration of the channel is limited, resulting in relatively narrow and intermittently deep channels. Lateral channel adjustment occurs via avulsion and chute cut-offs across meander bends. Bar erosion and development coupled with pool-infilling and riffle erosion characterise the bed adjustment, particularly in presence of sediment wave. Woody debris creates local scour and sedimentation-steps in long profile
Wandering gravel-bed rivers	Generally, they can be viewed as a transition channel type between braided and lowland meandering channels. These reaches exhibit characteristics of braided and meandering channels simultaneously, or, if studied over a number of years, display a switching between divided and undivided channel types. Wandering channels typically occur where a reduction of bed material size and channel slope is combined with a widening of the valley floor. Presence of lateral, point and mid-channel bars with pool and riffle sequences	Wandering channels are susceptable to channel avulsions during high flow events, where the channel reoccupies old channels. Bank erosion processes are active with lateral migration and channel widening forced by bend curvature and sediment accumulation. Phases of incision and aggradation build sequences of terraces on the valley floor. Woody debris important part of island formation and flow deflection
Braided rivers	Braided reaches can occur in a variety of settings. Typically characterised by relatively high gradients and/or abundant bedload with high width/depth ratio. Channel splits into a number of threads around instream bars. Nevertheless, poor bank strength renders them highly dynamic and channels will generally change even in relatively small flood events	Braided channels are susceptable to channel avulsions, chute cut-off and bar development during high flow events. Bank erosion processes are active with lateral migration and channel widening forced by sediment accumulation and flow deflection. Phases of incision and aggradation build sequences of terraces on the valley floor. Confluence–difluence processes of scour and aggradation maintain divided planform. Woody debris important part of island formation

Active meandering alluvial channels	Bordered by floodplains, the single channel is characterised by pool-riffle sequences and point bars. Counter-point bars occur at wide bends. Silt berms extend from point bars, often colonised by riparian vegetation. Wooded riparian corridors. Bed material typically gravel with fines	Bank erosion and lateral migration of the channel dominated adjustment processes. Bends develop through a range of forms, leading in some cases to meander cut-off. Chute cut-off processes also prevalent where channel is not incised. Sinuosity changes over time resulting in progressive reduction in slope, and accumulation of sediments on bars. Riffle-pool sequence is dynamic with addition riffles and pool units developing as channel length extends with bend migration. Laterally stable reaches often occur in between active bends. Large wood creates complex bar and flow structures that can influence bend development
Passive meandering	Generally lower slopes, flowing through resistant materials, for instance boulder or marine clay deposits. They are generally sinuous – meandering. Channels are often incised and display low width/depth ratios. The beds typically comprise shallow layer of armoured or paved gravels with fine sedimentary materials (sands and silts). Bars are typically low amplitude and have a high fines content. Fine sediment berms also prevalent where channel width increases. Pool and riffle sequences occur but often in association with other transitional bed forms such as glides and runs. Primary production is strong in these channels and, coupled with stable beds with much fine sediment, allows extensive growth of macrophyte vegetation. Riparian corridor is typically wooded	Combination of low slopes and resistant bank materials results in limited rates of lateral adjustment often characterised by widening or narrowing through deposition of fines. Woody debris important feature of adjustment processes, resulting in localised chute cut-off channels at bends, widening around jams and local plunge and scour pools and upstream backwater pools at dams. Bar migration occurs but typically in response to large wood dynamics
Groundwater-dominated rivers	Groundwater-dominated rivers and low-gradient channels are characterised by a stable flow regime although limestone rivers with cave systems may display hydrological characteristics similar to freshet rivers. Typically, sediments are derived from catchment sources, although large macrophyte beds provide a source of in-stream organic detritus. Lack of bed disturbance promotes the accumulation of large quantities of fine sediment. Substrate generally comprises gravels, pebbles and sands, and glides and runs are the dominant flow types. Localised areas of riffle may be present, particularly where woody debris is available. Dense macrophtye beds and wooded riparian corridor	Bed and bank migration is infrequent and sediments are predominantly transported in suspension. Lateral channel migration is absent or at very low rates. Bar development and gravel transport is highly localised, resulting in stable channel morphology. Large wood is present in the channel for long periods and creates local scour and deposition and possibly avulsion where the main stream is blocked. Macrophyte development controls much of the flow and fine sediment transport

heavily influenced by ecological interactions that rarely or no longer exist – for example, the recruitment of significant coarse woody debris into watercourses. The valuable role of vegetation on channel processes and the important role that livestock play in accelerating processes is most clearly demonstrated by recent experiments in stock fencing river banks. Isolation of one biological factor (livestock) permits regeneration of another (vegetation), the net effect of which is to reduce bank erosion.

The correct interpretation and use of channel morphology in river channel management should therefore be one founded on understanding the link between:

- morphology and processes (this helps to decide if the processes exist to create the morphology)
- morphology and the sediment system (this helps to diagnose problems from channel form, but also the implications of creating different morphology)
- morphology and the physical habitat/ecology (this provides the link between biodiversity goals and geomorphology).

The following section provides some brief guidance on the more common landforms associated with UK rivers, and establishes what is known about their relationship to geomorphological processes and physical habitat. It will start off at the largest scale with the catchment, and descend in scale to the river reach and individual bedforms such as the riffle-pool unit. More detailed information on geomorphological features can be found in the literature (e.g. Thorne, 1997; Schumm, 2005; Bridge, 2003).

2.6.1 River catchments

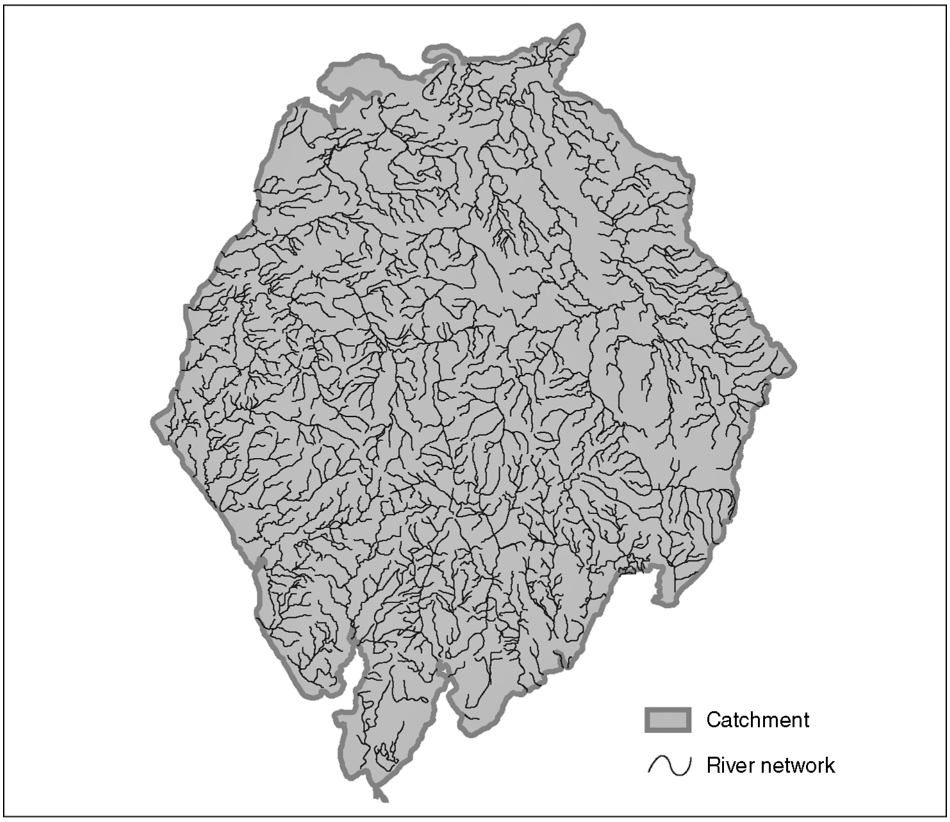
At the heart of sciences such as hydrology, ecology or fluvial geomorphology is the view that the river channel should be seen as part of an interconnected transport system of water, sediment, nutrients and biota (Frissell *et al.*, 1986). The largest unit in such a system is the river catchment that includes the land surface as well as the network of streams and rivers within it. The topographic boundaries of the river catchment contain within it not only the stream network but also most of the available sediment sources (some is transported atmospherically from outside of the catchment) and supply links to the river network. Significant modification to either the river network (for example, extending it through land drainage) or the supply of sediment (through changes in land management) will alter the sediment yield of a catchment and correspondingly the river and floodplain environment.

Sediment yield from a land surface is a function of a range of factors that vary over regional scales according to the topography, geology (drift as well as solid), hydroclimatology, soil types, land cover and land management practices. At one end of the sediment transport spectrum are catchments in regions characterised by erodible geology, high relief, flashy high rainfall hydroclimatology, relatively low-density vegetation cover and a dense river network. At the other end of the sediment yield spectrum would be catchments in regions characterised by resistant geology, low relief, stable moderate rainfall hydroclimatology, high-density vegetation cover and a sparse river network. In practice, each of these variables influences the others, so that high relief is typically associated with resistant geology, resistant geology is typically associated with dense stream networks, and low stream density is typically associated with permeable geology such as chalk or limestone (Sear *et al.*, 1999). Identifying the distribution of these broad factors in a river catchment forms the first level in the understanding of the geomorphological functioning of a river catchment. For example, sourcing of the fine sediment transported in salmonid spawning gravels in the chalk rivers of the Avon catchment revealed that most were derived from discrete areas of the Greensand geology rather than the more extensive chalk areas (Heywood and Walling, 2006). Such information is vital in attempting catchment scale management of a diffuse sediment problem.

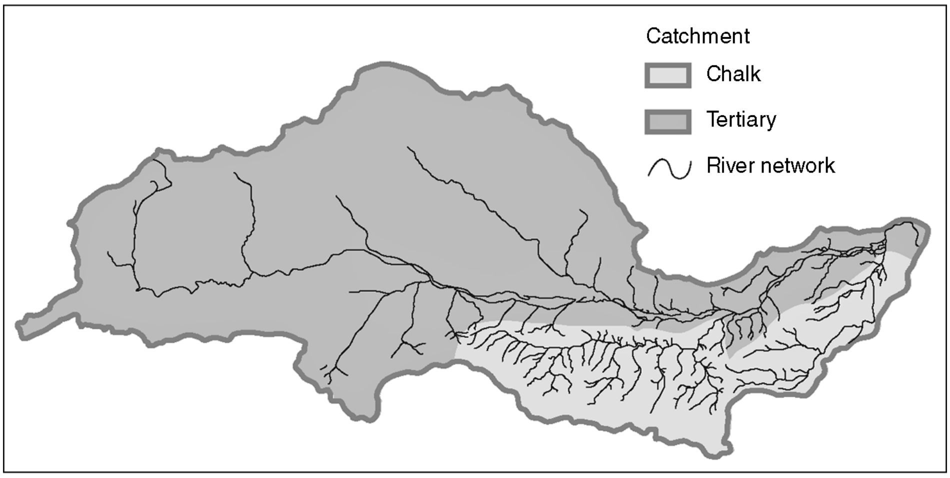
2.6.2 River network

On of the most significant features of the river catchment is the pattern and extent of channels that comprise the river network (Gardiner, 1995). The river network is the main routeway for the transmission of water, sediments and nutrients and organic matter in the river ecosystem, yet its significance is seldom considered outside flood routing and hydrological modelling. The form of the drainage network is largely conditioned by catchment geology, relief and rainfall intensity (Gardiner, 1995); indeed, the shape of the river network can provide important clues as to the structure of the geology of an area. Figure 2.4 depicts the influence of geology on drainage networks at regional and catchment scales. One of the most important measures of the river network is the density of channels per unit area or drainage density. The density of channels in an area has been shown to be directly related to the sediment yield and the flood hydrology (Knighton, 1998). Simply, those areas with a high density of channels per unit area have much more opportunity to access sediment and water from the catchment surface (the land and channel system are strongly coupled). The value of drainage density is also dynamic both during flood generation (drainage density increases as the drainage network grows) and over time in relation to climate change (Gregory and Gardiner, 1975; Reid *et al.*, in press). This view should warn river managers of the potential consequences of increasing drainage density in the catchment, through for example, forestry or agricultural land drainage schemes (Sear *et al.*, 2000). Drainage density, and the structure of the drainage network, are basin scale characteristics that provide contextual information that can help explain the differences in channel characteristics across the catchment. They can also indicate areas of potential vulnerability to sediment delivery from the land surface, especially when combined with other sources of land cover, soil and topographic information. Recent geomorphological modelling studies have demonstrated the significance of drainage network extension during flood generation in linking up sediment source areas with the channel network (Reid *et al.*, 2008).

An important feature of the river network is the junction or confluence of two channels. Recent research has demonstrated that tributary cofluences create discontinuities within the hydrological, sediment transfer and ecological system of a river (Rice *et al.*, 2006). Channel dimensions typically scale at the confluence with the abrupt addition of discharge. Furthermore, sediment texture changes at the junction, usually resulting in increases in grain size, though this depends on the calibre of the sediment input. Channel morphology at tributary confluences reflects the angle of junction and the flow structures created by the merging of two water bodies. Typically, as the angle of confluence increases, flow separation occurs and tributary confluence bars develop downstream of a scour pool (Best, 1987; Bradbrook *et al.*, 2001). Benthic organisms respond to the hydraulic and substrate changes, resulting in changes in community structure (Rice *et al.*, 2006). River confluences are therefore highly sensitive to changes in the balance of supply of nutrients, water and sediment from each river.



(a)



(b)

Fig. 2.4 Drainage networks: (a) Geological controls on regional drainage networks; Lake District rivers radiate out from the central areas of uplift and (b) geological controls on drainage network; River Kennet catchment, UK

2.6.3 *Valley form and long profile*

The connectivity of the river network to the catchment land surface is moderated by the form of the valley in which the channels flow. Figure 2.5 illustrates this point, and shows clearly how the presence of a wider valley floor (including floodplain) progressively buffers the channel in that reach, from the sediment sources present on the valley side and catchment land surface (Fryirs *et al.*, 2007). What is also apparent in the figure is that the form of the valley is the significant control on

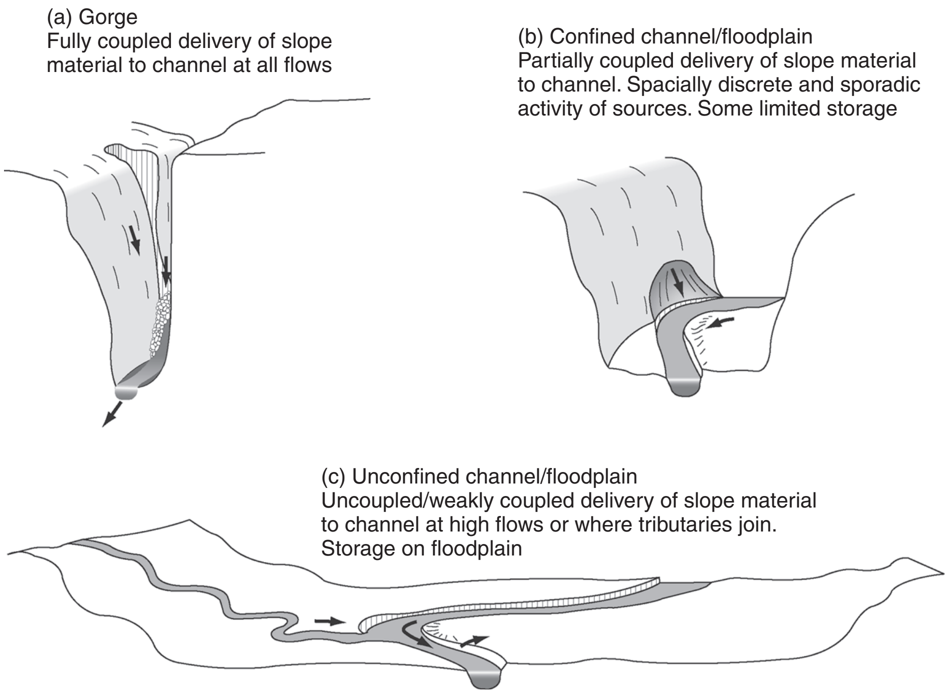


Fig. 2.5 Valley form and its control on connectivity between the catchment surface and the river network

this connectivity, and that this is itself controlled by the local geology and longer-term evolution of the landscape. In the UK, therefore, there is a distinction that can be made between those areas that have been glaciated, and those that have not, and those that have experienced tectonic uplift of the land surface and those that have not. A further control on the valley form of UK river systems (that tend to be relatively short steep watercourses on a global scale) is the role of changing sea level on the long profile, which over geological time has risen and fallen, creating opportunities for incision and aggradation.

The long profile of a river is defined by the shape of the elevation: distance diagram (Fig. 2.6). Rate of energy expenditure (an important surrogate for sediment transport capacity) in a river is not uniform over distance as is evidenced by the long profile shown in Fig. 2.6. What is clear in UK rivers is the influence of past changes in uplift and sea level, that have 'moved the goalposts' during the evolution of the river valley, producing increases in the gradient of the river valley. Superimposed on these changes are those arising from local variations in geology, that again produce steps and basins in the long profile. Response to these variations has resulted in the formation of a suite of large-scale river geomorphology, characterised by changes in valley floor (and river channel) gradient, the creation of basins that have subsequently become filled by alluvial sediments, rock gorges and narrow valley forms, and terraced valley floors. The latter are evidence of river channel incision into sediments that arises once the supply of sediment is reduced, or where local gradient increases following uplift or lowering of sea levels. More recently, it has become clear that some river terraces result from phases of sediment storage and incision created by shorter-term fluctuations in flood frequency that create periods of sediment deposition on the valley floor, followed by periods of incision (Macklin and Rumsby, 1994).

At the reach scale, long profiles are influenced by geological structures (e.g. resistant rock steps), past processes such as glacial erosion or depositional landforms, and

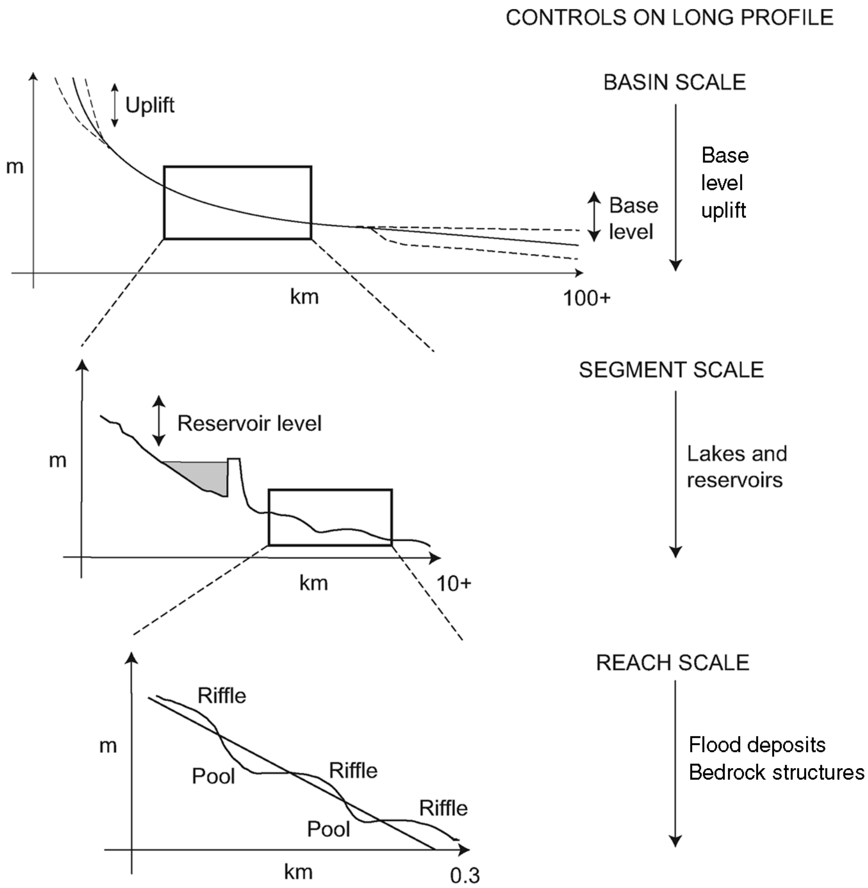


Fig. 2.6 The long profile of a river; illustrating geological and base level controls on valley gradient. Reproduced, with permission, from Sear, 1996. © 1996 John Wiley & Sons Limited

by sequences of sediment accumulation and incision. The long profile of the river channel is influenced by the development of transverse bed forms such as step-pool and pool-riffle sequences, and by river management structures (e.g. dams, weirs) or river management modifications (gravel extraction, dredging, etc.). Thus at the reach scale, the long profile of the UK's rivers is significantly influenced by the legacy of past human activity (Sear *et al*., 2000).

The form and downstream changes in the valley floor and long profile provide diagnostic value for interpretation of the longer-term and regional controls on sediment production and storage in the river network. Mapping these is one of the aims of the Geomorphological Assessment Procedure.

2.6.4 *Floodplains*

The floodplain is that part of the valley floor that is still inundated by flows under current climatic conditions. The floodplain is of particular relevance to river managers since it:

- defines the area of land that is at risk from flooding
- determines the volume of flood storage
- possesses a diverse ecology and habitat that lies between aquatic and terrestrial environments
- functions as a fine sediment store or, where cultivated, sediment supply to the river network

- functions as a nutrient and chemical processing system buffering the river from the catchment.

The floodplain provides the land into which the river channel can migrate as it adjusts to changes in sediment and water discharge. In so doing, the floodplain also provides a ready source of new sediment to the river, while also storing sediments brought into the reach from the upstream catchment. As a result, there has been much investment in defining the indicative floodplain of rivers as a means of providing decision support for flood and channel erosion protection (Rapp and Abbe, 2003).

Fluvial geomorphology has a role to play in helping to define the floodplain since the topography used to model indicative floodplains does not include the local variations in the floodplain surface that conditions inundation. In addition, in many cases, modelling of the 1 : 100 or 1 : 200-year recurrence flood provides a conservative estimate of potential flood extent compared to the evidence from floodplain geomorphology (Thompson and Clayton, 2002). Mapping floodplain geomorphology using high-quality, large-scale air photography or LiDAR has been advocated in support of planning and development control, although it remains problematic in the more intensively managed lowland areas of the UK where topography has been ‘ploughed’ out.

Floodplains are formed by:

1. processes of lateral accretion (whereby the river moves across the valley floor and lays sediments down behind it)
2. vertical accretion (whereby a river builds floodplain elevation through overbank deposition)
3. in-channel deposition of fine sediment benches
4. a combination of 1–3.

In some systems, obstacles to the flow such as debris dams, or other structures can produce locally accelerated deposition on the floodplain and the erosion of new floodplain surface channels (Jeffries *et al*., 2003). Similarly, the breaching of flood embankments can result in either deposition or erosion of the floodplain surface (Gilvear *et al*., 1994).

Figures 2.7a–d depict typical views across UK floodplains for upland, piedmont (the region on the margins of upland areas) and lowland river reaches. The topography and features associated with each vary, owing to the processes associated with their formation.

2.6.5 River channel form

River channels form the main conduits for the transfer of water, sediment, nutrients and organic matter. They comprise the river network, and they provide particular suites of physical habitat. The river channel may be divided into *reaches* that have been defined as ‘a length of river in which channel dimensions and features relate characteristically to identifiable sediment sources and sinks’ (Newson, 2002). Thus changes in the definition of a river reach will be determined by changes in channel dimension, features, sediment supply or sediment storage. Reaches in turn nest within floodplain and valley floor defined reaches, which in turn nest within segments defined by the local variations in geology and long profile (Fig. 2.8). Such a scaled hierarchy is useful for identifying the relationship between the larger network scale controls and local channel morphology and process that are more often the concern of river management.

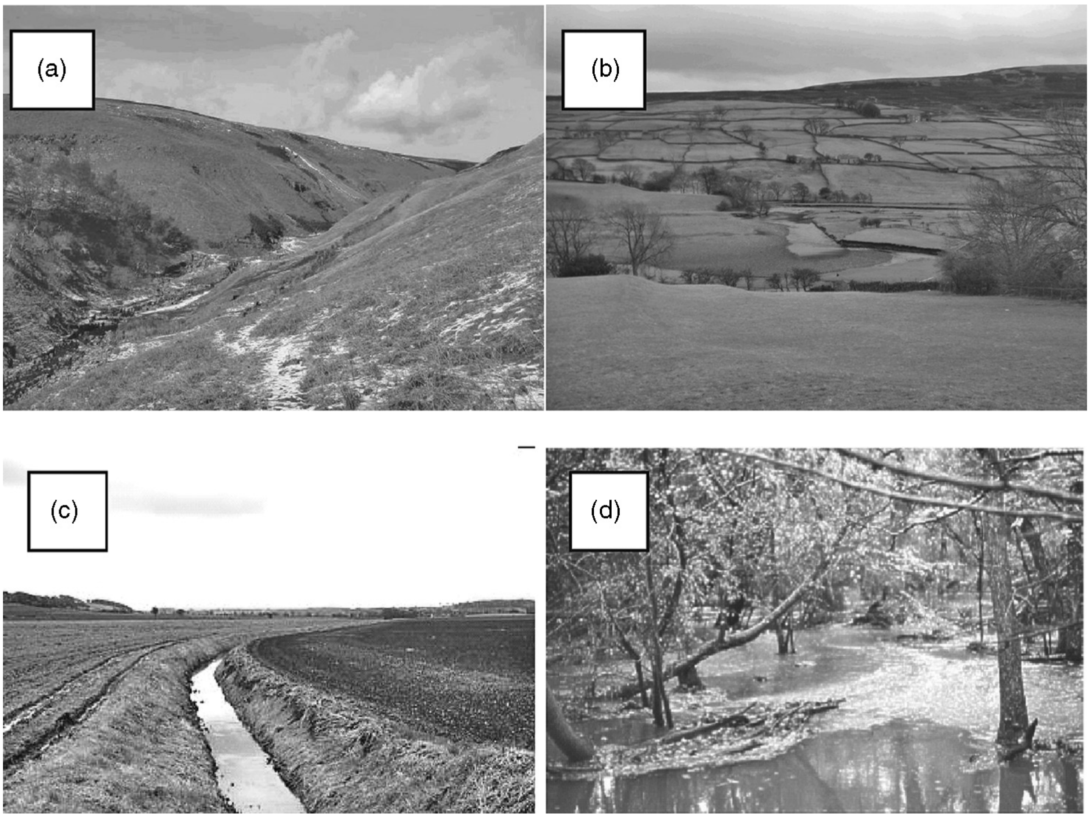


Fig. 2.7 (a) High-energy confined floodplain; (b) high-moderate energy alluvial floodplain, (c) low-energy modified floodplain; (d) low-moderate energy forested floodplain

A river channel may be defined in terms of three dimensions: the cross-section form, the planform, and the long-profile down the reach (Fig. 2.9). The level of definition of these dimensions depends on the use of the information. For example, detailed estimates may be necessary in support of river channel design, whereas qualitative estimates of channel form may only be necessary for the development of a network or national classification such as the River Habitat Survey or Catchment Baseline Survey. Figure 2.9 illustrates the measures generally needed to

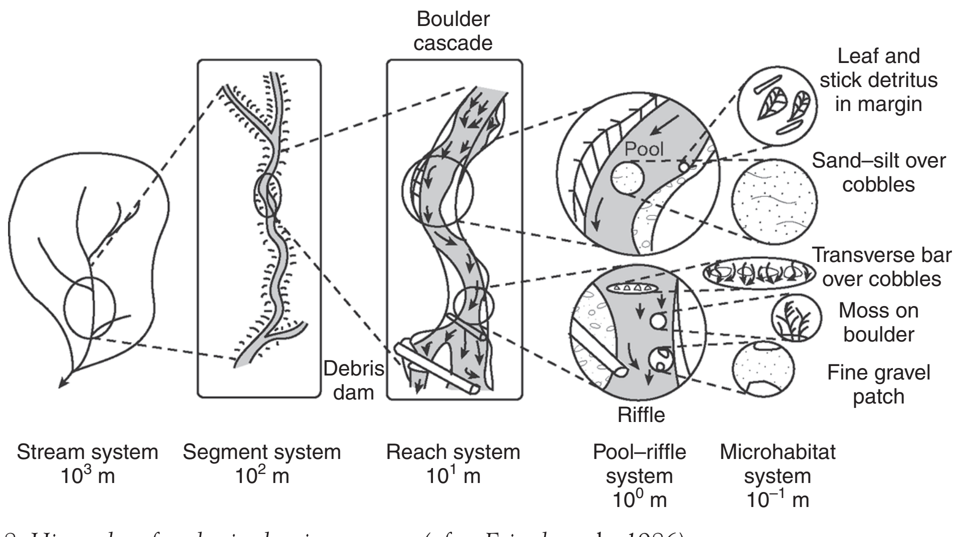


Fig. 2.8 Hierarchy of scales in the river system (after Frissel et al.*, 1986)*

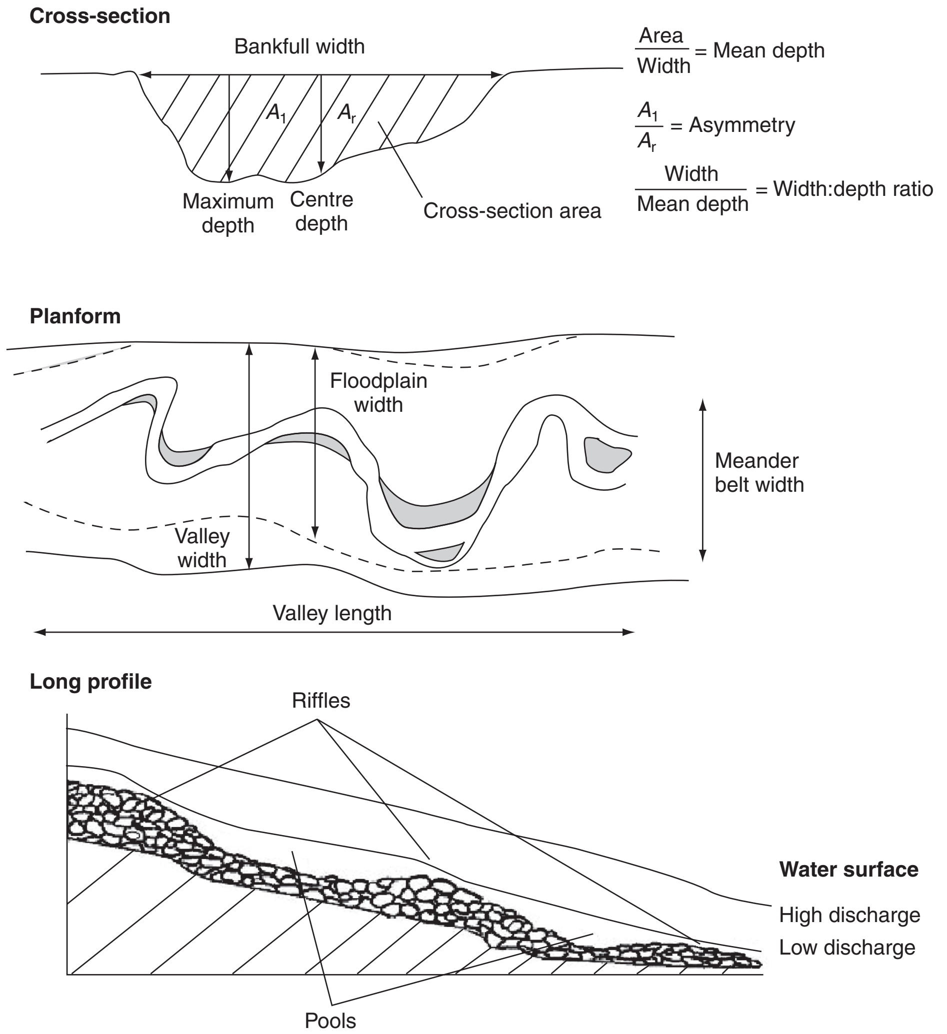


Fig. 2.9 The three dimensions of river channel form

define the form of a river channel. The dimensions are frequently standardised to bankfull values, since these are relatively easily understood by fisheries, flood defence and conservation staff, and relate to a discharge with significance for sediment transport. Definition of bankfull is however problematic, and in the field is usually defined by the break of slope between the river banks and the floodplain (Wharton, 1992). Clearly the presence of two-staged channel cross-sections or incised gorge-like reaches makes this difficult to define.

The size of a river channel is governed by the water flow through it, particularly flood peak flows that affect erosion and deposition. Many people have associated bankfull channel dimensions with floods that recur on average once in 1.5–2.5 years. Many have also associated bankfull discharge with the most effective flows for sediment transport. However, Church (1992) makes the point that ‘there is no universally consistent correlation between bankfull flow and a particular recurrence interval, nor between flood frequency and effectiveness in creating morphological change’. This arises because rivers with different calibre bed material require different discharges for sediment transport and bank erosion. The dimensions and planform of a river channel must therefore depend locally on the materials into which it is cut and the legacy of past processes and management. Figure 2.10

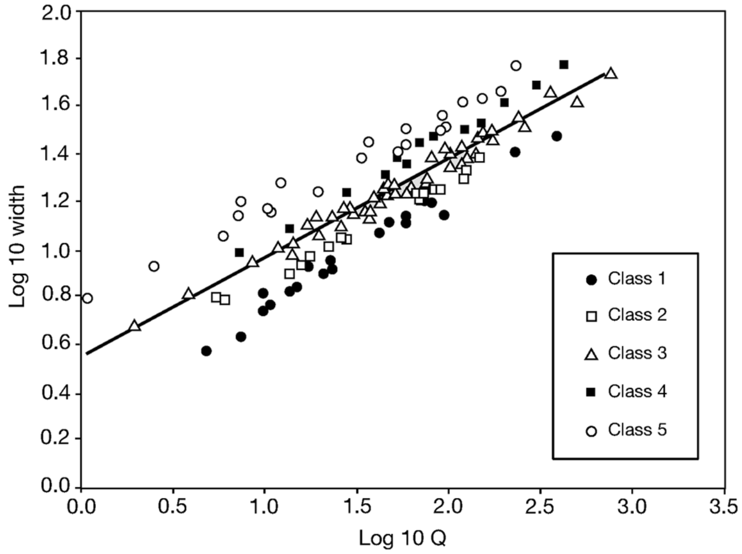


Fig. 2.10 Variation in channel width as a result of bank material and hydrology (after Dangerfield, 1999). Class 1, chalk streams; clay/silt banks dominate. Class 2, sand/gravel banks dominant. Class 3, mixed bed or cobble bed. Class 4, bedrock dominated bed, fine materials in banks. Class 5, silt/sand bank materials – slumping

illustrates this point, demonstrating that channel width increases with bankfull discharge at similar rates but offset according to the substrate and bank material. The implications for river management are that in any river restoration or channel design, river managers must pay attention to the local site conditions – one design will not fit all!

2.6.6 Channel planform

One of the most important features of a river channel is the planform. The planform controls the local stream gradient, affects the three-dimensional structure of the flow within the channel banks, and, through these, influences the range of depositional and erosional features and sediments that make the physical habitat. The planform is diagnostic of the type of channel processes present in the river system at that point; for example, a braided channel is indicative of high rates of sediment transport and local storage in the river channel.

The channel planform can be inherited from past processes and river management. In UK rivers, and particularly lowland chalk rivers, channel planform is relatively stable, with little movement of the river across the floodplain. Despite this, many rivers exhibit a tightly meandering planform set within broad floodplains. These rivers have low stream energy relative to the strength of the river bank and bed material. They can be thought of as 'naturally canalised' (Sear *et al*., 1999). Therefore any modification to the planform in these river systems tends to be permanent. In chalk streams the planform in particular can take on a highly complex form. In part this is due to the permanence of past management – for example, the presence of mill channels that result in multiple anastomosing planforms.

A further distinction can be made between rivers whose planform are confined by material or topography, and those that are free to migrate within the floodplain. Confinement results in irregular relationships between planform and geometry (the size, spacing and shape of bends) and instream features such as riffle-pool and bar spacing. Confined channels tend to have low rates of lateral migration

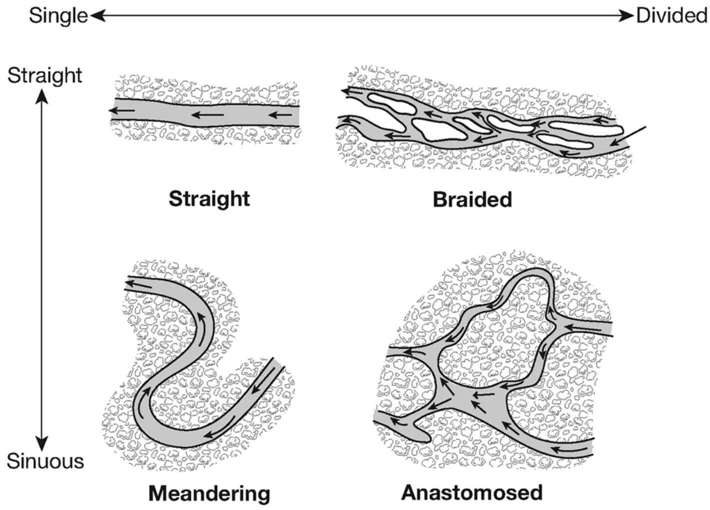


Fig. 2.11 Definitions of channel planform (after Rust, 1978)

and bank erosion. An exception is where confinement is by erodible sediments, such as a river terrace made of former fluvial sediments. This can lead to local areas of braiding where the channel cuts into the terrace and the river becomes choked with sediment. Channels whose planform is free to migrate develop a predictable relationship between instream features and bend geometry (see below).

Channel planform is usually classified into four main classes, separated on the basis of total length of channel per unit valley length (termed sinuosity), and the degree of channel division (Fig. 2.11). In the UK, all four types of river occur, although the number of braided and anastomosed channels is small relative to meandering and straight. There is evidence to support the existence of more braided and anastomosing rivers in the past – a fact that reflects both climatic control, but more significantly, river and floodplain management activity (Brown, 2002).

Naturally straight river channels tend to occupy relatively short stretches of a river network, whereas the other types of channel may persist for several kilometres. Straight reaches tend to be found in steep upland valleys where the channel planform is confined by glacial sediments or bedrock. In alluvial floodplains, straight reaches are often confined by cohesive sediments or trees. Even though the planform appears straight, the flow within the channel is irregular, and is characterised by a meandering high-velocity thread, often influenced by local pool-riffles, or in mountain streams by bedrock and boulder steps. The meandering nature of the flow field within straight reaches explains the failure of channelisation schemes in rivers competent to mobilise their bed sediments during normal winter floods. Interaction between flow structure and sediment transport produces a sequence of bars and scour pools that amplify the meandering flow and can initiate bank erosion and with time reform the original sinuous planform (Fig. 2.12).

Meandering channels are those with a sinuosity greater than 1.2, and are characterised by a series of bends and intervening sinuous sections. Although the planform may be meandering, it is important to recognise that this does not mean that the river is actively eroding the outer bends and migrating across the floodplain. Thus meandering channels can be usefully divided into those that are actively meandering and those that are passively meandering, depending on the degree of bank erosion and lateral movement. A good example of this is to be found in upland streams and lowland channels, where the sinuous planform is confined by cohesive glacial or alluvial sediments. The outer face of the meander bends may appear to be eroding,

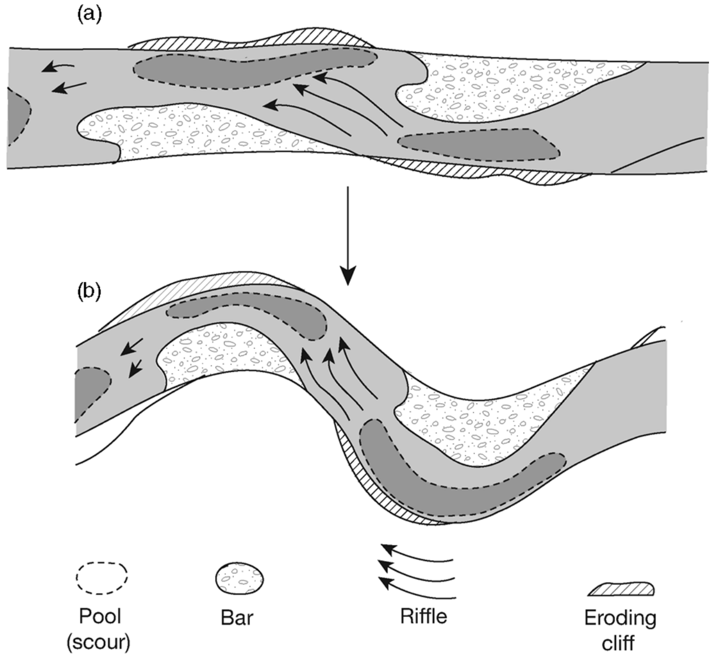


Fig. 2.12 The role of alternate bars in the development of meandering in alluvial rivers

displaying a vertical earth cliff, but in fact are kept clean of vegetation by weathering processes (the action of frost, rainfall, desiccation etc.); the bank line is stable. A good indicator of passive meandering is the lack of synchronicity between pool-riffle spacing and meander bend wavelength; in passive meandering channels, there are typically more pool-riffles per bend than would be expected if the channel were adjusting planform and bedform simultaneously (Thorne, 1997).

The geometry of meandering channels may be defined by a specific set of quantitative measurements (Fig. 2.13). These define the sinuosity (P), meander wavelength (L), meander belt width (B), the bend radius (R_c) (the tighter they curve the smaller the R_c), meander arc angle (θ) and spacing of the inflexion points between bends (Z). In alluvial rivers that can mobilise their bed and bank

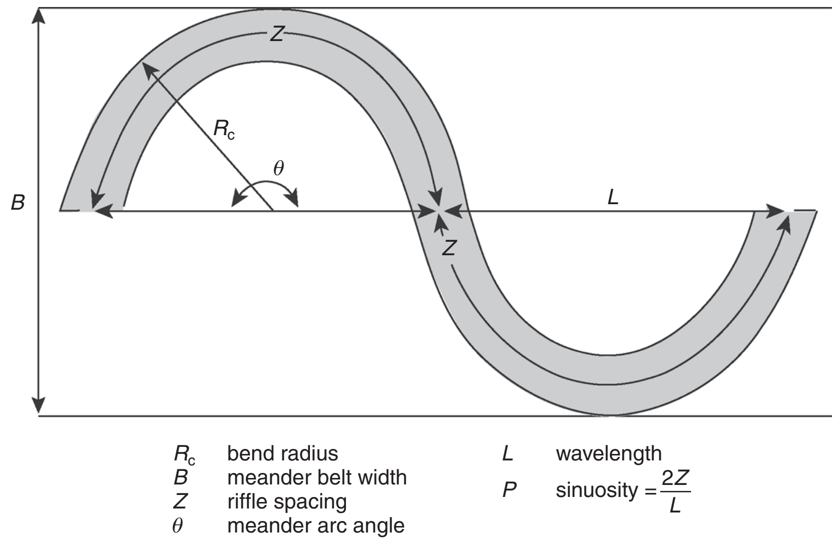


Fig. 2.13 Variables used in the definition of meander bend geometry. Reproduced, with permission, from Thorne, 1997. © 1997 John Wiley & Sons Limited

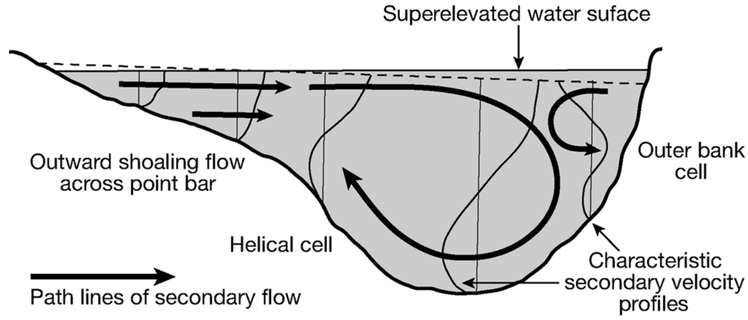


Fig. 2.14 Secondary flow structure in a meander bend and its relationship with scour and the form of the channel cross-section. Reproduced, with permission, from Thorne, 1997. © 1997 John Wiley & Sons Limited

sediments, the meanders exhibit a predictable relationship between channel width (typically bankfull) and these geometric descriptors of planform. However, the extent to which this occurs in UK rivers is uncertain, since factors such as variability in the erodibility of the floodplain sediments and banks imprints a random element into an otherwise ordered system.

In meandering channels, the flow of water is influenced by the curvature of the bends in such a way that currents are set up that draw water in from the point bar and out towards the outer banks (Fig. 2.14). The additional mass of water at the outer bank creates a downward pressure that in turn creates a vertical current that plunges towards the bed, returning water to the inside of the bend. Secondary components in meander bends are usually about 10% of the primary velocity. However, in very short radius bends the usual pattern of helical flow breaks down and very strong cross-stream velocities may occur. If R/W is less than 2, cross-stream and longstream velocities may be similar in magnitude. Secondary currents influence the pattern of force on the river bed and therefore sediment transport. The result is an asymmetric cross-section and the location of scour at the outside and base of the banks at the bend. In most cases, the focus for bend scour in meandering channels is in a zone immediately downstream of the bend apex. This frequently results in down-valley migration of the meander bend, and is often not appreciated in the design of bank revetment.

The river may exhibit more complex forms of adjustment, leading in some circumstances to the cut-off of the bend, and the development of an abandoned channel loop or ox-bow (Hooke and Redmond, 1992). The development of meandering channel planform to eventual cut-off is actually rarer than most imagine, and in Wales, 55% of cut-offs on adjusting gravel-bed rivers resulted from the development of a chute across the inside of the point bar (Lewis and Lewin, 1983).

2.6.6.1 Braiding

Braiding occurs when the transport capacity of a river is exceeded by the sediment supply, or when transport rates are typically very high (Fig. 2.15). The response of the river channel is to deposit sediment in bars (shoals) that are inundated at higher discharges and subjected to sediment transport. During higher flows, channels may be cut across shoals or blocked by aggrading sediment, leading to a planform that is characterised by a dynamic network of channels and bars. Braided channels are typified by relatively high bankfull channel width, and low bankfull depth (see below). Braided rivers occur across a range of valley slopes, depending on the grain size of the bed material in transport. Steep braided streams are characterised

Fig. 2.15 Braided reach of the River Swale, Yorkshire. Note multiple channels flowing between active gravel shoals within a channel bounded by a vegetated and elevated floodplain surface

by relatively large grain sizes; lower gradient braided rivers tend to form in sand-sized bed material.

The description of braided channel planform is based on the total length of channel per unit valley length, or some measure of the number of bars per unit channel length (Thorne, 1997). Variability in these measures defines the extent to which a braided river is bar or channel dominated. Channels that locally widen around a central bar are not braided rivers. However, sections of a river network may be braided. These are diagnostic of a change in bed load transport or sediment supply, often associated with changes in gradient.

Braided rivers were once more common in UK rivers, a fact attributed to the recent management of bank erosion, but also due to increased flood frequency and channel activity during the 17th–19th centuries (Macklin and Rumsby, 1994; Passmore *et al.*,1998). Braided planforms often occur in response to increased sediment transport during extreme floods in upland watercourses, only to return to a meandering planform once the sediment supply and transport rates decline (Harvey, 2001). Channels that exhibit this switching of planform morphology are termed *wandering*, and are close to the threshold of channel planform change (Passmore and Macklin, 2000).

Vegetation of bar surfaces is one of the main mechanisms by which natural braided rivers become stabilised. This occurs following incision of the river channel into the bed, progressively abandoning the bar surfaces and enabling colonisation by plants. In natural braided systems, large wood helps create bars and islands by acting as local sites for sedimentation (Gurnell *et al.*, 2003).

2.6.6.2 *Anastomosed channels*

Anastamosis is a medical term that refers to the branching of arteries in the body. Anastomosed river channels are distinct from braided rivers for several reasons.

- The channels are separated by vegetated surfaces of elevation similar to the floodplain (and in fact form the floodplain surface).
- Anastomosis occurs in low-gradient valleys experiencing long-term aggradation of fine sediment.
- The individual channels function and appear like separate river reaches, with channel geometry and features adjusted to the flow and sediment load in each branch.
- The planform activity of anabranched channels is typically low.

- The number of channel junctions per valley length is much lower than equivalent braided channels.

Anastomosed rivers are most clearly identified in lowland UK river channels, but are difficult to distinguish because of the history of channel management in these environments. Multiple channels across UK lowland floodplains may therefore retain old river branches, or may appear anastomosed as a result of valley drainage schemes. The characteristic feature of anastomosed rivers is the deposition and accretion of the floodplain by fine sediments. Therefore one indicator of anastomosis is a depth of fine cohesive sediments in the floodplain.

The branching of river channels to form anastomosis reduces the capacity of each channel, and therefore the sediment conveyance. Stream energy is therefore focused into smaller channels that can retain their form. Management of anastomosed river systems typically revolves around balancing the hydrological demands of each branch. The plugging of one branch will obviously lead to adjustment in the remaining branches as flow and sediment loads are re-apportioned.

2.6.7 Channel cross-section form

The cross-section of a river channel under natural processes will reflect the local balance between erosion and deposition of the bed and banks. The precise geometry of the river cross-section will be influenced by the channel planform through the structure this imparts to the flow field. The resulting cross-section form can be described according to the channel dimensions (width and depth), the capacity (area of the cross-section) and the shape (degree of asymmetry). Asymmetry is an important measure of the shape of the cross-section and may be indexed by:

$$A^* = \frac{A_r - A_1}{A}$$

where A^* is a value between 1.0 and -1.0 (though natural channels rarely exceed 0.65 or -0.65), A_r and A_1 are the cross-section area of the bankfull channel capacity to the left and right of the centreline of the channel and A is the total cross-section area. In pool-riffle sequences, for example, the pool cross-sections are typically asymmetrical, whereas those at riffles tend to be more symmetrical. Monitoring the change in A^* at cross-sections can provide clear evidence for the development of shoaling and may help diagnose the onset of bank erosion and meandering.

Measures of channel cross-section geometry are usually made for the bankfull condition, defined by the lowest level at which flows would spill onto the floodplain. The rationale is that this provides a standard against which to compare other reaches, is readily identifiable in the field, and is related to the flows that have maximum stream energy and sediment transport rate; subsequent flows tend to dissipate energy across the floodplain. Measures of channel width, depth and capacity provide absolute values for comparison and as input to sediment transport and hydraulic equations.

Channel capacity in natural rivers is the outcome of water and sediment transport. Capacity is related to measures of channel width and depth, such that for an idealised rectangular cross-section, average channel width is the product of channel capacity divided by average channel depth. However, few natural channels have such regular cross-sections, and other values such as mean depth below bankfull, or maximum depth, are used to define channel form.

The width/depth ratio (F) of natural channels is influenced by the cohesiveness of bank materials and the protective role of vegetation. Channels flowing through cohesive sediments are unable to erode laterally but may cut down into underlying sediments to create a narrow, deep cross-section of low width/depth ratio. Conversely, channels cut into alluvium that is readily transported by normal flows are characterised by wide shallow cross-sections.

The effect of vegetation on river banks is generally to reduce the width/depth ratio by providing additional resistance to bank erosion and channel widening. Studies in the UK (Charlton *et al*., 1978; Hey and Thorne, 1986) show that tree-lined rivers are up to 30% narrower than would be the case otherwise. Vegetation increases bank strength but also diffuses the energy applied to the river banks during floods (see Chapter 3 for more details).

2.6.8 Depositional features

The accumulation of sediment in the river network over time results in a variety of morphological features that are often transient, but may also be apparently permanent. At the largest scale are zones of sediment accumulation. These comprise reaches of up to several kilometres in length, that are characterised by braided or wandering planforms, high rates of channel movement across the floodplain, and coarse/mixed grainsize sediments (Fig. 2.16). The form and behaviour of the channel in these reaches is contrasted by the stability of the adjacent reaches that may often be confined by glacial till or bedrock.

Sedimentation zones occur where local geological controls, such as the presence of a rock step, glacial moraine or alluvial fan, reduce the valley gradient and create an

Fig. 2.16 A sedimentation zone on the River South Tyne, Northumberland (photo courtesy of Northern Echo)

area of preferential sediment storage. Reworking of this sediment, and the accumulation of new sediment stores arriving from upstream, maintain the activity of the channel. Sedimentation zones also occur around major coarse sediment inputs, for example from tributaries, or alluvial fans, or an active river cliff. In some cases, the input of sediment can lead to the formation of a sediment wave. Sediment waves lead to a progressive downstream adjustment in the river morphology as the wave of sediment passes through. Once passed, the reach returns to its original form, although it may occupy a different location in the floodplain.

Sediment waves, and sedimentation zones are most commonly found at the margins of the uplands. Identification of a sedimentation zone helps explain the apparently untypical activity of a reach, and helps river managers understand the larger-scale reasons for such activity. Within the river channel, there exist in response to sediment transport processes and hydraulic patterns, localised accumulations of sediment that geomorphologists generally term *bars* but may be more commonly referred to as *shoals*. Bars typically form in channels that can create flows that are 10 times the depth of the median grain size of the bed sediment (Church, 1992), and that have general movement of the river bed. Bars exhibit a variety of forms depending on the geometry of the channel and the structure of the flow. A broad distinction exists between *forced* bars that are created and confined by the local channel geometry and associated hydraulic and *free* bars that are free to migrate and in fact influence the local hydraulics and sediment transport processes.

Examples of forced bars are point bars and tributary confluence bars; examples of free bars are mid-channel bars and alternate bars. This distinction is important for the diagnosis of river channel adjustment processes; free bars are often developed after rare large flood flows and produce very different flow patterns that can influence subsequent channel adjustment. A good example of this is the formation of 'free' alternate bars in a channelised section of the River Severn, that subsequently led to the initiation of meandering in the reach (Lewin, 1976; see Fig. 2.12).

Figure 2.17 presents a typology of bars as they are found in UK river systems. In upland rivers, the distribution of bars tends to be less ordered and owes much to the presence of obstructions such as boulder steps, rock steps and debris dams (Fig. 2.17a). In high magnitude floods, boulders themselves can become ordered into linear berms or chaotic 'dumps'; diagnostic of the role of large floods in the evolution of the river environment (Fig. 2.17b).

In alluvial sections of the river network, where the floodplain is comprised of past river sediments and the channel is able to transport most of the sediment load, bar forms become organised into relatively well-defined features, with typically finer sediments than adjacent parts of the river bed. In straight or gently sinuous channels, asymmetrical cross-sections develop, resulting in side bars or even alternating side bars (alternate bars) in response to the structure of the flow field (Fig. 2.17e). In meandering reaches, these side bars are more easily identified as point bars from their position on the 'point' of the inner bend of the meander (Fig. 2.17d).

Fine sediment can be deposited on the outside of a meander bend, constructing so-called 'counter-point bars'. These are diagnostic of cases where the outer bank of a meander erodes rapidly and leads to over-widening, or when bend curvature becomes particularly tight and the flow 'stalls' on the outside of the bend.

Mid-channel bars have a variety of forms in themselves, depending on the extent to which they have been dissected by subsequent flows following their formation (Fig. 2.17c). Mid-channel bars form under three basic mechanisms:

1. deposition on a riffle following high flows and scour of the upstream pool

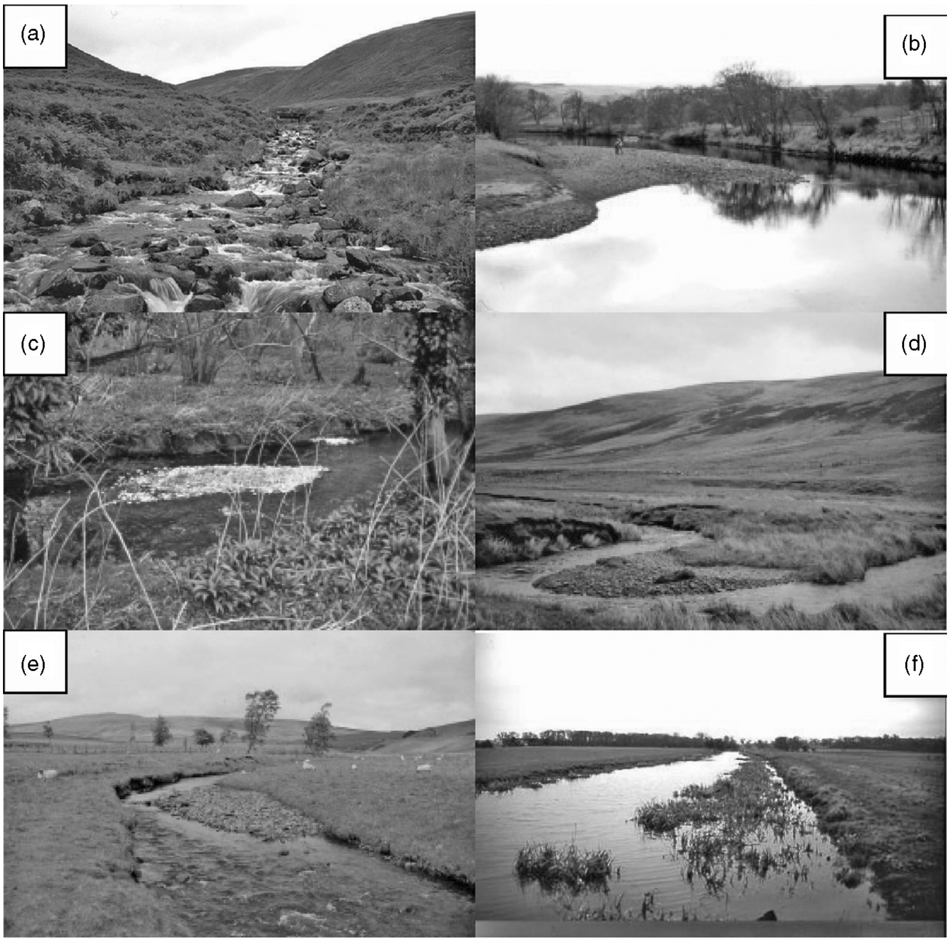


Fig. 2.17 Some typical sediment deposits in UK rivers: (a) chaotic boulder channel, (b) tributary confluence bar, (c) mid-channel bar, (d) point bar, (e) side bar, (f) fine sediment berm

2. deposition in an over-wide section due to a rapid reduction in transport capacity (often associated with (1) above)
3. erosion of a channel at the back of a point bar, followed by capture of the main channel and diversion through the new channel.

The final category of bar form found in UK rivers is the tributary confluence bar. This is a forced bar by virtue of the flow patterns formed when two rivers join (Fig. 2.17b). The extent of the bar is controlled by the junction angle of the tributary. Short, wide tributary bars that can occupy up to 50% of the trunk stream occur at high tributary junction angles. Long, narrow bars occur when junction angles are low. Tributary confluence bars can be large enough to reduce channel capacity by a significant amount in situations where the main channel is unable to transport all the sediment delivered by the tributary stream. This arises particularly in streams with a regulated flow regime (assuming higher flows are regulated) or where tributaries are delivering substantial sediment loads (Best, 1987).

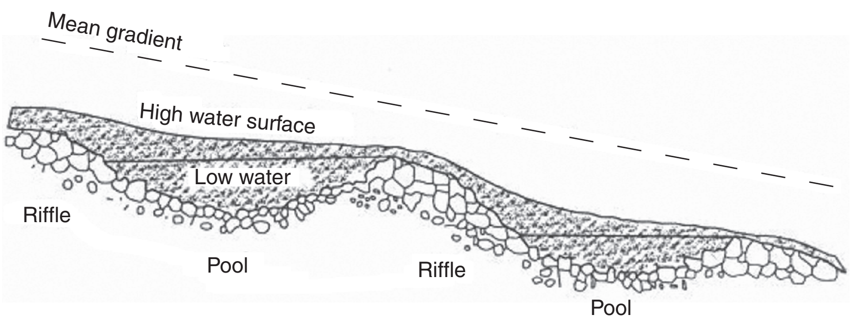
In lowland channels, and where a significant fine sediment load exists in the river network, fine sediments can be deposited in sufficient depth to form morphological features (Fig. 2.17f). Typically, fine sediments accumulate in areas of low velocity, such as the margins of river channels where the frictional resistance of the banks slows the flow, or in dead water areas formed in the lee of bars or where old channels create backwaters. In channels that are over-wide relative to the recent in-channel discharges, fine sediments can create low benches along the channel margins, called berms. Berm formation can be extensive and is diagnostic of artificial widening or widening during an extreme flood. Seeds and other plant propagules are deposited along with fine sediments in slack water areas (Steiger *et al.*, 2001). As a result, berms are very quickly colonised by vegetation; often making their identification difficult, and increasing their hydraulic impact.

The type, size and sedimentology of depositional features in the river network provide useful diagnostic indicators of the processes operating in the channel. For example, the presence of fine sediment berms along both sides of a channel is a clear indicator that the channel is over-wide. Similarly, the presence of few, coarse bars with little relief and vegetation colonising their surfaces is indicative of a reach that is being starved of sediment. Conversely, a reach with numerous, large, high relief bars with mixed sediments including fines and limited vegetation colonisation is indicative of a reach that is accumulating and storing sediment.

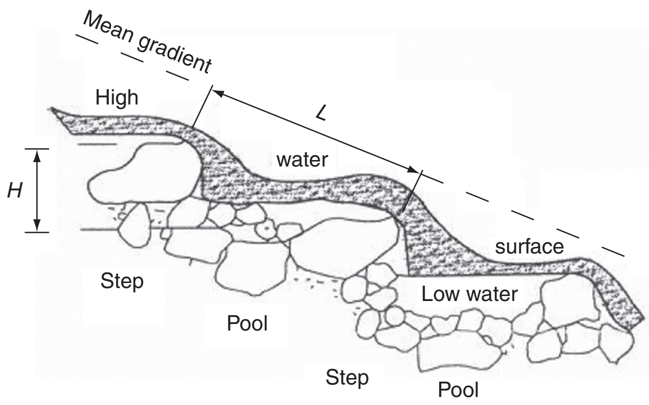
Recording the type, extent and sediments associated with bars is an important part of the Fluvial Auditing procedure within the Geomorphological Assessment Process.

2.6.9 *Pool-riffles and the geomorphology of river long profiles*

The reach scale (<1 km) long profile of rivers conveying coarse sediment (>8 mm) is characterised by semi-rhythmic undulations in bed elevation. Steep channels (slope typically 4–35% slope) are often characterised by a sequence of pools, dammed behind individual boulders or, in wider channels, lines of boulders, that create a step-pool bed profile (Fig. 2.18a). The steps can contribute significantly to the



(a)



(b)

Fig. 2.18 Variations in the local long profile: (a) step-pool sequence in steep coarse sediment channels and (b) riffle-pool sequence in alluvial cobble and gravel-bedded rivers total gradient and friction of the channel. They are thought to form during high flows by the re-arrangement of cobbles and boulders into 'dams' across the channel. As a result, once formed they tend to be persistent features that are only destroyed during higher-magnitude floods. However, the presence in bedrock of similar step-pool morphology points towards some inherent disturbance in the flow as a possible cause of formation. As a result of the steep gradients in these channels, the spacing of steps is typically small (three to four times channel width). Sediment transport is typically from pool to pool, with the steps remaining as stable elements in the low profile. The interlocking of the boulders/cobbles in steps is an important element of their stability.

In wider, shallower channels (slope <2%), the influence of individual boulders and groups of boulders on flow and sediment transport processes becomes less, and is replaced instead by accumulations of finer particles into bars and riffles (Fig. 2.18b). Riffles are constructional features that occur through the process of sediment transport. Riffles are locally raised gravel and cobble deposits that form shallow areas in the local long profile characterised by fast turbulent flows. They are most often associated with pools formed by locally intense sediment transport but may also occur with glides and runs. Riffles are seen both as a hydraulic roughness element and a valuable habitat. Riffles are known to aerate flows, provide spawning habitat for both cyprinid and salmonid fish, have specific invertebrate fauna and, in conjunction with pools, provide habitats for the adult life stages of many fish species. Many riffles have been removed from UK rivers as a result of past management activity that focused on improving flood conveyance. As a result, riffle reconstruction has become one of the main features of river rehabilitation and restoration programmes. In most cases this is undertaken in the absence of any geomorphological guidance. Thus many of the riffles created are simply piles of gravel in a river bed, and as such do not optimise their contribution to river habitat and ecosystem function, although they appear to mimic the desired feature. The absence of post-project monitoring makes confirmation of 'success' in many riffle rehabilitation schemes currently impossible.

There is no single explanation for the formation and maintenance of riffle-pool sequences. It seems clear though that riffles are created by the scour of an upstream pool. The formation of scour pools arises in response to:

- a local constriction in the channel (e.g. debris or large boulders) – the narrowing flow generates local acceleration and scour of a pool, with downstream deposition in the form of a riffle/bar
- a weir or debris dam where the scour pool again creates a riffle/bar
- the development of alternate bars as flow meanders during floods – the tendency for water flow to meander interacts with sediment transport to produce a sequence of alternating scour pools and bars; the surfaces of these bars become riffles.

Once formed, the morphology of the riffle-pool sequence promotes its own stability through several mechanisms:

- Turbulent flows over the riffles during low-moderate events organise the riffle sediments into a coarse, tightly packed surface that is resistant to erosion during floods.
- The downstream pattern of sediment transport created by the pool-riffle topography promotes preservation of the riffle as a site of sediment accumulation – hence continuously replenishing the riffle.

- The hydraulics of the flow in a pool-riffle sequence during floods may lead to the highest forces on the bed being exerted in the pools, hence leading to higher sediment transport rates and preservation of the pool by scour.
- The secondary flow structure induced by pool-riffle morphology tends to route sediments around the edge of pools so that once formed they tend not to infill.

In natural riffle-pool sequences, sediment is transported from pool to pool over the intervening riffle. The riffle often contributes little to the sediment load in transport, and may in some cases remain completely intact. A distinction can be made, between those riffles that are fixed 'fossil' features of the geomorphology, and those that are the product of active sediment transport processes. Stable riffles that are fixed tend to have dark, algae-stained surface sediments, often moss covered, with a compacted bed surface. A scattering of loose mobile sediment may be evident from recent deposition on the surface. Active riffles may have 'fresh' surface sediments with little compaction, and a pronounced downstream bar front. Over time these riffles may become compacted and fixed – a sure sign that bed mobilisation or upstream sediment supply has been reduced.

Clearly, an important step in optimising the design of riffle-pool sequences is to establish the ability of the river to transport bed material. If as is the case with many lowland and particularly chalk streams, the river is unable to mobilise its bed sediments, riffles are likely to be both infrequent and randomly spaced. Field evidence to date would confirm this. To create natural riffle-pools in such low-energy streams requires the stream energy to be focused by either constrictions or weirs. The natural process that creates these conditions is the input of large woody debris. Conversely, if coarse bed sediments are capable of being mobilised, then the absence of a riffle-pool sequence is probably due to excessive or absent sediment supply or recent maintenance. Options for rehabilitation in these circumstances include locally reducing or increasing sediment supply or managing maintenance regime.

The rehabilitation of riffles carries with it some potential limitations depending on the function of the rehabilitation. Table 2.3 highlights the possible limitations to achieving the desired function of a riffle rehabilitation programme, and highlights some solutions.

Riffles are not the only feature that introduces local increases in channel gradient. Stream ecologists have widely recognised the presence of glides, runs, rapids, cascades and falls, but geomorphology has been slower to associate these forms with specific sediment transport and adjustment processes. The significance of these features lies in their local control on channel gradient and flow resistance and in their contribution to the diversity in physical habitat (Sear and Newson, 2004).

Runs and glides often occur in association with riffles. Runs are intermediate between riffles and glides, and are characterised by deeper flow than riffles, and a steady gradient. Glides have deeper, slower flows at low flow than runs, but faster (discernible) flows than pools. Runs and glides may represent areas where a pool has been filled in by sediment or where scour is unable to deepen the long profile. Runs are often associated with salmonid spawning habitat in steeper upland streams. Glides and runs are typical of chalk streams, the runs replacing riffles as the local step in the long profile (Sear *et al.*, 1999).

In mixed-sediment, lower-gradient channels, riffles form rapids in the ecological definition of the feature. In steeper streams, rapids are formed by local breaks in channel gradient, and are characterised by lines and groups of isolated boulders

Table 2.3 Some potential limitations and solutions to the rehabilitation of riffles

Limitations to rehabilitation	Solutions
1. May initiate meander development	Protect bank/widen channel at riffle
2. May armour/cement in the absence of an upstream sediment supply and/or presence of significant fine sediment load	Provide upstream supply through initiating bank erosion of gravels or where fines are a problem introduce remedial strategies for reducing fine sediments (catchment scale most likely options)
3. Presence of excess fine sediment transfer can result in sedimentation and burial	Reduce fine sediment sources or provide upstream opportunities for deposition
4. Wash out during floods in absence of replenishing sediment supply	Careful design of substrate based on stability criteria. Provide large keystones
5. Can locally elevate flood levels if amplitude too high	Perform hydraulic analysis to estimate influence of form/grain roughness across flow range
6. May attract livestock for watering/access across channel	Fence off or provide alternative supply/access

Limitations to rehabilitation (numbers refer to above)

Desired function	Functional limitations	Practical limitations
Dynamic component of coarse sediment transport system	4	1, 5 and 6
Hydraulic diversity at low flows	3 and 4	1, 5 and 6
Aeration at low flows	3 and 4	1, 5 and 6
Salmonid spawning ground	2, 3 and 4	1, 5 and 6
Cyprinid spawning ground	2(?), 3 and 4	1, 5 and 6
Invertebrate habitat	3	1, 5 and 6
Aesthetic feature	4	1, 5 and 6

that stand above the water at low flows (Church, 1992). Flow occurs through a series of ill-defined chutes, created by the structure of the bed sediments. Sediment transport largely occurs in a series of threads, defined by the network of large boulders. Finer sediment, suitable for spawning habitat for salmonids, is found in the low-velocity regions downstream of large boulders.

In steeper reaches, often influenced by outcrops of bedrock, local steps in the channel gradient occur where the low flow tumbles over or is accelerated through boulders or bedrock steps to form *cascades*. Low-flow velocity is typically locally extreme, and during floods is chaotic. Sediment transport over smoothed bedrock reaches is typically in threads, and occurs rapidly owing to locally high-flow velocity and the high relative exposure of sediment grains above the bedrock surface.

Waterfalls vary in scale, but occur where locally resistant bedrock produces a step in the channel bed, below which a plunge pool is formed. Larger waterfalls owe their origin to local geological or glacial processes.

2.6.9.1 Pools

Much of the river habitat and morphology of UK rivers is characterised by relatively deep, slower-flowing water termed ‘pools’. However, the origin of pools in river channels distinguishes between those created by backwatering from an instream obstruction – ‘backwater pools’ – and those that result from local removal of sediment from the stream bed – ‘scour pools’. Backwater pools are typically shallower and longer than scour pools in the same river channel, although this depends on the height of the obstruction. Backwater pools are characterised by low velocities near the river bed across the flow range and are, as a result, areas of net sediment accumulation. The floor of backwater pools is characterised by finer than average sediments often in association with organic debris (Church, 1992). Examples of backwater pools include those formed upstream of large wood dams, or artificial structures such as weirs. In the latter case, backwater pools may occupy significant proportions of the channel network. On the River Wensum over 50% of the channel length is ponded by backwater pools formed at mill weirs (Sear *et al.*, 2006).

Scour pools occur in response to local increases in sediment transport capacity. These may include focusing of streamlines by bend curvature and sediment accumulation such as the pools opposite point bars in meander bends, or pools adjacent to lateral (or side) bars in the pool-riffle sequence termed 'lateral scour pools'. Plunge pools are scour pools that occur where the flow falls freely over a rock step, while vertical scour pools occur downstream of large wood dams where the flow is physically blocked by the dam, or at flow re-entry points from the floodplain (Church, 1992). Scour pools are floored by coarser than average sediments; however, these are often overlain by fine sediments temporarily stored during low flows.

2.6.10 The role of wood in rivers

It has become clear that clearance of riparian woodland and centuries of channel management have largely removed wood from UK and many other developed watercourses. Research to date makes it clear that the role of large wood (LW – defined as wood longer than 1 m and with a diameter >10 cm), or coarse wood (CW) as it is also termed, was, and in some places such as the New Forest still is, a significant control on the transfer of water and sediment through the river network and over the floodplain (Charlton *et al.*, 1978; Millington and Sear, 2007). Locally, and in some river systems extensively, LW significantly influences the morphology and associated physical habitat (Gregory *et al.*, 2003). The relative extent of its influence depends on the scale of the river and the degree of resistance offered by the boundary materials. For example, in small river channels where channel width is less or similar to that of the LW, dams may form that block the channel and provide local points at which water and fine sediment are directed on to the floodplain (Jeffries *et al.*, 2003). However, in larger watercourses, where channel dimensions are larger than LW, the role is frequently that of influencing patterns of channel sedimentation and bank erosion (Gurnell *et al.*, 2002). Deposition of LW is part of the formation of islands in wider alluvial rivers (Gurnell and Petts, 2002). Classifications of LW have emerged that recognise their variable influence on low-flow hydraulics, sediment transport and channel morphology (Fig. 2.19). The sites of debris dams that trap organic matter and sediment from upstream become points of local floodplain inundation, but also create highly diverse physical habitat. In lower-gradient watercourses, LW dams may be spaced as frequently as every three bankfull channel widths.

River management practices that focus on flood protection, remove LW accumulations or isolated tree fall on the premise that these locally increase flood height, or may become dislodged and create a flood hazard by trapping against bridges or other structures. In steeper upland watercourses, LWD accumulations can fail under extreme floods, generating flood surges (Dobbie and Wolf, 1953). While caution is required, it is possible to consider LW and floodplain forestry as an appropriate method for increasing upstream flood storage in the intermediate reaches of river catchments (Sear *et al.*, 2006). Furthermore, it is almost certain to be the major

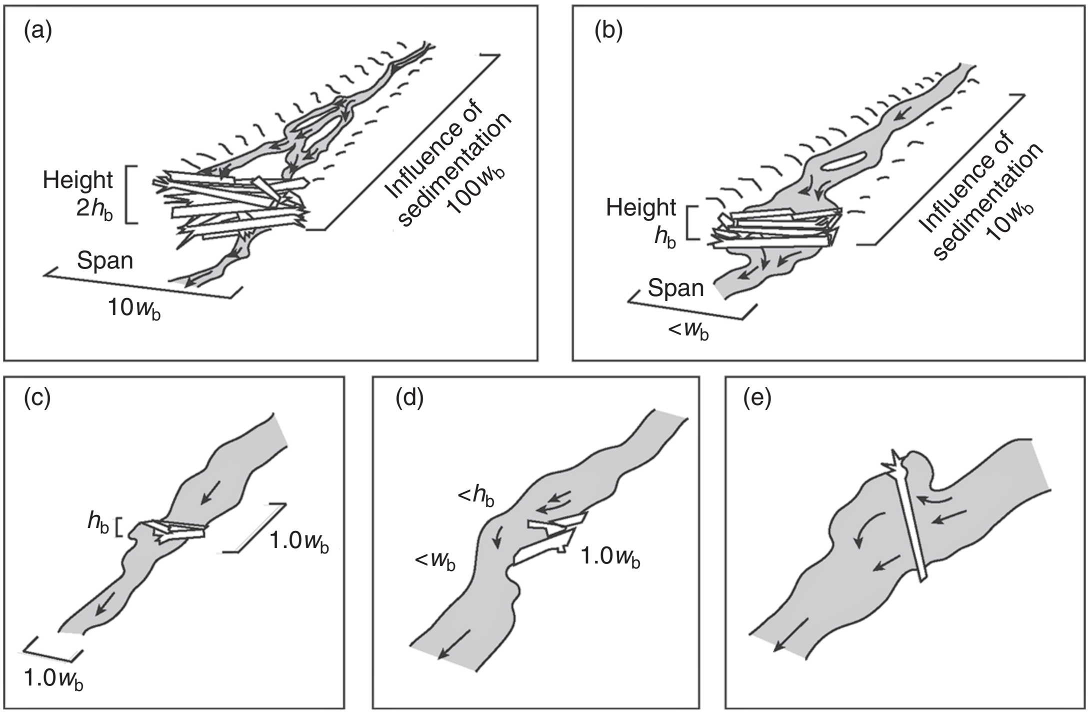


Fig. 2.19 A classification of debris dams and their relationship to channel morphology. Reproduced, with permission, from Hogan et al.*, 1998. © 1998 Water Resource Publications, LLC*

missing element of the natural habitat of lowland modified watercourses and groundwater-dominated rivers (Brown, 2002; German and Sear, 2003).

2.7 The role of river classification and typology in river management

The desire to impose order onto complex natural systems is at the root of all scientific disciplines. The process by which this is achieved is generally termed classification. The rationale for classification is to simplify complexity in order to better understand the relationship between natural processes and resulting adaptations (be they morphological or ecological); to aid communication between scientists through employing standard protocols for interpreting observations; and for interfacing across disciplinary boundaries. Classification has been applied in a wide range of environmental management including coastal protection, conservation and river management (Downs and Gregory, 2004). The history of attempts to classify rivers into different types spans at least 125 years, a period over which more than a hundred different attempts to divide and categorise rivers have been made (recent reviews of the extent of such efforts are given by Thorne, 1997 and Church, 2002).

Classification is the (artificial) process of ordering objects/systems into groups based on common characteristics or criteria (Newson *et al.*, 1998a). Newson *et al.* (1998a) identify three processes within the development of a classification: taxonomy, typology and allocation. Taxonomy is an inductive process that derives class boundaries from a dataset, for example the classification of animal species. Typology is a deductive process that utilises theoretical principles to define a set of thresholds that distinguishes between different classes such as the hydraulic classification of flow by Froude number. Allocation refers to the separate process by which observations are assigned to the classes derived from the typology or taxonomy. Examples of river classifications that are taxonomic include that derived for rivers in England and Wales based on the River Habitat Survey (Raven *et al*., 1998). River classifications based on typologies are more widespread, including those of Montgomery and Buffington (1997) for channel-morphology of mountainous regions of the Pacific Northwest USA, the river contiuum concept (Vanote *et al*., 1977) and hybrid classifications such as those by Newson *et al*., (1998a) that applied a process-based typology but refined the class boundaries using a large dataset of UK rivers.

A fundamental principle behind classification is that once class boundaries have been determined and a unique class identified, then it is possible to infer common characteristics or traits based on studies of other members of that class. Evaluation of these traits may allow the predication of behaviour under different circumstances such as past or future climates, or future river management. However, the definition of boundaries or thresholds within a river channel classification is dependent on the morpho-climatic region in which it was developed (e.g. Snelder *et al*., 1999; Brierley and Fryirs, 2001) and its application (e.g. water quality designations, ecological quality, morphological characteristics, fish species). There are as a result, many river channel classification systems proposed and applied (Downs and Gregory, 2004). Montgomery and Buffington (1997) identify the core values of a river typology as general applicability and adaptable to regional variability. The resulting classes are therefore widely relevant both to scientists in differing disciplines and applicable for environmental management. Central to such a river channel classification system is a typology based on the relevant physical processes.

2.7.1 Theoretical basis for differing channel types

A river channel classification is based on the premise that distinct river types are found in areas with differing sets of geomorphological controls (Church, 2002). The assumption of such a classification is that channel morphology is the dependent variable arising from activity of a number of independent forcing variables (Lane, 1955; Thorne, 1997; Church, 2002; Eaton *et al*., 2004). A significant change in one or more independent variables along the length of the river should therefore see an observed change in channel morphology. Fluvial geomorphology and allied disciplines, such as river engineering science and hydrology, have recognised key thresholds or bifurcations in the independent variables controlling river channel form (Hey, 1997; Montgomery and Buffington, 1998; Church, 2002). Most fundamental is the distinction between channel types that are formed by contemporary processes of sediment transfer (defined by erosion, transport and deposition of sediment) – so-called alluvial channels, and those whose bed and bank materials are currently stable. As with most natural boundaries, it is a transition rather than an abrupt break, thus a range of channels exist that can transport some portion of the bed and bank material under current flow regimes.

In theory, boundaries between channel types can be defined provided that we have a measure of the sediment size distribution of the bed and bank material (or more correctly, the force required to move assemblages of these sediments) and the forces generated by the combination of channel slope, discharge regime and flow resistance afforded by the channel (Church, 2002). An additional constraint in these terms is provided by the presence of riparian and in-channel vegetation (living and dead). These provide additional flow resistance (thereby reducing the force available to mobilise bed and bank material), and contribute additional strength to bed and bank materials (Darby and van de Weil, 1999).

Church (2002) recognises a further threshold between channels whose morphology is largely derived from the size of immobile material (e.g. boulder-bedded, or step-pool channels) and those where a significant (unspecified) proportion of the bed and bank material are mobile. In such channels, morphology is influenced by the ability of the channel to transfer the bed material load supplied to it from upstream and from within the reach.

River classifications are used in support of river management in several countries including the USA, France, Germany, South Africa and the UK.

Classification systems have been used in river management:

- to identify 'reference states' against which to assess channel quality and therefore the need for management intervention to improve or protect the river environment
- for splitting up a river network into functionally or morphologically similar reaches
- as the basis for channel design
- as a method for communication between the different disciplines involved in river management.

The degree to which a river reach behaves or looks the way it does results from the mix of controls due to (1) past processes, (2) off-site influences, or (3) local controls. This significantly affects the value of a classification system based on recording current channel features alone, and mitigates against the introduction of classification systems developed for other types of river or physical environment.

One of the drawbacks with classification systems is that, without a full understanding, they can appear to provide very clear guidance, while not providing the level of support necessary to fulfil the task demanded. Recent examples of this problem are arising in the US, where rigid application of the 'Rosgen' system for classification has been used to design and build river restoration schemes. Some relatively simple field measurements can rapidly get the river manager to a 'design' class. The problem inherent in the application of this system is that it is taken as robust enough to move from a 'class' to a channel design and build without the need for more detailed historical and geomorphological assessment. As a result, a useful classification scheme, when misapplied, has led to some spectacular river management problems (Downs, 1995; Kondolf *et al*., 2003).

In the UK, the RHS can provide a similar degree of apparent design support. Using only simple map-derived values, it is possible to identify the 'class' of channel one might expect to find at a site. Taking the approach above to its logical extreme, if that type of channel was not found at the site, then an appropriate river management action might be to 'restore' the channel to that class, effectively ignoring the importance of the local, historical and off-site controls on channel process and morphology. Therefore it is important not to use RHS information in isolation, but as part of an integrated and comprehensive design, implementation and monitoring approach.

In the Environment Agency, the Geomorphological Assessment Procedure (GAP) has at its basis the need to derive local catchment-based classifications based on geomorphological features and processes. However, before channel design can be undertaken, the procedure requires increasing levels of local information to ensure that the management activity is both geomorphologically suitable and sustainable.

References

Ashworth, P.J. and Ferguson, R.I. (1986) Interrelationships of channel processes, changes and sediments in a pro-glacial river. *Geografiska Annaler*, **68**A, 361–371.

Bradbrook, K.F., Lane, S.N., Richards, K.S., Biron, P.M. and Roy, A.G. (2001) Flow structures and mixing at an asymmetrical open-channel confluence: a numerical study. *ASCE Journal of Hydraulic Engineering*, **127**, 351–368.

Bridge, J.S. (2003) *Rivers and floodplains: forms, processes and sedimentry record*. Blackwell Publishing, Oxford.

Brierley, G.J. and Fryirs, K. (2000) River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management*, **25**, 661–679.

Brown, A.G. (2002) Learning from the past. *Freshwater Biology*, **47**, 817–829.

Brummer, C.J., Abbe, T.B., Sampson, J.R. and Montgomery, D.R. (2006) Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology*, **80**, 295–309.

Charlton, F.G., Brown, P.M. and Benson, R.W. (1978) *The hydraulic geometry of some gravel-bed rivers in Britain*. Hydraulics Research Station, Wallingford, Report IT 180.

Church, M.A. (1992) Channel morphology and typology. In Calow, P. and Petts, G.E. (eds) *The river handbook; hydrological and ecological principles*. Blackwell Scientific, Oxford, pp. 126–143.

Dangerfield, H.R. (1999) *A study of channel geometry–discharge relationships in semi-natural rivers as a basis for river restoration and management*. Unpublished PhD thesis, Queen Mary and Westfield College, University of London.

Dobbie, C.H. and Wolf, P.O. (1953) The Lynmouth flood of August 1952. *Proceedings of the Institution of Civil Engineers*, **2**, 522–588.

Downs, P.D. (1994) Characterization of river channel adjustments in the Thames basin, south-east England. *Regulated Rivers, Research and Management*, **9**, 151–175.

Downs, P.D. (1995) River channel classification for channel management purposes. In Gurnell, A.M. and Petts, G.E. (eds) *Changing river channels*. Wiley, Chichester, pp. 347–365.

Downs, P.W. and Gregory, K.J. (2004) *River channel management. Towards sustainable catchment hydrosystems*. Arnold, London.

Frissell, C.A., Liss, W.J., Warren, C.E. and Hurley, M.D. (1986) A hierarchical framework for stream habitat classification: viewing streams in a watershed context. *Environmental Management*, **10**, 199–214.

Fryirs, K.A., Brierley, G.J., Preston, N.J. and Spencer, J. (2007) Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. *Geomorphology*, **84**(3–4), 28, 297–316.

Gardiner, V. (1995) Channel networks. In Gurnell, A.M. and Gregory, K.J. (eds) *Changing River Channels*. Wiley, Chichester, pp. 65–85.

German, S.E. and Sear, D.A. (2003) *Geomorphological Audit of the River Wylye*. Conserving Natura 2000 Rivers, Conservation Techniques Series No. 9, Peterborough, English Nature, 89 pp. Accessed via http://www.english-nature. org.uk/lifeinukrivers/publications/Wylye%20audit.pdf.

Gilvear, D.J., Davies, J. and Winterbottom, S.J. (1994) Mechanisms of flood embankment failure during large flood events; River Tay, Scotland. *Quarterly Journal of Engineering Geology*, **27**, 319–332.

Gregory, K.J. and Garidner, V. (1975) Drainage density and climate. *Zietschrift für Geomorphologie*, **19**, 287–298.

Gregory, S.V., Boyer, K.L. and Gurnell, A.M. (eds) (2003) The ecology and management of wood in world rivers. *Proceedings of AFS Symposia 37*, Bethesda, MD.

Gurnell, A.M., Piegay, H., Swanson, F.J. and Gregory, S.V. (2002) Large wood and fluvial processes. *Freshwater Biology*, **47**, 601–619.

Gurnell, A.M. and Petts, G.E. (2002) Island-dominated landscapes of large floodplain rivers. *Freshwater Biology*, **47**, 581–600.

Harvey, A.M. (1997) Coupling between hillslope gully systems and stream channels in the Howgill Fells, northwest England: temporal implications. *Geomorphologie: Relief, Processes, Environment*, **1**, 3–20.

Harvey, A.M. (2001) Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity illustrated from the Howgill Fells, northwest England. *Catena*, **42**, 225–250.

Harvey, A.M. (2002) Effective timescales of coupling within fluvial systems. *Geomorphology*, **44**, 175–201.

Hey, R.D. (1979) Flow resistance in a gravel-bed river. *Journal of the Hydraulics Division of the American Society of Civil Engineers*, **105**(HY4), 365–379.

Hey, R.D. and Thorne, C.R. (1986) Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering*, **112**, 671–689.

Heywood, M.J.T. and Walling, D.E. (2006) The sedimentation of salmon spawning gravels in the Hampshire Avon catchment: implications for the dissolved oxygen content of intragravel water and embryo survival. *Hydrological Processes*, **21**, 770–778.

Hogan, D.L., Bird, S.A. and Hassan, M.A. (1998) Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitat. In Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B. (eds) *Gravel-bed rivers in the environment*. Water Resources Publications, CO, pp. 365–392.

Hooke, J.M. (2003) Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology*, **56**, 79–94.

Hooke, J. and Redmond, C. (1992) Channel planform change in England and Wales. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (eds) *Dynamics of gravel-bed rivers*. Wiley, Chichester.

Hup, C.R., Osterkamp, W.R. and Howeard, A.D. (eds) (1995) *Biogeomorphology – terrestrial and freshwater systems*. Elsevier Science, Amsterdam.

Jeffries, R., Darby, S.E. and Sear, D.A. (2003) The influence of vegetation and organic debris on floodplain sediment dynamics: a case study of a low-energy stream in the New Forest, Hampshire. *Geomorphology*, **51**, 61–80.

Kondolf, G.M. and Larson, M. (1995) Historic channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **5**, 109–126.

Kondolf, G.M., Montgomery, D.R., Piegay, H. and Schmidt, L. (2003) Geomorphic classification of rivers and streams. In Kondolf, G.M. and Piegay, H. (eds) *Tools in geomorphology*. Wiley, Chichester, pp. 171–204.

Lewin, J. (1976) Initiation of bed forms and meanders in coarse-grained sediment. *Bulletin of the Geological Society of America*, **87**, 281–285.

Lewis, G.W. and Lewin, J. (1983) Alluvial cutoffs in Wales and the Borderland. In Collinson, J. and Lewin, J. (eds) *Modern and ancient fluvial systems*. IAS, Special Publication 6, Blackwell, Oxford, pp. 145–154.

Macklin, M.G. and Lewin, J. (1994) Holocene river alluviation in Britain. *Zeitshrift für Geomorphologie*, **88**, 109–122.

Millington, C.E. and Sear, D.A. (2007) Impacts of restoration on small wood dynamics in a low gradient headwater stream. *Earth Surface Processes and Landforms*, **37**(8), 121–133.

Newson, M.D. (1993) Sustainable integrated development and the basin sediment system: guidance from fluvial geomorphology. In White, R.A. (ed.) *Integrated river basin management*. Wiley, Chichester, pp. 1–9.

Newson, M.D. (2002) Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**, 365–379.

Newson, M.D. and Newson, C.L. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*, **24**(2), 195–217.

Newson M.D., Clark, M.J., Sear, D.A. and Brookes, A. (1998) The geomorphological basis for classifying rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**, 415–430.

Passmore, D.G. and Macklin, M.G. (2000) Late Holocene channel and floodplain development in a wandering gravel-bed river: the River South Tyne at Lambley, northern England. *Earth Surface Processes and Landforms*, **25**, 1237–1256.

Passmore, D.G., Macklin, M.G., Brewer, P.A., Lewin, J., Rumsby, B.T. and Newson, M.D. (1993) Variability of late Holocene braiding in Britain. In Best, J. and Bristow, C. (eds) *Braided rivers: from process and economic applications*. Geological Society, London, pp. 205–229.

Rapp, C.F. and Abbe, T.B. (2003) A *framework for delineating channel migration zones*. Washington State Department of Ecology, Report 03-06-027.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J., Everard, M., Fozzard, I. and Rouen, K.J. (1998) *River habitat quality: the physical character of rivers and streams in the UK and Isle of Man*. National Rivers Authority, Bristol.

Reid, S.C., Lane, S.N., Montgomery, D.R. and Brookes, C.J. (2008) Does hydrological connectivity improve modelling of coarse sediment delivery in upland environments? *Geomorphology*, **90**, 263–282.

Rice, S.P., Ferguson, R.I. and Hoey, T.B. (2006) Tributary control of physical heterogeneity and biological diversity at river confluences. *Canadian Journal of Fisheries and Aquatic Sciences*, **63**, 2553–2566.

Rust, B.R. (1978) A classification of alluvial systems. In Miall, A.D. (ed.) *Fluvial sedimentology*. Canadian Society of Petroleum Geologists, Calgary, Memoir No. 5, pp. 187–198.

Schumm, S.A. (1977) *The fluvial system*. Wiley, New York.

Schumm, S.A. (1991) To *interpret the Earth: ten ways to be wrong*. Cambridge University Press, Cambridge.

Schumm, S.A. (2005) *River variability and complexity*. Cambridge University Press, Cambridge.

Sear, D.A. (1996) Sediment transport in pool-riffle sequences. *Earth Surface Processes and Landforms*, **21**, 147–164.

Sear, D.A. and Arnell, N.W. (2006) The application of palaeohydrology in river management. *Catena*, **66**(1), 164–187.

Sear, D.A. and Newson, M.D. (2004) The hydraulic impact and performance of a lowland rehabilitation scheme based on pool-riffle installation: the River Waveney, Scole, Suffolk, UK. *River Research and Applications*, **20**, 847–863.

Sear, D.A., Armitage, P.D. and Dawson, F.D.H. (1999) Groundwater dominated rivers. *Hydrological Processes*, **11**(14), 255–276.

Sear, D.A., Kitts, D.R. and Millington, C.E. (2006) *The geomorphic and hydrological response of New Forest streams to river restoration*. Hampshire County Council.

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment-related river maintenance: the role of fluvial geomorphology. *Earth Surface Processes and Landforms*, **20**, 629–647.

Sear, D.A., Wilcock, D., Robinson, M.R. and Fisher, K.R. (2000) Channel modifications and impacts. In Acreman, M. (ed.) *The changing hydrology of the UK*. Routledge, London.

Skinner, K.S. (1999) *Geomorphological post-project appraisal of river rehabilitation schemes in England*. Unpublished PhD thesis, University of Nottingham.

Steiger, J., Gurnell, A.M., Ergenzinger, P. and Snelder, D. (2001) Sedimentation in the riparian zone of an incising river. *Earth Surface Processes and Landforms*, **26**, 91–108.

Thompson, A. and Clayton, J. (2002) The role of geomorphology in flood risk assessment. *Civil Engineering*, **150**, 25–29.

Thorne, C.R. (1997) Channel types and morphological classification. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 175–222.

Trimble, S. (1992) Geomorphic effect of vegetation cover and management: some time and space considerations in predicting erosion and sediment yield. In Thornes, J.B. (ed.) *Vegetation and erosion*. Wiley, Chichester, pp. 55–65.

Werritty, A. (1997) Short-term changes in channel stability. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 47–65.

3

Driving forces I: Understanding river sediment dynamics

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3.1 Introduction

There has long been a perception within the river management and engineering communities that sediment in rivers is not a problem in the UK in the way that it is in countries in other, more dynamic, morphogenetic regions of the world. To a degree, this perception stems from the view widely expressed by physical geographers that the British landscape is, in large part, the legacy of climatic and environmental conditions that have not existed here for over 10 000 years. In this context, 'para-glacial geomorphology' is defined as the study of earth-surface processes, sediments, landforms, landsystems and landscapes that are directly conditioned by former glaciation and deglaciation. There is indeed a body of evidence that modern land-forms and morphological features in the UK may be largely attributed to glacial, peri-glacial, glacio-fluvial and, particularly, post-glacial sediment processes that no longer operate today (Ballantyne, 2002). This has led to description of the landscape in general, and streams in particular, as being 'arthritic'. The conclusion that follows from these arguments is that the capacity of a majority of British rivers to erode, transport and deposit sediment is naturally limited due to the relatively low levels of stream power and catchment sediment yield currently available to drive fluvial processes in comparison to those that operated during deglaciation, when the fluvial systems and floodplains that exist today were *actively* being formed.

That the view that sediment is not a problem in British rivers remained largely unchallenged for so long, and to an extent still persists, is perhaps surprising when set against the fact that sediment-related maintenance has been a feature of river management for decades. For example, during the 1990s the Environment Agency spent in excess of £10 million annually on sediment-related work (Environment Agency, 1998) and a recent briefing note indicates that expenditure on sediment and vegetation management remains above £11 million per year (Environment Agency, 2008). Historically, sediment-related maintenance has involved trapping, dredging or mechanically redistributing sediment in aggrading reaches, often coupled with hard engineering to stabilise eroding reaches. Not only are these actions expensive, they also treat the *symptoms* rather than the *causes* of sediment-related problems. At best, such solutions provide only temporary relief (because the problems recur, requiring maintenance that continues indefinitely or further capital works – either of which are likely to be unsustainable). At worst, they risk triggering further problems through the 'knock-on' effects of disrupting the relationship between sediment sources, transfers and stores within the river–floodplain system. In this context, recent research has established that local gravel extraction is capable of triggering morphological

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responses and patterns of channel instability similar to those caused by larger-scale changes to river and catchment sediment delivery processes (Wishart *et al.*, 2008). This finding raises concerns about the extent to which sediment removal from rivers can ever be sustainable, and suggests that the true costs and system-wide impacts of sediment removal may be greater than previously recognised.

However, perceptions of the significance of sediment in British rivers and the need to understand sediment processes and dynamics have changed markedly in the last few years and the increased attention now being paid to fluvial sediment seems likely to presage a paradigm shift in the way sediment is dealt with in river management and engineering. This change is not the result of a single driver but is the outcome of multiple developments, nationally and internationally, that are further reviewed in Section 4.2 of the next chapter, which deals specifically with sediment management.

One outcome of the 'new thinking' on sediment and its management is ambitious research sponsored by Defra and the Environment Agency on river sediments and habitats that is intended to:

- identify new and innovative approaches to river maintenance capable of delivering the required Standards of Service in terms of flood defence and land drainage, while reducing adverse impacts on channel morphology and ecosystems, and promoting habitat recovery through natural processes
- produce guidance documents and e-learning materials for end users in Asset System Management and Operations Delivery on sediment-related aspects of Flood Risk Management.

The aims are to reduce the expenditure on and environmental impacts of capital and maintenance works while also providing the basis for implementation of the Water Framework Directive and helping to protect and sustain Sites of Special Scientific Interest (SSSIs) and Special Areas of Conservation (SACs).

It is clear from results to date that achieving these objectives, though possible, requires a deeper understanding than presently exists of sediment processes, their interaction with infrastructure, their part in driving morphological channel adjustments and their role in providing the functional habitats essential to supporting diverse ecosystems in different types of river (Environment Agency, 2004; HR Wallingford, 2008).

This is the case because, despite decades of research on sediment transport theory, the capability of existing engineering-geomorphic methods accurately to predict sediment loads and patterns of sedimentation in practical (rather than research) applications remains severely limited. Consequently, there is no engineering handbook of standard techniques that can be applied with confidence in answering a sediment-related question and every application of a sediment analysis technique turns out, in practice, to be context specific (Lane and Thorne, 2007). This requires that practitioners must possess a deep understanding of sediment dynamics and deploy sound judgement in addressing sediment-related issues and selecting methods appropriate to the geographical case in point and the particular question being posed. In doing so, they must rely on their thorough grasp of how sediment erosion, transport and deposition operate within the fluvial system. This requires not only a sound understanding of the *mechanics* of sediment transport but also proper appreciation of the significance of connectivity, linkages and feedback loops in the sediment transfer system and insight regarding how rivers of different types characteristically evolve through time, adjust to extreme events and respond to changes in the flow and sediment regimes. In essence, the required appreciation and insight stems from knowledge and understanding of those aspects of the fluvial system that cannot be reduced to the form of a partial differential equation, but which are nevertheless fundamental to explaining *how rivers work*.

It is in this spirit that this chapter describes the driving processes responsible for morphological stability, adjustment and response to human interventions in alluvial streams, with the aim of supplying the knowledge necessary to underpin accurate investigation, characterisation and management of river sediment dynamics.

3.2 Fluvial processes

3.2.1 *Significance of the sediment system*

It is universally recognised that rivers convey sediment as well as water, and yet the processes responsible for sediment movement receive far less attention from researchers and managers than those responsible for fluid shear flow. What is known is that the flow of water and transport of sediment through the river–floodplain system act as driving variables that operate within the context of the valley terrain, bed and bank materials and riparian vegetation (boundary characteristics) to generate and then modify the three-dimensional form of the channel (see Fig. 2.1). The parameters defining the form, or morphology, of the channel have been described as the 'degrees of freedom' which the river may adjust through time when evolving towards an equilibrium condition or responding to changes in the driving variables (Hey *et al.*, 1982). While a natural, alluvial stream is free to adjust any parameter in response to a change in a driving variable, the links between some parameters and particular controlling variables are typically stronger than others (Table 3.1).

However, while process-form linkages are reasonably well understood conceptually, predicting sediment movement and routing sediment through the fluvial system quantitatively remain difficult challenges. This is in stark contrast to prediction and modelling of water flow through drainage networks, where advances in hydrological science and engineering hydraulics allow the equivalent calculations to be performed quickly and relatively accurately. In fact, while flow routing can and is now undertaken routinely, it is often difficult in practice even to identify sediment pathways that link sediment sources to sinks qualitatively (Lane *et al.*, 2008). This is significant because it limits the potential for river scientists and engineers to identify causal links between sediment problems at different locations in the same river system, thereby limiting the scope for finding sustainable solutions that treat those causes rather than the symptoms they produce. The search for sustainable solutions must necessarily span multiple scales for the reasons set out in Table 3.2, and this must be acknowledged when dealing with sediment-related problems.

Table 3.1 Links between channel parameters (dependent variables) and controlling variables typically displayed by alluvial streams. Data taken from Hey et al.*, 1982*

Degree of freedom (dependent variable)	Process driver (controlling variable)
Mean velocity	Flow regime
Channel slope	Sediment load
Hydraulic radius (mean and maximum depth)	Bed material characteristics
Wetted perimeter (channel width)	Bank material properties
Planform sinuosity	Valley slope
Meander bend arc length	Riparian vegetation

Table 3.2 Significance of sediment dynamics in the river system

No.	Impact	Significance
1.	Long-catchment change	The sediment system may be divided into source, transfer, exchange and storage reaches that link the headwaters to the sea over geologic timescales
2.	Morphodynamics	Sediment movement drives short-term morphological stasis or evolution of the river-floodplain system
3.	Dynamic equilibrium	Continuity of sediment supply and transport maintains dynamic equilibrium locally in stable reaches
4.	Morphological response	Disruption or disconnection of the sediment transfer system through capital works or maintenance triggers rapid morphological responses up and downstream
5.	Sediments and habitats	Sediment processes and sedimentary features underpin morphological complexity and provide the range of in-stream and riparian habitats vital to high biodiversity

Sediment movement through the fluvial system is highly unsteady and non-uniform. In coarse bedded streams, sediment transport may indeed be episodic and the sediment transfer system has, on this basis, been described as a 'jerky conveyor belt'. Individual particles travel from headwater sources to lowland sinks through a series of rapid, short-duration transport events, separated by much longer periods of storage in channel sediment features (bars, shoals etc.) and floodplain sediment bodies. Nevertheless, long-term continuity of sediment transfer means that any significant alteration or interruption of the sediment transfer system will eventually result in tangible effects downstream (through elevated or depressed sediment supply) and upstream (through slope and/or planform adjustments) (Lane *et al.*, 2007).

In most rivers, the sediment transfer system is complicated and involves multiple linkages between the flow and sediment regimes, as well as complex interactions between the driving variables and the sedimentary features that result in the channel and on the floodplain (Fig. 3.1). However, before the sediment transfer system can be considered as a whole, it is necessary to understand the operation of its component parts: erosion, transport and deposition.

3.2.2 Erosion

3.2.2.1 Catchment erosion and sediment yield

The original source of all sediment in the river network is catchment weathering and denudation. Sediment is derived from a variety of geomorphic processes, operating at different scales and in different parts of the drainage basin (Lane *et al.*, 2008). Some sources are localised and site specific; for example an unstable hill slope, prone to landsliding (Harvey, 2007). Other sources are broad-scale and diffuse, such as soil erosion by surface runoff in arable fields (sheet wash) (Quine and Walling, 1991).

Catchment denudation through erosion is a natural process that is active to some degree in every landscape but both the intensity and extent of erosion may be increased by human activities. Not only may natural erosion be accelerated but also new, *anthropogenic* erosion processes may be introduced to the landscape. Generally, the effect of primary industries (such as farming, forestry and quarrying) that disturb natural landforms and vegetation assemblages is to increase catchment

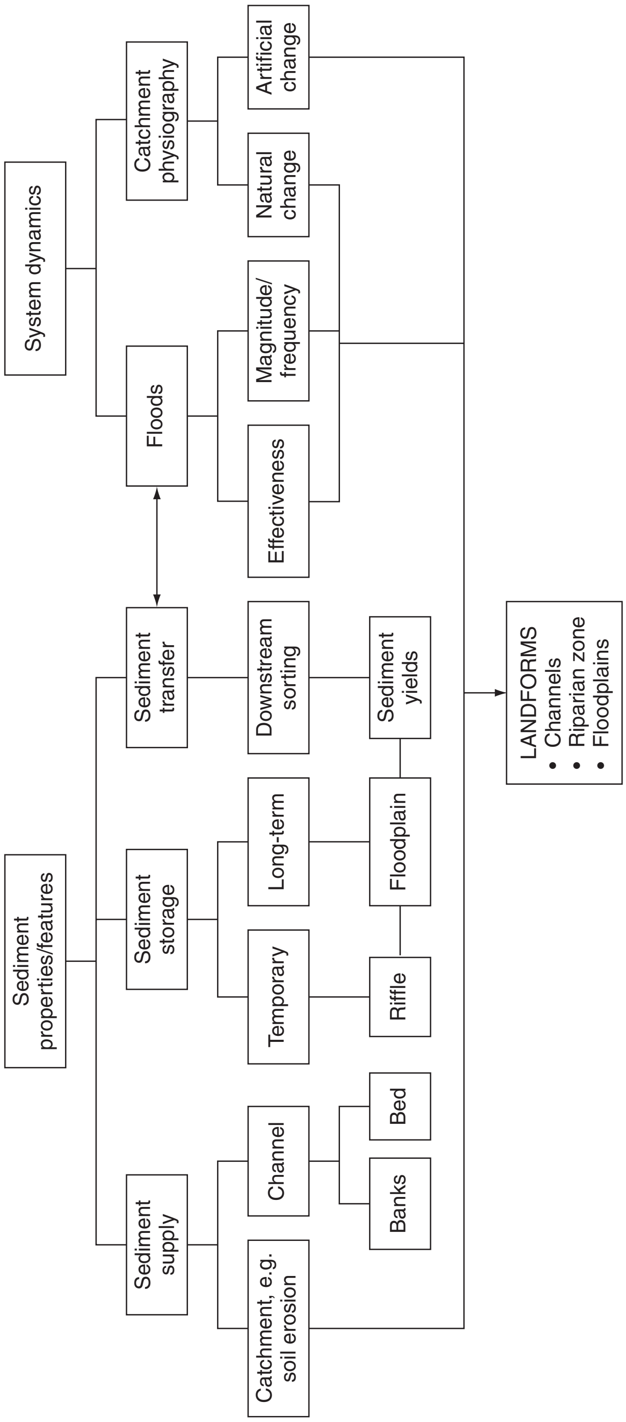

Fig. 3.1 Links and interactions between sediment processes and fluvial landforms

Table 3.3 Typical catchment sediment sources

Upper course	Middle course	Lower course
Rock fall	Valley side slope	Overland flow
Scree slope	Terrace slope	Tributaries
Debris flow	Soil creep	Cultivated farmland
Landslide	Floodplain erosion	Wind-blown soils
Freeze–thaw	Tributary stream	Construction sites
Sheet flow	Cultivated farmland	Urban runoff
Rills and gullies	Field drains and ditches	Gravel workings
Overgrazed, burnt or rabbit-infested areas	Urban runoff	Marine sediments (estuaries)
Ditches (forest and road)	Ditches (forest and road)	
Quarries	Mining and gravel extraction	

erosion. Urbanisation also increases erosion during the construction phase, although rates of erosion in urbanised areas usually decrease to a level lower than that associated with natural environments once building ceases and the urban fabric becomes fully established.

The characteristic types of catchment erosion operating in an area and the significance of different landscape features as sediment sources vary between upland, piedmont (middle course) and lowland regions (Table 3.3).

There is, however, a great difference between the quantity of soil eroded in the catchment and the amount that is supplied to the channel network in that only a fraction of the sediment created by erosion in any period actually reaches the river. The portion of eroded material that is supplied to the channel network is termed the catchment sediment yield while the ratio of sediment yield to catchment erosion is termed the sediment delivery ratio. The relationship between catchment erosion and sediment yield depends mostly on two factors: first, the efficacy of earth surface processes responsible for carrying eroded sediment from its point of origin to the channel; and, second, the distance over which the sediment must be transported by these processes.

Typically, either gravity or overland flow drives surface processes responsible for carrying sediment to the channel, through, for example, slope processes or sheet wash, respectively. The capacity of these surface processes to carry eroded sediment increases in a non-linear fashion with the slope of the land surface. As a result, processes delivering catchment-derived sediment to the channel are usually most efficient in the steeper, upland areas of a catchment, corresponding to the headwater basin. This effect is reinforced by the relatively short distances over which surface processes must transport sediment in small, upland catchments, where channels flow at or near the foot of steep, eroding slopes to form coupled channel-slope systems, and the existence of numerous, short tributary channels that collect the sediment from coupled hillslopes and deliver it efficiently to the trunk stream (Harvey, 2001).

For example, where fluvial undercutting of the base of a crag or a talus (scree) slope removes slope debris to maintain a steep slope angle, continued slope retreat ensures an abundant supply of coarse sediment to the stream. The high relative efficiency of surface processes removing eroded material and transporting it to the channel ensures that, in upland areas, soil and debris layers mantling the solid geology are either absent or thin, so that weathering and erosion processes are able to operate directly on intact rocks to promote further erosion and produce a plentiful supply of coarse particles. The overall result is that, at least in natural systems, catchment sediment yield per unit area of the drainage basin is usually highest and coarsest in the upland headwaters of the basin. Additionally, the relatively harsh climates and steep terrains of the UK uplands, coupled with the legacy of Holocene deforestation, makes these areas particularly sensitive to accelerated erosion due to development and primary industries (Macklin and Lewin, 2003). Given this, it is not surprising that land-use changes involving over-stocking and forestry ditching have long been known to elevate sediment yields in UK headwater catchments (Moore and Newson, 1986). The controlling variable for sediment delivery from hillslopes to rivers has been found to be the occurence of high-intensity, short-duration rainfall events responsible for generating slope wash and slope instability, with sediment delivery being independent of the level of catchment saturation (Reid *et al.*, 2008).

In the middle reaches of a river basin (piedmont or foothill landscapes), the channel interacts less frequently with the valley side slopes, and catchment sediment supply consists mainly of mixed-size sediment re-eroded from older floodplain and colluvium (mixed hillslope/fluvial materials) deposits in valley fills, together with coarse sediment input by steep tributary streams that supply sediment from adjacent, upland sub-basins. Lower land surface slopes and longer transport distances reduce the efficacy of surface processes removing sediment relative to the processes creating it. As a result, soil and debris thicknesses are greater – providing better cover to the underlying solid geology and reducing weathering rates compared to headwater basins.

Catchment sediment yields per unit basin area in the middle courses of natural drainage systems are lower than in the headwaters as a result of reduced rates of erosion and less efficient sediment delivery, although this may not hold for catchments affected by human occupation and primary industries. Activities such as intensive pastoral and arable farming, and mineral extraction (especially gravel mining) are known to elevate catchment sediment yields in the middle reaches of rivers (Quine and Walling, 1991).

In the lower course, relief is usually low, soils are deep and the channel is located within a wide valley – limiting opportunities for direct inputs of locally derived sediment to the river. Sediment yield is characteristically fine-grained and the catchment contribution is usually low here, at least in natural catchments. However, people have occupied many lowland catchments for thousands or tens of thousands of years and so catchment processes are often heavily affected by human activities. Consequently, it is common for the catchment yield of fine sediment to be elevated in the lower course by agriculture (especially arable cropping), forestry, other primary industries or urbanisation (Boardman *et al.*, 2003). Where the natural vegetation cover has been disturbed or removed for farming, primary industry or development, aeolian processes may also be significant in transporting sediment eroded from the bare soil surface. The relative importance of wind-blown sediment increases in very low relief areas, where the lack of slope in the landscape makes gravity-related processes particularly ineffective.

It follows from these descriptions that the characteristics of sediment delivered to the river system are sensitive to changes in catchment land-use and channel management throughout its course (Table 3.4).

The delivery ratio for catchment-derived sediment is particularly sensitive to changes in the drainage density – that is, the total length of channels in the drainage network divided by the drainage basin area. Drainage density in natural systems is primarily controlled by two factors:

Table 3.4 Possible changes in catchment sediment characteristics due to changes in land-use or channel engineering

Land-use change	Sediment quality	Sediment size	Sediment compaction	Size (after 20 years)
Forestry	0	–	–/+	–
Road construction	–	–	?	+/–
Channelisation	0/–	+	+	+
Urban runoff	–	–	+	+
Accelerated erosion	–	–	–/+	–
Channel management				
Narrowing/embanking	0/–	–	+	+
Widening	0/–	–	–	–/+
Upstream of a dam	–	–	+	–
Downstream of a dam	0	+	+	+
Downstream of sediment trap	0	+	+	+

+ = increase; – = decrease; 0 = little change

1. the relationship between rainfall and runoff generation: drainage density increases as moisture losses to interception, evaporation and transpiration decrease
2. infiltration capacity: drainage density increases as the capacity of the soil to absorb water through infiltration decreases.

Natural changes in drainage density occur slowly, in response to climate change or long-term catchment weathering and erosion, but artificial increases in drainage density may be wide-ranging and sudden, inducing a rapid rise in catchment sediment yield. This is the case because drains and ditches effectively extend the drainage network, drastically reducing the distance over which eroded sediment must be transported in order to reach the channel system. Effective drainage density may thus be increased artificially by construction of ditches (forest and road), drains (field, quarry, urban) and storm sewers, leading to particularly sharp increases in catchment sediment yield.

It is clear from this brief review that each river basin will have different dominant sediment sources due to the wide ranges and combinations of catchment erosion types, sediment delivery processes and accelerating factors that are possible in UK streams. Similarly, the proportion of the eroded sediment delivered to the channel network is highly variable and site specific. This makes it extremely difficult to generalise and almost impossible to predict catchment sediment yield *a priori* except in general terms.

3.2.2.2 Channel bed scour

Sediment is eroded (scoured) from the bed of an alluvial channel when the fluid forces of drag and lift applied to bed grains by flow in the stream overcome the resisting forces due to the grain's submerged weight and friction between adjacent grains. In theory, motivating and resisting forces are exactly balanced just prior to the entrainment of a grain and, under this condition, the bed is said to be at the 'threshold of motion'. As it is practically impossible to measure the fluid forces of drag and lift acting on the individual grains at the bed of a river, the bed shear stress is often used as a surrogate measure of flow intensity. Bed shear stress is the average fluid shear force per unit area applied to the bed of the channel by the flowing water. Under uniform, steady conditions, the time-averaged bed shear stress may be calculated from the DuBoys' equation:

$$\tau_o = \gamma_w RS$$

where, τ_o = average bed shear stress (kPa), γ_w = unit weight of water (kN/m^3), R = hydraulic radius (m) and S = channel slope (m/m). While this equation is often used to represent the potential of stream flow to scour the bed, it should be borne in mind that it strictly applies only to uniform, steady flow over a flat surface, which is a poor representation of flow in most natural, alluvial channels.

A dimensionless form of the bed shear stress equation derived by Shields is commonly used to predict the onset of bed motion:

$$\theta = \frac{\tau_o}{\gamma_w(Ss - 1)D_{50}}$$

where θ = dimensionless shear stress or Shields' parameter, Ss = specific gravity of sediment, and D_{50} = median size of bed sediment (m). Shields correctly identified that motion actually begins under a range of dimensionless shear stresses ranging between about 0.03 and 0.06, depending on the degree to which bed grains are closely packed or imbricated. However, the middle value of 0.047 suggested by Meyer–Peter is often applied as the critical dimensionless shear stress necessary to mobilise bed material under conditions typical of alluvial rivers (Julien, 1998).

In nature, the time and space distributions of applied fluid forces are variable and complex due to turbulence in the velocity field. Turbulent phenomena such as 'bursts and sweeps' operating near the bed and larger 'coherent flow structures' and 'macro-eddies', scaled on the dimensions of the channel drive spatially non-uniform, short-duration, high-magnitude peaks in the bed shear stress that are actually responsible for the detachment and entrainment of individual grains (Sechet and le Guennec, 1999). Consequently, the precise conditions under which a particular grain will be eroded from the bed of a channel are impossible to predict mechanically because they are, in fact, physically indeterminate.

What is known is that, in dynamic, alluvial streams the bed is mobilised during high, in-bank flows, although bed material motion begins at different times at different locations in the channel depending on the spatial distribution of local conditions that promote scour. On this basis, bed sediment motion and the spatial distribution of scour are somewhat predictable on the basis of channel morphology and the presence of natural obstructions or artificial structures in the river (Table 3.5).

The susceptibility of the bed to scour depends mostly on the size of the bed material, although other factors (the way in which grains are layered, packed and arranged at the surface and the degree of compaction) may also be significant. For example, gravel-bed rivers often display a coarse surface layer that is closely packed and imbricated (that is, platy particles making up the bed surface are arranged like the scales on a fish) (Hey *et al.*, 1982). This armour layer acts to protect finer, looser material beneath it, tending to limit bed scour and restricting the transport of gravel downstream (Thorne *et al.*, 1987). Disturbance of the armour layer during, for example, dredging or gravel mining can increase the mobility of bed sediments, destabilising the reach and elevating sediment supply downstream. It is not surprising, therefore, that river engineering and maintenance practices involving the disturbance or destruction of gravel armour layers have been identified as particularly likely to trigger bed scouring, changes in sediment supply to downstream

Table 3.5 Types of bed scour in dynamically stable channels

Scour type	Description
General scour	Lowering of the elevation of the bed throughout a reach due to entrainment and removal of bed sediment during a high flow event. When the stage falls at the end of the event, sediment is redeposited and the elevation of the bed recovers. Hence, bed lowering due to general scour is temporary and the extent of the scour can only be assessed by measurements made actually during high flow events. General scour is significant in rivers with erodible bed materials, but it is quite predictable given sound data on channel geometry, channel slope, size distributions of bed surface and substrate material, sediment supply from upstream, and the volumetric flow rate
Constriction scour	Lowering of the elevation of the bed across all or part of the channel due to a reduction in width in a reach where the banks are either naturally erosion resistant or protected. This is commonly associated with reaches where the banks have been moved closer together artificially to allow a bridge or pipeline crossing to be built. Constriction scour is likely wherever channel width is reduced, but it is readily predictable as a function of the degree of width constriction compared to the width in the approach channel
Confluence scour	Bed lowering where two (or more) flow streams merge to form a single stream. Scour occurs due to macro-turbulent eddies generated along the mixing layer, coupled with large-scale secondary flow structures caused by flow curvature. Confluence scour is observed at tributary junctions along the main stream and also at the confluences of sub-channels (anabranches) of rivers with braided or anastomosed planforms. The degree to which confluence scour lowers the bed below its 'normal' elevation depends on the relative discharges of the approach streams, the angle at which they converge and the size distributions of bed surface and substrate material. It can, however, be excessive, especially in braided rivers. Various empirical formulae are usually used to predict confluence scour, although theoretical, analytical methods are now being developed
Bend scour	Strong secondary currents (Prandt's flow of the first kind) are generated at bends by skewing of spanwise vorticity into the streamwise direction. These secondary currents carry fast, near-surface water to the bed in the outer half of the channel, generating deep bed scour and asymmetry of the cross-section. Scour depths so produced may exceed twice the scour depth found in straight approach channels. Analytical and empirical models exist to predict bend scour in conventional meander bends, although few methods are applicable to very tight bends of low radius-to-width ratio. Impinging flow at the out bank of bends with radius-to-width ratios less than about 2, can cause extreme scour under some circumstances. Prediction of bend scour requires information on bend geometry, approach channel dimensions, discharge, sediment load, bed material composition and the geotechnical properties of bank materials – which may limit scour bank height and influence maximum scour depths
Local scour	Lowering of the elevation of the bed over part of a cross-section due to intense turbulence and secondary currents generated by an obstruction to the flow. Local scour is typically encountered around natural obstructions such as accumulations of large woody debris and artificial obstructions suchas bridge piers. Local scour is likely to be an issue around the supports placed in the channel if an elevated crossing is used. If guide bunds, walls or hardened abutments are used to guide the river in the vicinity of the crossing then local scour of the bed will occur adjacent to the toe of these structures, especially during high flows. In either case, empirical predictors of the degree of bed lowering may be applied to estimate maximum scour depth on the basis of the size and shape of the obstruction, its orientation relative to the approach flow, the approach velocity, bed material size, upstream sediment supply and the volumetric flow rate
Combined scour	Occurs when two or more scour-generating phenomena act at the same time and location. For example, bend scour due to curved flow in a river may combine with confluence scour where a tributary joins the main stream. Experience demonstrates that the effects of combined scour may be additive – producing extreme scour depths much greater than any produced or expected when a single scour process is operating alone

Table 3.6 Physical and ecological impacts associated with sediment removal from alluvial streams in California (after Cluer, 2004)

Element of instream sediment removal	Physical effect	Possible consequence for Salmonid habitat
Removal of sand and gravel from a location or from a limited reach	Propagates stream degradation both upstream and downstream from removal site	Loss or reduction in quality of pool and riffle habitats
	Scour of upstream riffles	Lower success of spawning redds
	Reduced pool areas	Loss of spawning and rearing habitat
	Bed surface armouring Scour or burial of armour layer Surface caking or pore clogging	Lower quality of spawning and rearing habitat; changes to invertebrate community
Removal of sand and gravel from a bar	Loss of sand and gravel from neighbouring bars	Possible loss of riffle and pool habitats
	Wider, more uniform channel section. Less lateral variation in depth, reduced prominence of the pool-riffle sequence Surface caking or pore clogging	More difficult adult and juvenile migration. Reduced trophic food production. Lower quality of rearing habitat
Removal of sediment in excess of the input	Channel degradation	Deeper, narrower channel. Dewatered back channels and wetlands
	Lower groundwater table	Possible reduction of summer low flows; possible reduction of water recharge to off-channel habitat
	Complex channels regress to single-thread channels	Less habitat complexity
	Armouring of channel bed may lead to erosion of banks and bars or scour or burial of armour layer	Less spawning area. Reduced water quality. Prompt new bank protection works – reducing habitat
Reduced sediment supply to downstream	Induced meandering of stream to reduce gradient. Erosion on alternate banks downstream Armouring of bed, or scour of armour layer	Reduced riparian vegetation Increased local sedimentation Prompt new bank protection works. Propagate river management and habitat losses downstream
Removal of vegetation and woody debris from bar and bank	Reduce shade	Increase water temperature in inland, narrow rivers
	Decrease channel structure from wood	Possibly reduce cover; reduce number and depth of pools; reduce area of spawning gravel; limit channel stability
	Decrease drop-in food, nutrient inputs	Decrease stream productivity

reaches, knick points that migrate upstream, and system-wide impacts on river morphology and ecology (Cluer, 2004; Wishart *et al.*, 2008). For example, Table 3.6 lists the major morphological and ecological impacts observed to be associated with gravel removal in California.

3.2.2.3 *Channel bank erosion*

In addition to material scoured from the bed, sediment may also be derived from erosion of the banks. Bank erosion in dynamically stable streams is associated with lateral shifting of the channel through retreat of one bank at a rate that is, on average, matched by advance of the bank opposite through sediment accretion. Rates of bank erosion and lateral channel shifting in dynamically stable alluvial channels in the UK are characteristically low – averaging around 1% of the width per year and rarely more than 5% of the channel width per year. Nevertheless, the yield of sediment can still be highly significant. Actually, in cases where catchment sediment yields are modest, bank erosion is likely to be the most important source of sediment contributed to the fluvial system. Bank retreat rates are likely to be much higher in unstable channels. Rapid widening associated with mass bank failure due to toe scour and bank oversteepening can yield substantial amounts of sediment, supplying as much as 70% of the sediment load carried by the stream (Andrew Simon, personal communication 2007). However, the processes and mechanisms by which material is eroded from the banks of a channel are even more diverse and complicated than those involved in bed scour.

In nature, serious bank retreat and the input of significant amounts of sediment to the fluvial system rarely result from the operation of a single erosion process or mechanism of instability. In fact, bank retreat is usually the result of complex interactions between a number of processes and mechanisms that act on the bank either simultaneously or sequentially. These may be grouped into three categories:

1. Bank erosion processes: which detach, entrain and transport individual particles or assemblages of particles away from the surface of the retreating bank.
2. Bank failure mechanisms: which lead to collapse of the full height or part of the bank.
3. Weakening and weathering processes: which operate on or within the bank to increase its erodibility and reduce its geotechnical stability.

While these processes and mechanisms usually act together, it aids clarity when describing them to treat them separately. However, in order to appreciate the causes of serious and sustained bank retreat it is necessary to consider how the bank profile responds to different combinations of erosion and mass instability, and this is dealt with at the end of this subsection.

Explanation of why, where and how bank retreat occurs in a river requires a sound understanding of the weakening/weathering processes, erosion processes and failure mechanisms that have the potential to contribute significantly to bank retreat and these phenomena are described in Table 3.7. Figure 3.2 illustrates and outlines some of the more widely observed modes of bank failure schematically.

When analysing bank instability, desegregating the effects of multiple factors that may contribute to bank retreat is insightful because each factor is influenced by different process drivers (Table 3.8). Understanding the nature of the geomorphological processes driving retreat is the first step towards explaining how that retreat relates to the local climatic, fluvial and soil environments. In turn, a sound explanation of process–form linkages underpins the ability to predict geomorphological responses (through adjustments to the intensity and/or extent of bank retreat) to changes in climate, fluvial regime, soil conditions, vegetation cover, human activities, maintenance practices, or engineering works.

The wide range of processes and mechanisms that may be responsible for destabilising a river bank, and the potential for weakening factors to increase the vulnerability of a particular bank to destabilisation, complicate bank retreat issues and can make it difficult to accurately identify the causes of a bank erosion problem. However, in cases of serious and sustained bank retreat, a geomorphological concept termed *basal endpoint control* can usefully be applied to help clarify the underlying process driver responsible for bank recession (Thorne, 1982; Lawler *et al*., 1997).

Table 3.7 Classification of bank erosion processes, failure mechanisms and weakening factors
I. Classification of bank erosion processes

Erosion process	Description	Impacts on bank retreat	Significance
Parallel flow (fluvial entrainment)	Soil is detached and carried away by flow parallel to the bank	This is a primary cause of bank retreat. It often drives rapid bankline retreat and planform evolution	Indicates that bank materials cannot withstand shear stresses exerted by flow along the channel
Impinging flow (fluvial entrainment)	Soil is detached and carried away by flow striking the bank at an angle to the long-stream direction	This is a primary cause of bank retreat. It occurs at tight bends and around obstructions to the flow	Impinging flow is usually a sign of a poor channel alignment or an undesirable obstruction of the flow
Boatwash	Soil is detached and carried away by waves and currents generated by passing boats	Boatwash can be a primary cause of bank erosion. It tends to be concentrated on the inside of meander bends and around marinas	Boatwash erosion due to normal cruising indicates that speed limits are too high. Local protection inside bends and around marinas may be justified
Wind-waves	Soil is detached and carried away by waves and currents generated by the wind	Wind-waves are seldom a primary cause of serious erosion in British rivers and inland waterways	Wind-waves cannot initiate an erosion problem but they may perpetuate one by generating secondary erosion
Rills and gullies (surface erosion)	The bank is eroded by concentrated surface runoff draining across the bankline	Serious erosion is usually localised at places where drainage has been artificially funnelled	Rills and gullies can damage a bank severely by destroying vegetation and removing surface layers
Piping (seepage erosion)	Subsurface erosion by water draining through the bank	Piping can open up cavities and notches that can lead to serious and widespread bank retreat in vulnerable soils	Piping operates within the bank to erode and weaken it. It is often overlooked in protection schemes
Freeze–thaw (frost erosion)	Soil particles or aggregates are loosened by freezing and either fail off the bank face during the frost event or are removed later by flow or boatwash	Freeze–thaw in Britain is only significant in eroding unvegetated bank faces. It is not itself a primary cause of bank retreat	Freeze–thaw typically makes a bank more vulnerable to erosion by winter flows

To explain the concept of basal endpoint control, it helps to visualise the sediment transfer system in the near bank zone of the channel (Fig. 3.3). Sediment is supplied to near bank zone from upstream and/or from the bank itself through either erosion or bank failure. Sediment may be removed from the near bank zone and washed downstream by the main current, or it may move laterally towards the centre of the channel due to the action of gravity, secondary currents and/or wave action.

These sediment fluxes allow three conditions of sediment balance to exist at the foot of the bank: output greater than input (scour), output equal to input (dynamic equilibrium), or output less than input (deposition). These three conditions define three possible states of basal endpoint control (Table 3.9).

Bank retreat may result from the action of any of the processes and mechanisms listed in Table 3.7 acting singly or in combination but sustained, long-term retreat of a river bank ultimately depends on the near bank flow being competent to remove sediment and debris from the foot of the bank at the same rate that it is being generated by bank erosion and failure. This demonstrates that while the

Table 3.7 II. Classification of failure mechanisms

Failure mechanism	Description	Impacts on bank retreat	Significance
Shallow slide	Shallow seated failure along a shear plane parallel to and just below the bank surface	Can be a serious form of instability in weakly cohesive bank materials	Indicates that the bank is too steep to remain stable in its present condition
Rotational slip	Deep-seated movement of all or part of the bank profile in which block of soil slips along a curved surface	A severe type of failure that involves the movement of a large volume of soil and generates serious bankline retreat	Indicates serious, deep-seated instability that must be eliminated to halt bank retreat. This requires heavy intervention to be successful
Slab failure	Blocks or columns of soil topple forward into the channel, often with deep tension cracks separating the failure blocks from the intact bank	A severe type of failure that involves the movement of a large volume of soil and generates rapid bankline retreat	Indicates serious instability due to toe scour, over-steep bank angles and tension cracks. All these must be controlled to halt retreat
Cantilever failure	Overhanging blocks of soil collapse into the channel by shear, beam or tensile failure	Cantilevers follow flow, wave or piping erosion of the lower bank	Indicates active undercutting and presence of a weak, erodible layer in the bank profile
Soil fall	Soil falls directly no the channel from near-vertical or undermined, cohesive bank face	Important on unvegetated soil surfaces weakened by desiccation, frost action etc.	Indicates that soil surface is vulnerable to weakening. Surface cover is important
Dry granular flow	Avalanching of dry, granular bank material down the upper part of a non-cohesive bank	A mechanism whereby erosion of the lower bank causes instability of the upper bank and bankline retreat	Indicates zero operational cohesive strength due to lack of root reinforcement or negative prewater pressures in the bank material
Wet earth flow	Liquefaction and flow of a section of bank due to saturation and high pore water pressures	Can result in rapid bankline retreat in zones of strong seepage and poor drainage	Indicates seepage-related instability and soils prone to liquefaction. Bankline stabilisation must include enhanced subsurface drainage

processes and mechanisms responsible for bank instability are not always directly related to flow intensity in the channel, it is nonetheless the competence of the sediment transfer system to continue to carry away the products of bank retreat that sustain retreat in the long run. These arguments reveal that long-term bank retreat in rivers is tied inexorably into the wider sediment system as an integral component of sediment transfer and exchange that occurs in all reaches that are active laterally.

In light of this, useful insights can be gained when examining an eroding bank by inspecting the bank profile, the degree of instability and the sediment balance at the foot of the bank to identify the current state of basal endpoint control. This allows the observer to appreciate how closely an eroding bank site is coupled into the sediment transfer system and so place the retreating bank in the correct catchment, river and reach-scale contexts. Also, where continued bank retreat poses unacceptable risks to people, properties or infrastructure identifying the state of basal endpoint control will help guide selection of an appropriate management or engineering response.

Table 3.7 III. Classification of weakening factors

Weakening factor	Description	Impacts on bank retreat	Significance
Leaching	Reduction of cohesion due to removal in solution of clay minerals by groundwater seepage	Can seriously reduce both the stability and erosion resistance of the bank	Indicates that the mineralogy of the soil and the chemistry of pore water are important
Trampling	Destruction of the soil fabric by crushing under the weight of pedestrians or grazing animals	Impacts can be severe since the stability and erosion resistance of many banks depends almost entirely on soil fabric	Indicates that the bank soils are vulnerable to damage by trampling and that access should be reduced or protection provided
Destruction of riparian vegetation	Damage or destruction of riparian vegetation by a variety of natural processes and human actions	Impacts are usually severe as vegetation can play a crucial role in determining the erosion resistance and stability of banks	Riparian vegetation is an integral component of the bank system. Its destruction is highly undesirable and its conservation should figure in most bank management schemes
Mechanical damage	Damage of banks formed in alluvial materials by boat mooring, stock access or angling practices	Damaged areas suffer serious erosion and can generate locally impinging flows that accelerate bankline retreat	Mechanical damage provides a foothold for erosion on stable banks. In sensitive reaches erosion problems may spread widely
Positive pore water pressures	Occurs when drainage of water through the bank is restricted to allow a build-up of seepage pressure	Can be very effective in weakening the soil to promote failure or liquefaction	Poorly drained banks are always likely to fail if high pore water pressures occur
Desiccation	Cracking and crumbling of a soil due to intense drying that breaks electrochemical bonds	Loosens soil crumbs on exposed bank surfaces during hot summers	Significance is limited to river cliffs and other places where vegetation is absent

Field inspection of stream banks to ascertain their stability and basal endpoint status is facilitated by guidance that is available on stream reconnaissance more generally (Thorne, 1998).

3.2.2.4 *Channel instability*

In unstable channels, the range of channel sediment sources expands to include material eroded during active adjustment of the dimensions, geometry and morphology of the channel, as well as sediment removed from the floodplain as a result of radical changes to channel position or configuration. Channel instability characteristically involves the redistribution of large amounts of sediment with major impacts on the local balance between erosion, transport and storage, adjustments to the channel slope that may progress upstream through the system, and marked changes to the supply of sediment to downstream reaches.

Much attention has been focused on progressive lowering of the bed at the reach-scale through time – a process termed *channel incision* or *degradation*. Degrading reaches produce large amounts of relatively coarse sediment and supplies this to downstream reaches, often at a rate that overwhelms the downstream transport capacity and so induces heavy in-channel deposition (forming extensive shoals and bars) and raising the bed elevation through time. The process whereby the

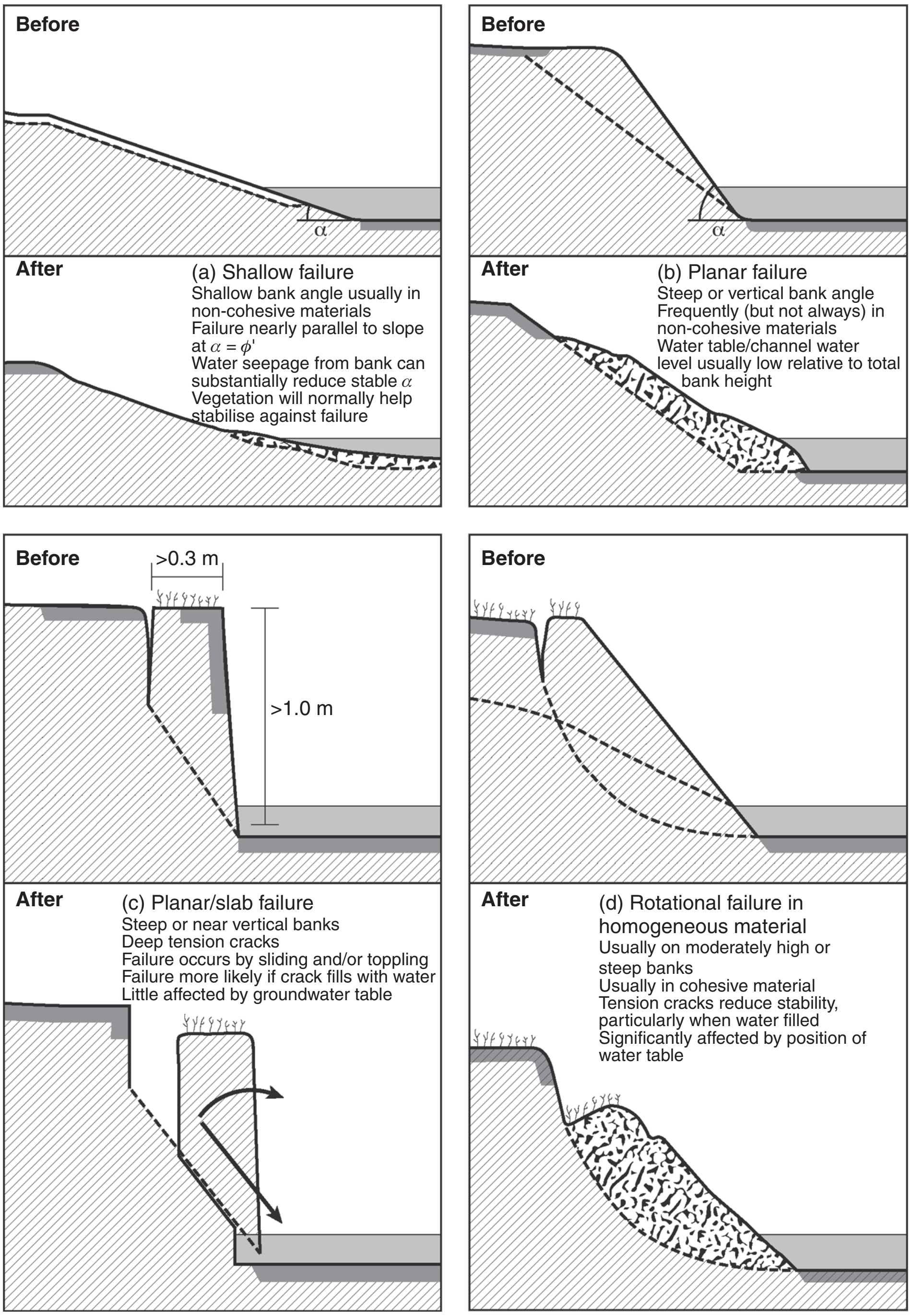

Fig. 3.2 Commonly observed modes of bank failure. Modified, with permission, from Hemphill and Bramley, 1989. © 1989 CIRIA. www.ciria.org

elevation of the channel bed increases progressively through time at the reach-scale is termed *aggradation*.

However, in nature, instability rarely if ever occurs simply through degradation or aggradation alone. In fact, channel change in unstable streams is characterised by simultaneous adjustment of bed elevation, channel width, cross-sectional geometry and planform. Figure 3.4 illustrates diagrammatically a range of commonly observed types of river channel instability that involve different combinations of simultaneous adjustment to bed elevation, cross-sectional geometry and planform pattern (Downs,

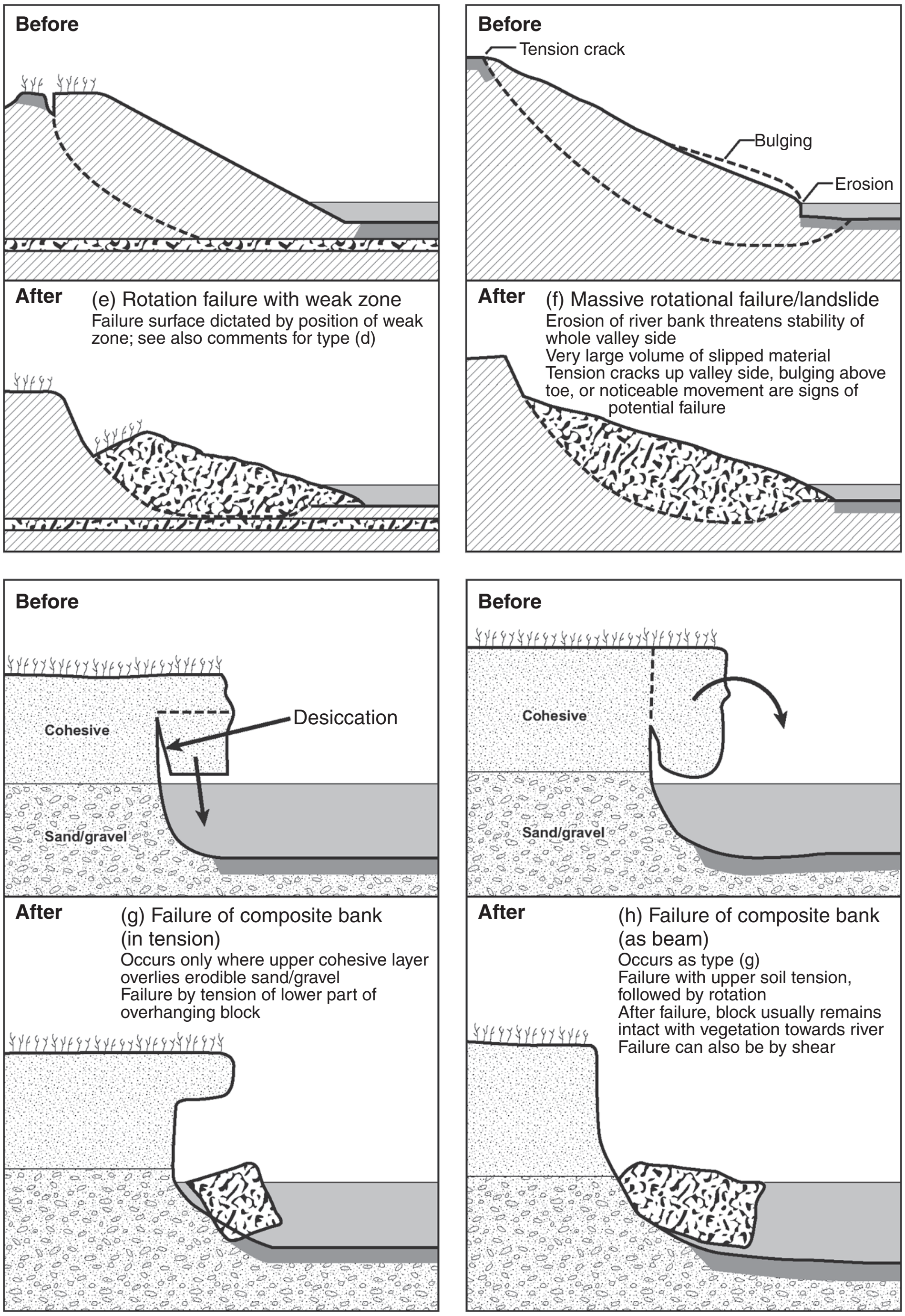

Fig. 3.2 Continued

1994). The balance between changes at the bed and at the banklines strongly affects the trend of change as well as the amount and the calibre of sediment derived through channel adjustments in an unstable channel (Simon and Thorne, 1996).

Neither is change due to instability confined to the channel itself. Significant erosion of the floodplain may occur during out-of-bank events, remobilising sediment held in long-term storage in the deposits filling the floor of the valley. Such instability may produce marked changes in floodplain topography leading in extreme cases (and especially where floodplain vegetation has been removed) to

Table 3.8 Process drivers influencing bank retreat

Category	Process/mechanism/ factor	Processes driver
Erosion	Flow erosion	Intense or near-bank flow – represented by velocity, bank shear stress or stream power and influenced by channel form, flow deflection, flow impingement and flow curvature effects (secondary currents)
	Boat wash	Significant wave height and frequency – controlled by vessel design, speed, and distance from bank, navigation traffic density and size/shape of channel
	Rills and gullies	Concentration of surface water draining over bank – influenced by floodplain topography, land use, land drainage, vegetation, bank height/ steepness and stock access
	Piping	Concentrated subsurface drainage – caused by strong seepage pressures in banks with adjacent permeable and impermeable layers in their stratigraphy. Promoted by compaction and land drainage
	Freeze–thaw	Freezing temperatures and frost – influenced by microclimate and lack of vegetation cover
Mass failure	Shallow slide	Oversteepening of a non-cohesive bank by fluvial undercutting due to intense near-bank flow
	Rotational slip	Overheightening or steepening of cohesive bank by fluvial scour at toe due to intense near-bank flow, usually combined with surcharging, intense precipitation, or adverse drainage
	Slab failure	Overheightening or steepening of a weakly cohesive bank due to fluvial undercutting by intense near-bank flow, usually combined with soil cracking in tension
	Cantilever failure	Instability in an overhanging bank due to fluvial under-mining, soil cracking and high degree of soil saturation
	Soil fall	Loss of soil strength caused by action of one or more weakening factors (see below)
	Earth flow	Positive pore water pressures in saturated soil caused by adverse drainage conditions that produce liquefaction
Weakening	Leaching	Concentrated subsurface drainage that leads to loss of minerals in areas of vigorous soil seepage flow
	Trampling	Uncontrolled livestock access (also termed poaching) especially when ground is wet
	Vegetation loss	Inappropriate management of the riparian corridor leading to loss of vegetation protection/reinforcement
	Mechanical damage	Inappropriate bank activities such as boat mooring. Poorly managed angling or stock access
	Positive pore water pressure	Restricted or adverse drainage conditions following bank inundation by high stages in the channel and/or heavy precipitation
	Desiccation	Strong soil moisture deficit and shrinkage driven by intense drying of bank material due to lack of rain, exposure of soil surface to wind/sun and high evapotranspiration rates

the phenomenon of 'floodplain unravelling' (Smith, 2004) and it can alter the location and planform pattern of a river significantly. Table 3.10 lists the main types of scour in unstable rivers, including both in-channel and overbank processes.

3.2.3 *Sediment transport*

3.2.3.1 *Transport mechanics*

Transfers of sediment in the fluvial system take place through the transport of particles downstream from erosive source to depositional sink. It is, therefore,

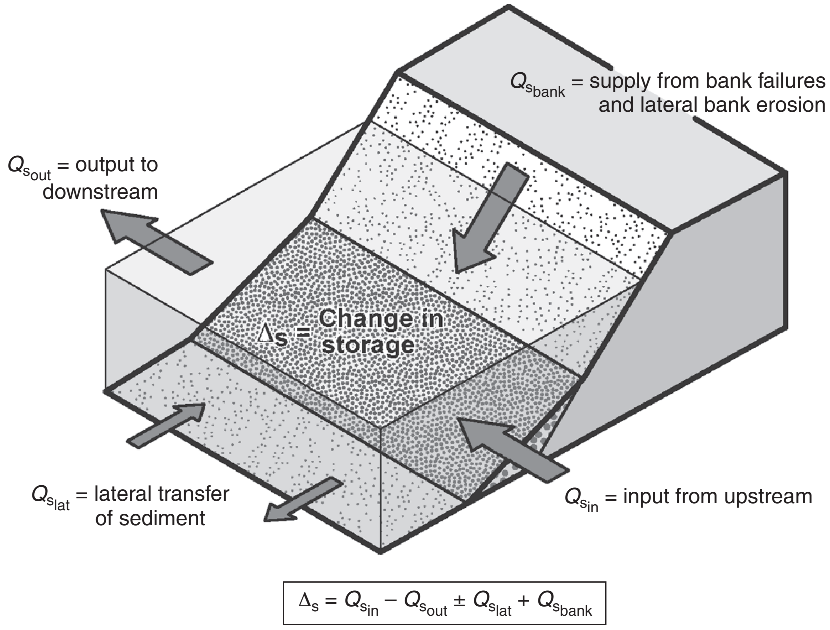

Fig. 3.3 Sediment fluxes in the near-bank zone. Modified, with permission, from Thorne et al., *1997. © 1997 John Wiley & Sons Limited*

sediment transport that drives the fluvial transfer system. For sediment transport to occur, two conditions must be met:

1. flow must be sufficiently vigorous to carry available sediment along with it;
2. sediment of a calibre that can be carried must be available for transport.

In practice, either one of these conditions may limit the quantity of sediment of a given size that is actually transported by a river. When the availability of sediment for transport is unlimited and the quantity of sediment carried by the river is controlled solely by the capability of the flow to carry it, the sediment load is said to be transport limited. When there is ample flow capacity to transport sediment,

Table 3.9 States of basal endpoint control

State of basal endpoint control	Description
Excess basal capacity	Rate of sediment removal exceeds rate of supply (output > input). Bed and lower bank are scoured to make up difference, generating increased bank height and angle. Bank stability is reduced, triggering mass failures that increase sediment supply to bank base. The rate of bank retreat accelerates, tending towards a state of unimpeded removal, with rate of bank retreat adjusted to match rate of sediment removal at the base of the bank
Unimpeded removal	Rate of sediment removal equals rate of supply (output = input). No net scour or deposition occurs at base of bank. The rate of bank retreat is matched to rate of sediment removal by currents and waves. The bank retreats through parallel retreat (i.e. bank profile does not change through time) at a rate governed by rate of sediment removal at base of the bank
Impeded removal	Rate of sediment removal lower than rate of supply (output < input). Sediment accumulation at base occurs to account for the difference, forming low angle, sediment beach, wedge or berm. Accumulated sediment protects the intact bank behind it from erosion and tends to stabilise bank, reducing the rate of sediment supply. The rate of bank retreat decelerates, tending towards a state of unimpeded removal, with rate of bank retreat adjusted to match rate of sediment removal at the base of the bank

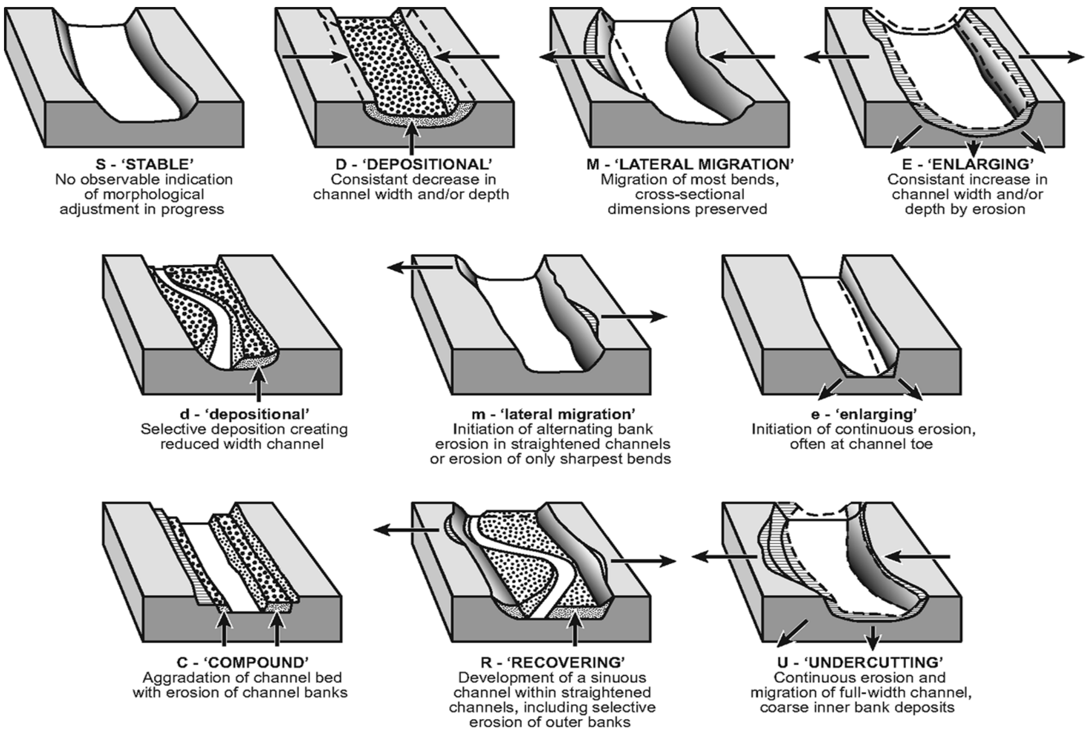

Fig. 3.4 Types of adjustment commonly observed in unstable channels. Modified, with permission, from Downs, 1995. © 1995 John Wiley & Sons Limited

but the quantity of sediment actually in motion is restricted by its availability, the sediment load is said to be supply limited. As a general rule, the quantity of coarse-grained material (cobbles, gravel, coarse sand) in the sediment load is transport limited, while the quantity of fines (fine sand, silt, clay) is supply limited, although this is not universally true.

The movement of sediment, particularly coarse bedload, requires that the transport threshold for bed material erosion is exceeded, and in headwater streams with flashy regimes this makes significant bedload movement in the UK rare and episodic. This may be illustrated using long-term records from sediment traps in streams draining the English Lake District (NRA, 1994a). Figure 3.5 shows the maintenance record for a gravel trap on Coledale Beck, illustrating that the great majority of the 5958 tonnes of gravel trapped during the 50-year period of record was actually transported during just four transport events that occurred in June 1952, May and October 1954, and June 1956 (months 130–170). In the case of Coledale Beck, the relatively low yields associated with floods in the 1960s and 1970s (months 370–480) that were of similar magnitude to those in the 1950s but which transported far less coarse sediment, may indicate that gravel transport was at that time supply limited due to lack of fresh inputs from landslides, leading to exhaustion of in-channel gravel storage areas.

The distribution of sediment transport through time and space actually during a transport event is also unsteady and non-uniform. Data obtained from gravel traps fitted with equipment to record the rate of sediment accumulation (Reid *et al.*, 1985) demonstrate that bedload characteristically moves in pulses, so that the shapes of the water and sediment hydrographs do not correspond to one another (Fig. 3.6).

It is believed that bedload pulses, like those in the record for Turkey Brook, are ubiquitous to upland and gravel-bed rivers. Flume experiments and field observations

Table 3.10 Types of channel scour in unstable channels

Scour type	Description
Degradation	Occurs when the bed elevation is lowered progressively through time along a substantial length of the channel. Degradation may be caused by base level lowering, straightening (e.g. meander cut-off), sediment starvation or increased discharge. If sustained, degradation markedly increases downstream bed material loads and, if it destabilises the banks, it also boosts the yield of fine sediment and threatens bridge abutments and floodplain infrastructure. The degree of bed lowering due to degradation depends on flow hydraulics, sediment load, bed material composition and the presence of geologic or artificial bed controls (rock outcrops or grade control structures). Degradation can be predicted using numerical models of hydro-dynamics, sediment transport, bank stability and morphological channel evolution (Thorne and Osman, 1988: Darby and Simon, 1999)
Widening	Occurs when both banks in the same reach of a river retreat. Widening occurs when the channel capacity increases to accommodate higher discharges or coarse sediment loads. On average, widening occurs annually at a rate related to the scale (width) of the channel, and on this basis it is empirically predictable. One serious widening phenomenon occurs when the banks of a degrading river become so high that they are unstable with respect to mass failure. Rapid widening then occurs and can increase the width of the channel by a factor of 3 in just a few years and produce very high inputs of fine sediment to downstream reaches (ASCE, 1998a, 1998b)
Overbank scour	Occurs when water flowing over the floodplain during a flood event scours the land surface significantly. While floodplain flows are usually aggradational, scour can occur around obstructions or due to local constrictions. Experience has demonstrated that overbank scour can lead to removal of considerable volumes of soil and transmit this downstream to drive accelerated sedimentation. In extreme cases, overbank scour can lead to floodplain unravelling and/or channel avulsion (Smith, 2004)
Avulsion	Is the abandonment of the channel along a substantial length of river and adoption of a new course at another location. Avulsion can occur in response to a major flood event, or due to the cumulative effect of years or decades of incremental change that lead to diversion of the flow into a new and different alignment. Avulsion can result in flow scour and erosion at entirely new and unexpected locations with marked increases in sediment production and serious implications for channel stability both up and downstream in streams of any size (Aslan *et al.*, 2005; Tooth *et al.*, 2007)
Planform metamorphosis	Defined by the switching of the channel from one planform pattern to another, in response to the crossing of an intrinsic geomorphic threshold (Schumm, 1977). For example, aggradation of the channel and floodplain of a sinuous, single-thread river may increase the valley slope to the point that the meandering course of the river is replaced by a braided pattern. Rapid widening to accommodate multiple sub-channels may liberate large volumes of fine sediment from floodplain storage with implications for downstream sedimentation. Conversely, metamorphosis of a braided channel into a meandering channel could result in much more efficient sediment transport and greater scour depths in the resulting, single channel, elevating downstream supplies of coarse bedload (Sarker and Thorne, 2006)

suggest multiple causes for bedload pulsing, related to the input of sediment to the channel in discrete pulses, the influence of pebble clusters and the occurrence of low-amplitude bedforms (Reid *et al.*, 1992; Cudden and Hoey, 2003; Cui *et al.*, 2003). Pulsing in the form of sediment waves is also apparent at larger time and space scales. For example, the downstream passage of sediment waves has been studied by Coulthard *et al.* (2005), who show that the wavelength and amplitude of sediment waves are related to the rate of sediment delivery and the frequency of sediment transporting events, which are in turn controlled by the occurrence of both extreme (sediment delivery) and moderate floods (sediment transport). In the case of small streams draining unstable headwater basins, it can take decades before fluvial transport

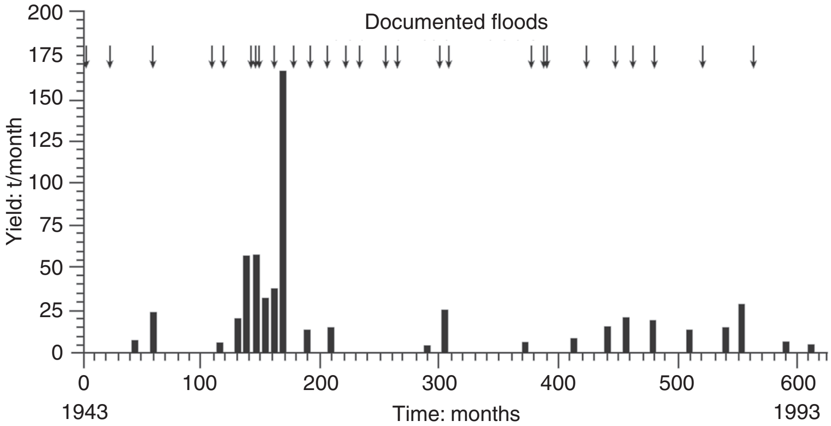

Fig. 3.5 Fifty-year record of gravel yield (in-trap accumulation) in a gravel trap on Coledale Beck in the Lake District. Arrows indicate occurrence of flood events

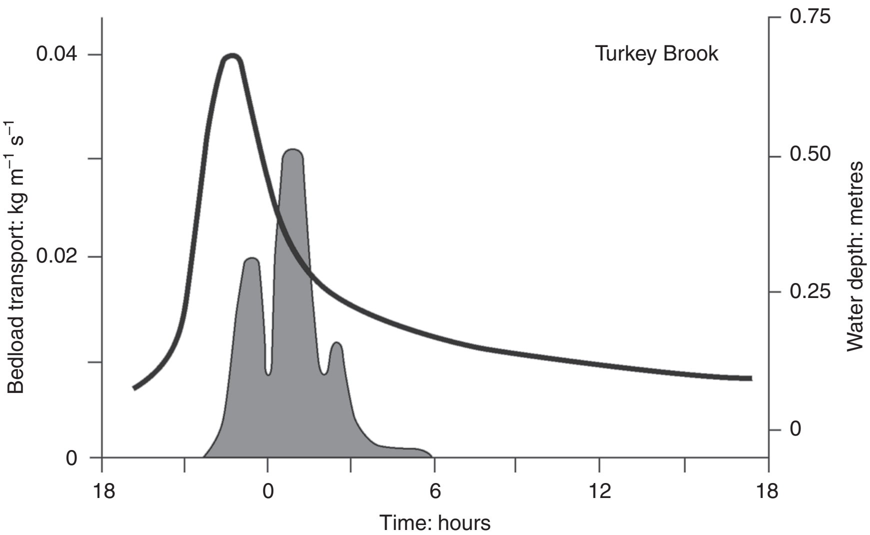

Fig. 3.6 Storm hydrograph and sediment hydrograph showing pulses of bedload movement out of phase with variation in stream flow. Modified, with permission, from Thorne et al., *1997. © 1997 John Wiley & Sons Limited*

finishes responding to a discrete, high-magnitude sediment input event (Harvey, 2007).

This short review of mechanisms generating variability and complexity in sediment transport through time and space illustrates why it is problematic to attempt to predict sediment loads based only local, contemporary flow hydraulics and a simple measure of sediment size. It also indicates that knowledge and understanding of additional factors (including but not limited to: sediment supply from diffuse catchment sources, spatial distributions of discrete (point) sediment inputs outside the channel, availability of material from re-entrainment of sediment stored in the channel, the input from bank erosion, the existence and influence of armouring, clustering and bedforms, and the record of antecedent transporting events) are also required to make accurate predictions of the sediment load associated with a particular discharge event at a particular point in the fluvial system.

Table 3.11 Classification of the sediment load

Basis for classification	Classification	Description
Source	Bed material load	Sediment mainly derived from scour of the channel bed and which is of a size found in significant quantities in the bed. Transporting bed material load requires that the flow expend a noticeable percentage (usually ~3 to 5%) of its stream power.
	Wash load	Sediment mainly supplied by catchment erosion and which is finer than that found in substantial quantities in the bed of the channel. Transporting wash load does not involve the flow expending a noticeable percentage of its stream power
Transport mechanics	Bedload	Relatively coarse fraction of the load, in frequent contact with the bed and moving by sliding, rolling or bouncing (*saltating*).
	Suspended load	Relatively fine fraction of the load, seldom in contact with the bed and carried within the body of the flow by turbulence
Measurement	Measured load	Portion of the load that is sampled and represented by measurements of sediment load made using conventional equipment and routine sampling strategies.
	Unmeasured load	Portion of the load that is unsampled when using conventional equipment and sampling strategies

3.2.3.2 *Classification of sediment load*

Erosion of the catchment takes place through the removal of soil and rock material that is either dissolved in the river water (the solute load) or transported as solid fragments carried by the flow. It is the solid load that has most significance to river geomorphology and which is referred to herein as the sediment load. There are three bases on which to classify the sediment load in a river (Table 3.11).

The existence of multiple bases for describing, classifying and accounting for the sediment load continues to be the source of a great deal of confusion concerning sediment dynamics and its morphological significance. This arises because terms such as *bedload* and *bed material load* are not interchangeable, even though they sound similar. Some frequent misconceptions concerning sediment load terminology illustrate the problem:

- Gravel derived from catchment erosion actually constitutes wash load in a steep mountain stream with a boulder bed – even though it moves as bedload.
- Much of the bed material load in a sand-bed river travels in suspension.
- In a gravel-bed river, a conventional pump sampler captures some, although not all, of the suspended load but is incapable of sampling any of the bedload.

Table 3.12 illustrates the relationship between the different constituents of the sediment load definitively. To avoid river scientists, engineers and managers talking at crossed purposes, frequent reference to such a diagram is recommended and a set

Table 3.12 Definition of relations between constituents of the sediment load

<table>
<tr><th>Source</th><th>Transport mechanics</th><th>Measurement</th></tr>
<tr><td>Wash load</td><td rowspan="3">Suspended load</td><td rowspan="2">Sampled load</td></tr>
<tr><td rowspan="2">Bed material load</td></tr>
<tr><td rowspan="2">Unsampled load</td></tr>
<tr><td></td><td>Bedload</td></tr>
</table>

of definitions should be agreed by all parties whenever sediment transport and the make-up of the sediment load are being discussed.

However, while the wash load–bed material load concept has proven useful in regional sediment management (Biedenharn *et al*., 2006a), it must be acknowledged that the definitions of different classes of sediment load remain deeply contested (Biedenharn *et al*., 2006b).

3.2.3.3 *Bed material grading, armouring, sorting and fabric (or structure)*

The ease with which sediment is picked up by the flow (*entrained*) and carried downstream (*transported*) is described by its *mobility*. The mobility of sediment making up the bed of the channel depends primarily on the size of the particles, but several other factors may also be significant and it is necessary to appreciate this when trying to understand and explain how sediment moves through the fluvial system. Potentially important factors include grading, sorting, armouring and fabric.

Grading describes the range of sizes of particles making up the sediment body. Well-graded sediments are made up of particles of almost uniform size, while poorly graded sediments consist of a mixture of widely differing sizes of material. For example, in an upland stream the bed is often poorly graded, being made up of particles ranging from boulders (material with a median diameter larger than 256 mm) to sand (material finer than 2 mm). Grading is highly significant to sediment transport because the mobility of a grain has been found to depend not only on its physical size but also on its size relative to that of other particles making up the channel bed (Wiberg and Smith, 1987). This is the case because of what has been termed the 'hiding factor'. When part of a mixture, smaller grains are to some extent protected from fluid shear forces and turbulence because they are sheltered by larger particles. This hiding effect decreases the mobility of the smaller grains in a sediment mixture. Conversely, when part of mixture, the largest grains tend to protrude above the bed and are overexposed. Consequently, they bear a disproportionately large fraction of the bed shear and are exposed to heavy turbulence, both of which increase their mobility relative to that in a bed of uniform grains.

The effects of grading are most pronounced in cobble, gravel and mixed gravel–sand bed rivers and require that grading be taken into account when bed material load is being calculated or sediment is routed through the system in a mobile-bed model. While a single representative grain size, usually close to the D_{50}, can be used to estimate the load in a river with a poorly sorted bed (Proffit and Sutherland, 1983), grading is now usually accounted for in sediment transport equations by calculating the transport rate for multiple-size fractions (D_{10}, D_{20}, D_{30} … D_{90}, etc.) and summing the results to find the total bed material load (Ackers and White, 1973). In sediment routing by size fraction, the model must keep track of the size distributions of both the bed and the bed material load through budgeting for each size fraction, rather than simply satisfying an equation for overall sediment continuity along the channel.

The effect of 'hiding' is to reduce the mobility of smaller grains compared to their mobility in a bed of uniform sediment but, despite this effect, the smaller grains in a mixture are still a little more easily entrained and transported than the larger ones. As a result, during transport events, smaller grains are selectively entrained earlier and transported faster than the larger ones, with important impacts on the local composition of the bed.

Importantly, selective entrainment and transport of the smaller grains in a mixture leads to development of a coarse surface layer composed preferentially of the larger, less mobile grains – a process termed 'downstream winnowing'. Gaps between large particles in the coarse surface layer then allow finer particles to fall through to the substrate, meaning that they are lost from the active layer – a process termed *vertical winnowing* (Whiting and King, 2003). In extreme cases, where there is no resupply of mobile gravels from upstream, a stable, immobile surface layer develops. Beds with immobile coarse surface layers are found downstream of dams and in degraded reaches where the bed has scoured away all the mobile sediment. Where there is a supply of bed material load from upstream, the result of selective entrainment is less extreme, forming a mobile, coarse surface layer that almost but not quite offsets the intrinsically higher mobility of the finer grains – a condition of *equal mobility*. Evidence from field measurements and flume experiments indicates that the size distribution of the bed material load in a river with a mobile coarse surface layer approximates to that of the substrate, even though the bed surface is considerably coarser (Andrews and Parker, 1987). The terms *pavement* and *armour* have been used to describe static and mobile coarse surface layers, respectively. However, this usage is reversed by some authors (see for example Andrews and Parker, 1987), while Gomez (2006) has recently questioned whether there is in any case a genuine distinction in process terms between static and mobile coarse layers.

Decades of research have demonstrated the huge significance of armouring to bed scour, sediment loads and benthic habitats in gravel-bed rivers (Hey *et al*., 1982; Thorne *et al*., 1987; Billi *et al*., 1992; Klingeman *et al*., 1995; Mosley, 2001). Armouring greatly reduces bed material loads, limits scour and provides spawning sites for fish and secure substrate for invertebrates and the roots of aquatic and emergent plants. All these advantages are lost if the armour is destroyed due to an exceptionally large flood, gravel extraction or dredging. Similarly, the ingress of fines can block the spaces between particles in a gravel matrix or even blanket an intact armour layer, smothering it and the habitats it provides. Hence, downstream sediment loads, bed stability and in-stream habitats in gravel-bed reaches are all particularly vulnerable to elevated wash loads, in-channel activities that disturb the bed and many other forms of careless management.

Sorting occurs because the effects of armouring and paving do not entirely eliminate selective entrainment of finer grains from a coarse surface layer and because the transport distance for a grain during an event increases as its size decreases. The results of sorting are a downstream fining in the median size and increased uniformity (that is, heterogeneous sediment mixtures become better graded) in the distribution of the material making up the bed and sediment load, with increasing travel distance downstream. It was hypothesised in the 1980s that downstream fining resulted from wearing down of grains during transport due to granular breakage and abrasion. However, subsequent field research and sediment transport modelling has demonstrated that sorting through selective entrainment and transport of finer grains is able to explain observed downstream trends in bed material size (Ferguson *et al*., 1996; Hoey and Bluck, 1999).

Fabric (or structure) describes the way that particles making up the bed are arranged and packed. These factors have also been found to have a significant effect on grain mobility. Particles (especially platy ones) deposited by flowing water tend to be imbricated – that is, they display a fish-scale pattern with grains overlapping in the downstream direction. Imbrication, like armouring, reduces the mobility of bed grains compared to conditions in a randomly arranged sediment bed. The stability of an imbricated bed is, however, vulnerable to reduction if the pattern is disturbed by, for example, a four-wheel drive vehicle. Bed sediments that are frequently moved by bedload transport have a loose packing pattern with relatively open interstices that allow water to flow freely through the gravel matrix. Such deposits are termed 'over-loose'. When grains are immobile for long periods the bed settles and the matrix becomes compacted. Grains in such 'under-loose' beds are much more difficult to entrain than similar grains in an over-loose bed. For example, it has long been recognised that the critical dimensionless shear stress (Shields' parameter) for entrainment of very loose gravel is as low as 0.03, but that this rises to in excess of 0.06 for compacted gravels. Recent research in Canada has reinforced this finding, indicating that sediment transport in gravel-bed rivers is strongly influenced by bed structure (Oldmeadow and Church, 2006). Also, with time the interstices of compacted, immobile gravels tend to fill with fine sediment that filters down into the bed from the wash load. Clogging of gravels by fines further reduces mobility, reduces water flow within the hyporheic zones and greatly reduces the value of the bed in terms of providing benthic habitats and spawning gravels.

This brief discussion of factors affecting the mobility of sediments serves to illustrate the complexities encountered when attempting to characterise and quantify sediment transport in geomorphological or engineering analyses. It is clear that knowledge of the gradation, structure and fabric of the bed is required to explain the sediment transport associated with a given discharge, as well as data defining a characteristic sediment size.

3.2.3.4 *Transport models and equations*

A range of models and equations exist to predict the capacity of a stream to transport sediment. However, considerable uncertainty surrounds the applicability and accuracy of available prediction methods, especially when equations are applied without calibration against long-term, reliable data derived from field measurements of sediment load actually made in the watercourse in question. Without a substantial volume of site-specific field data, collected over a wide range of discharges, predictions of sediment load based on uncalibrated equations are, at best, indicative and may, in practice, be in error by as much as one or two orders of magnitude. Table 3.13 lists some of the more popular sediment transport formulae used by the NRA and more recently the Environment Agency in geomorphological studies, together with some comments on their performance based on past experience.

One of the better documented applications of a transport equation concerns use of the Ackers–White equation in conjunction with river modelling tools on the River Eden. Considerable experience was gained in the use of sediment transport calculations as an aid to morphological modelling and, somewhat unusually, the findings are available in a substantive academic paper (Walker, 2001).

The transport of coarse sediment derived from the bed of the channel is often limited by the carrying capacity of the flow and may, therefore, be predicted on the basis of flow hydraulics. Many transport formulae exist but, following a comprehensive review of sediment transport formulae, Gomez and Church (1989) concluded that the bedload formula of Bagnold (1966) gives the most reasonable predictive results for the movement of a range of relatively coarse sediment sizes. This view has been challenged in subsequent learned papers although no consensus on a preferred equation has emerged. Conversely, Bagnold's equation has been endorsed in a number of NRA/Environment Agency R&D projects, which have

Table 3.13 Sediment transport formulae used in NRA/Environment Agency R&D studies concerning fluvial geomorphology

Formula	Bed material size	Basis	Sample applications	Comments
Bagnold (1980)	Sand, gravel	Stream power	Mimmshall Brook, R. Sence, R. Idle, Shelf Brook (C5/384/2) Grt Eggleshope Beck (Carling, 1984)	Performed well in tests against field data using reach-average values. Both under- and overpredicts
Bathurst *et al.* (1987)	Gravel, cobble	Discharge	Shelf Brook (C5/384/2), R. Dunsop, R. Whitendale (Newson and Bathurst, 1991)	Performed well for steep, headwater streams ($S > 0.1$). Overpredicts and can produce negative loads
Ackers-White (1973) updated by HR Wallingford (1990)	Silt, sand gravel	Shear stress	R. Sence, Usk, Colne, Stour, Ecclesborne (HR Wallingford, 1992)	Performed well in tests based on flumes and rivers. Much better when calibrated against data from site in question. Overpredicts
Newson (1986) updated in Project Record 232/1/T	Silt, sand gravel	Catchment area	Shelf Brook, Sence, Tawe, Idle (C5/384/2), Dunsop, Whitendale (Newson and Bathurst, 1991)	Provides estimate of annual sediment yield to river. Empirical basis for UK streams, but uncalibrated to date

used the formula with success, and on this basis it may be appropriate for general usage in geomorphological applications.

The bedload transport rate per unit width of the active channel bed (kg/m/s) is given by:

$$I_b = 0.1\left[\left(\frac{(\omega' - \omega'_o)}{0.5}\right)^{1.5}\left(\frac{d}{0.1}\right)^{-2/3}\left(\frac{D_{50}}{0.0011}\right)^{-0.5}\right]$$

where ω' = index of specific stream power, ω'_o = critical value of w' for the initiation of bed sediment motion, d = depth, and D_{50} = median bed material size. All parameters must be expressed in SI units. For use in Bagnold's equation, the stream power is defined by:

$$\omega' = \frac{\rho Q S}{w}$$

where ρ = water density, Q = stream discharge, S = energy slope (usually approximated to the water surface slope), and w = channel bed width. This gives stream power expressed in kg/m/s – the same units as the predicted bedload transport rate. The critical stream power value for initiation of bed motion is defined by:

$$w'_o = 290(D_{50})^{1.5}\log\left(\frac{12d}{D_{50}}\right)$$

While Bagnold's equation may be used to predict bed material load, it does not include the load of fine-grained sediment moving in suspension. In UK rivers, this is mainly derived from catchment sources and constitutes wash load – that is, it is made up of sediment sizes finer than those found in appreciable quantities in the bed. Transport of wash load is usually limited not by the transport capacity of the flow but by its availability for transport. Hence, wash load is not predictable using

Bagnold's formula or indeed any of the equations based on flow hydraulics. As wash load usually makes up 80% or more of the total load carried by a river, it is an error to believe that the total load can be predicted on the basis of the bed material attributes and hydraulic conditions alone. Such computations can only indicate the bed material load.

In fact, much of the wash load is derived from catchment erosion and/or bank erosion. Under these circumstances, Environment Agency R&D projects have demonstrated that a more fruitful approach to estimating the fine load is to use an approach based on catchment area, terrain, soils and land use. This topic is developed further in Chapter 4. Where bank erosion may also be a major source of sediment, the load of bank-derived wash load may be estimated through stream reconnaissance to identify the locations and extent of eroding banks, coupled with application of appropriate bank stability and retreat models (Thorne, 1998; Simon *et al.*, 2000).

3.2.4 Sediment deposition and storage

3.2.4.1 Overview

Sediment rarely if ever travels from its primary source in the headwaters to the coast in a single transport event. In fact, sediment is usually deposited and re-eroded several (sometimes numerous) times before it reaches the coast. Consequently, sediment spends periods stored in the landscape in the form of *alluvium* – that is, material making up sediment features and bodies in the channel, along its margins and on the floodplain. The duration of storage varies widely depending on the type and location of the sedimentary feature involved. For example, in-channel sediment storage in active bars and riffles tends to be short-term, while marginal berms act as medium-term stores, and floodplain sedimentary units represent long-term, sometimes semi-permanent, sediment reservoirs. The process dynamics and storage timescales associated with sediment deposition in and outside the channel are sufficiently distinct to deserve separate consideration.

3.2.4.2 Channel deposition

Channel deposition occurs when the flow loses the capacity to transport some, or all, of its sediment load. This may happen for two reasons:

1. The sediment transport capacity of the river decreases through time due to reduction in discharge on the falling limb of an event hydrograph.
2. The sediment transport capacity of the river decreases in the long-stream direction due to a reduction in the channel slope, a flow obstruction that reduces the energy slope, or an increase in width and/or flow resistance that reduces the stream power per unit bed area available to transport sediment.

Characteristic in-channel depositionary features include bars (often termed shoals), riffles, berms and banks with a variety of forms and morphologies.

Channel deposition dominates sediment storage in upland and headwater zones, where channels may contain relatively large amounts of very coarse material (boulders and cobbles), eroded from nearby steep slopes and valley sides. This is the case because transport in this zone occurs only infrequently and because opportunities for overbank deposition are generally limited by the narrow width of the valley floor. Characteristic depositionary features include boulder steps in the channel bed with cobble deposits in the pools between them (Whittaker and Jaeggi, 1982), and boulder berms along the channel margins (Carling, 1989).

In the middle course, channel deposition is dominated by the formation of cobble and gravel bars, including riffles and shoals. A wide range of bar forms is possible, with the precise form taken by in-channel depositionary features depending on the cross-sectional morphology and planform pattern of the river. A great deal of time and effort has been expended by geomorphologists and sedimentologists in creating hierarchical classification systems for coarse-grained bars (Bluck, 1982; Bridge, 2003) and Fig. 3.7 presents a summary diagram of the more common bar configurations observed in gravel and cobble-bed rivers that transport significant quantities of bedload (Hey, Bathurst and Thorne, 1997). Bars adjust and shift their positions during every event that entrains and transports significant quantities of coarse sediment, to produce the dynamic morphology characteristic of channels in the middle reaches of the drainage network.

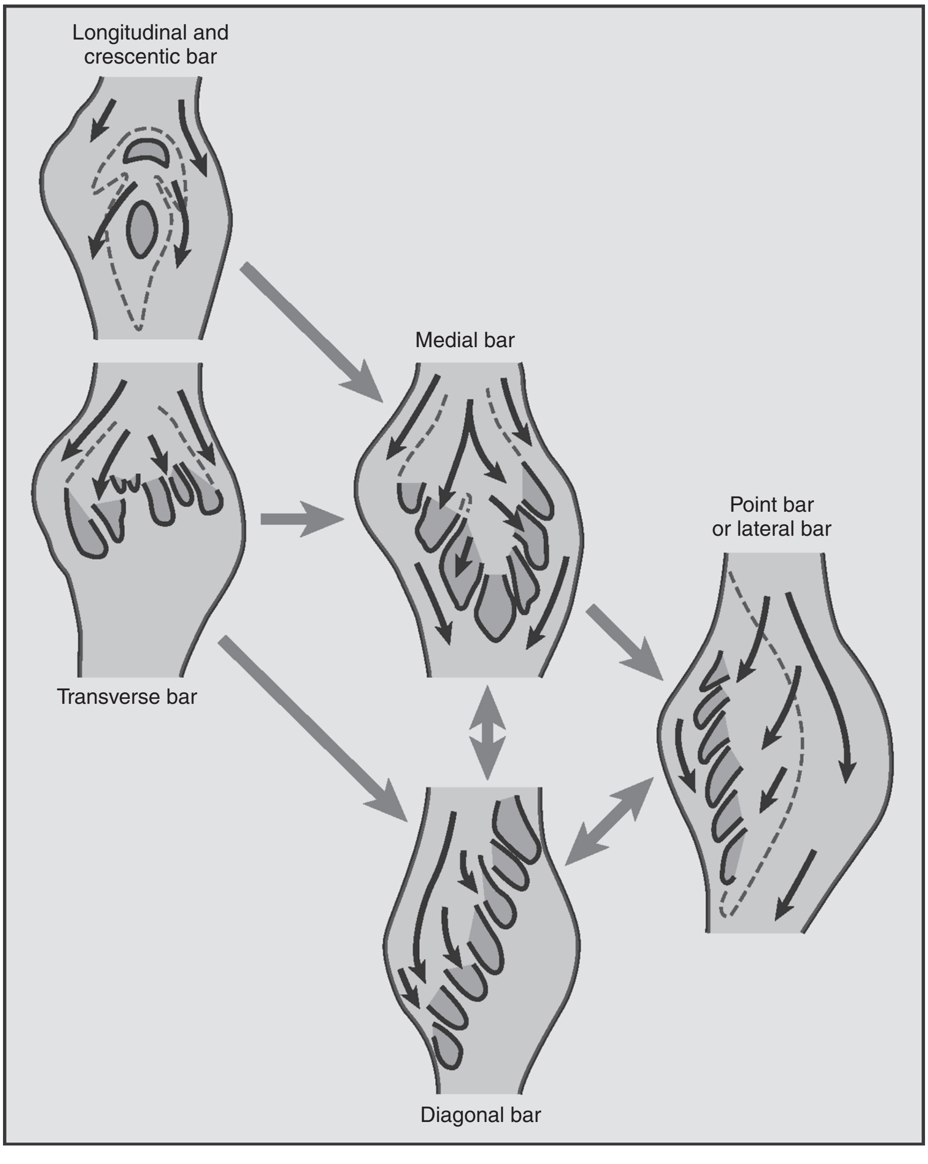

Fig. 3.7 Typical channel bars observed in gravel and cobble-bed rivers with active bedload transport. Modified, with permission, from Hey et al., *1982. © 1982 John Wiley & Sons Limited*

In natural alluvial reaches, patterns of in-channel deposition and the development and movement of bars are closely associated with localised bank erosion that remobilises finer-grained sediment from floodplain storage. This is the case because adjustments to bar sizes and locations interact with flow hydraulics to condition the distribution of bank retreat which, in turn, drives planform evolution and change (Hooke, 1979; Lawler, 1992; Lawler *et al*., 1997). It is coupling of bar, bank and planform adjustments that allows the sediment transfer system in the middle course of the river to *exchange* coarse sediment moving as bedload for finer sediment eroded from retreating banks that is transported further downstream, in suspension. This form of sediment exchange takes place predominantly through point bar growth that drives bend initiation and evolution in sinuous channels (Howard and Knutson, 1984; Blondeaux and Seminara, 1985), and through the genesis and development of bars and bank floodplain embayments in braided rivers (Thorne *et al*., 1993; Goff and Ashmore, 1994).

To understand sediment exchange in meandering rivers, it is necessary to consider briefly how water and sediment moves through a sinuous channel (Fig. 3.8a). In sinuous channels secondary currents, established due to flow curvature effects, heavily influence the distribution of both cross- and long-stream velocities. At bends, fast, surface water is thrown outwards to plunge near the outer bank before returning towards the inner bank as a near-bed current. Interaction between the helical cell so formed and the outer bank sets up a small, counter-rotating cell adjacent to the steep, retreating bank (Hey and Thorne, 1975; Bathurst *et al*., 1977). The combined effect of these secondary cells is to concentrate bed scour in the outer half of the channel and undermine the outer bank, promoting asymmetry in the cross-section and driving outer bank retreat (Bathurst *et al*., 1979). Conversely, deposition and bank advance is promoted at the inner bank, where outwardly directed secondary flow moving sediment across the upper point bar (the point bar platform) meets upwelling water in the main helical cell as it sweeps bed sediment up the point bar face (Dietrich and Smith, 1983; Thorne *et al*., 1985). Taken together, these processes lead to point bar accretion, outer bank retreat and meander bend evolution (see Fig. 2.14).

Erosion of the outer bank causes it to retreat into the floodplain (as well as eroding any terraces it encounters), removing sediment from storage and adding it to the sediment load. At the same time, deposition on the growing point bar at the inner bank removes material from the sediment load. It should be noted, however, that material eroded from the outer bank does *not* cross the channel to deposit on the point opposite. As shown in Fig. 3.8a, sediment transport is concentrated over the point bar and it is predominantly relatively coarse, bed material load that is deposited there (Dietrich and Smith, 1984). Material eroded from the outer bank travels downstream to the riffle at the inflection point between bends, often under the influence of stacked secondary circulations that occur between bends (Thorne and Hey, 1979). Around the meander inflection point, the coarsest fraction tends to accumulate on the riffle; medium-sized material passes through to be stored in the next point bar (on the same side of the channel), while the finer fraction carries on downstream to the lower course. In this way, the river exchanges relatively coarse sediment supplied from upstream with finer sediment eroded from floodplain and terrace stores, tending to reduce the characteristic size that it supplies downstream as it does so.

The configuration of bars and the pattern of planform change through time are related to interactions and changes in: coarse supply, local exchange with material derived from lateral shifting, and throughput to downstream. Typical patterns of

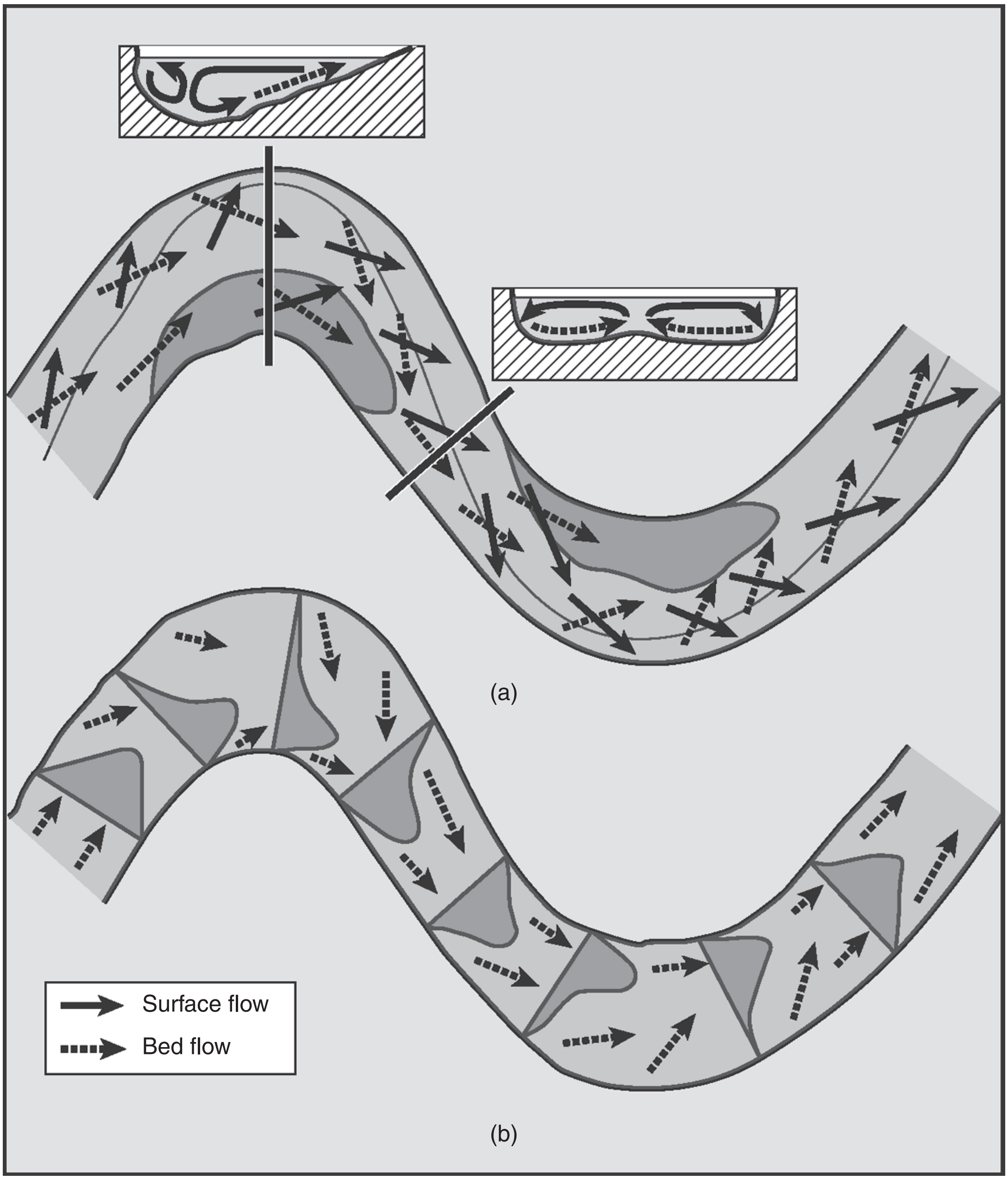

Fig. 3.8 (a) Distributions of surface and near-bed flow, and bedload transport in meandering channel; (b) pattern of secondary currents around the bend apex. Modified, with permission, from Markham and Thorne, 1992. © 1992 John Wiley & Sons Limited

change due to contemporary erosion and sedimentation are illustrated in Figs 3.9 and 3.10.

The fluvial processes responsible for sediment exchange in braided rivers are less well documented but are believed to bear many similarities to those in meandering rivers. Ashworth *et al*. (1992) went as far as to suggest that the divided flow around a braid bar may be conceptualised as consisting of back-to-back meanders (Fig. 3.11).

However, field observations of secondary currents, bar growth and bank retreat in a braided anabranch of the Jamuna River in Bangladesh indicate that the analogy between flows around braid bars and in meander bends is somewhat more complicated. Measurements by Richardson (1997) reveal that a single braid bar

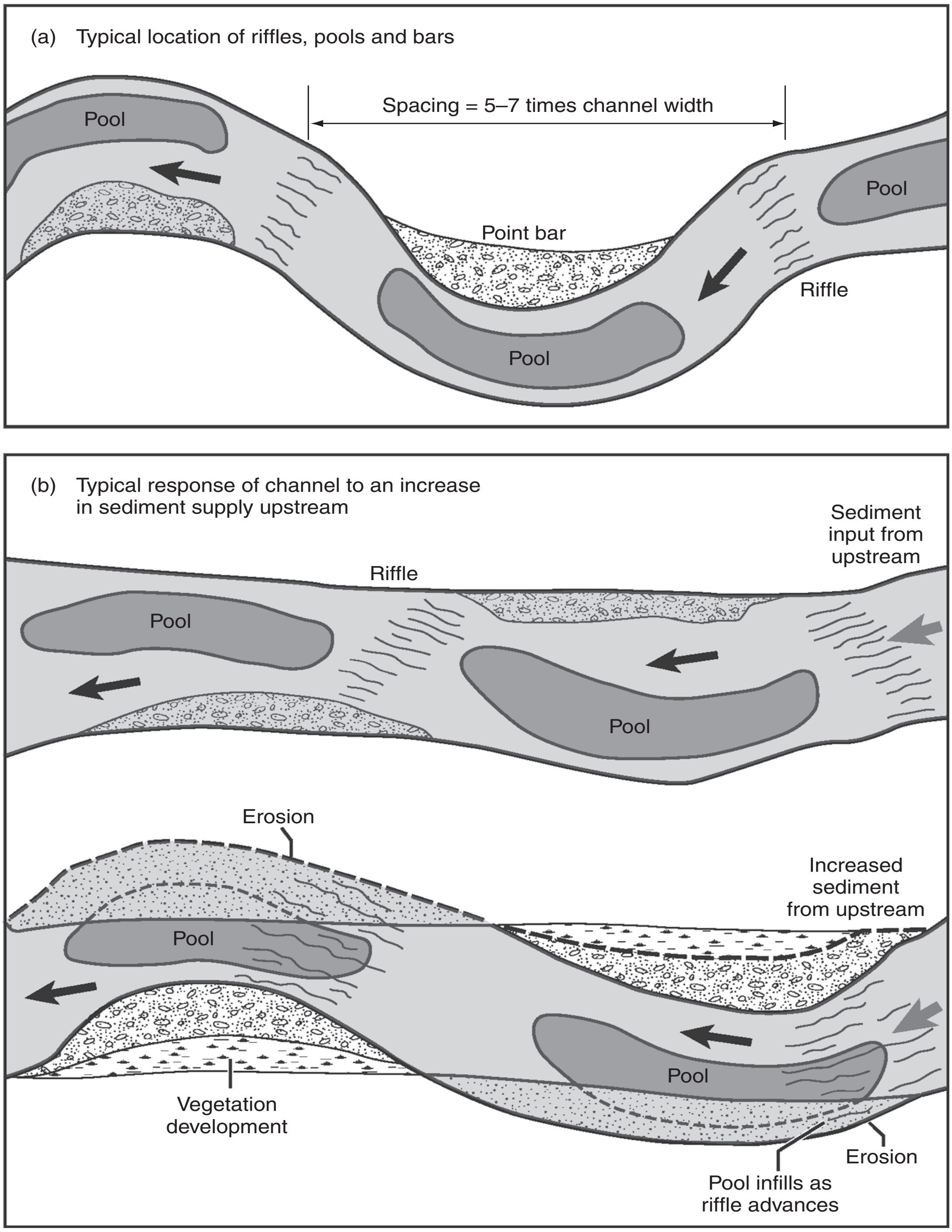

Fig. 3.9 Contemporary erosion and sedimentation in the middle course associated with: (a) sediment exchange and lateral channel shifting; (b) an increase in sediment supply

corresponds more closely to not one but three meander bends, with the first bend eroding the bar head, the second driving retreat of the outer bank and bar growth in the mid-bar region, and the third leading to converging flow and redistribution of eroded sediment at the bar tail (Fig. 3.12).

In the lower course of large rivers, deposition is usually dominated by fine sediments (sands, silts and clays) and channel bed features are often less prominent, in terms of the quantity of material deposited and the impact on channel

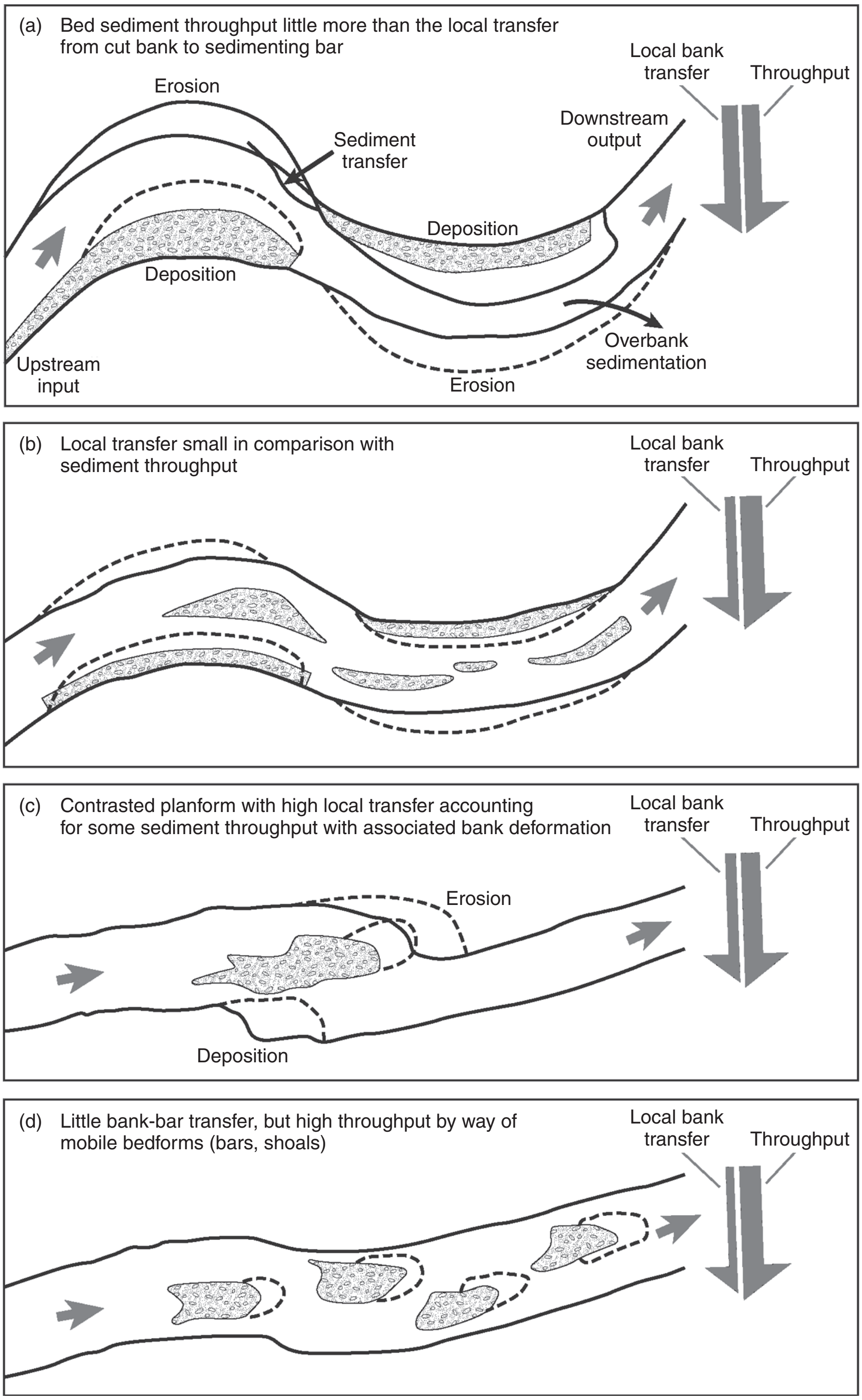

Fig. 3.10 Dynamic response in the sediment exchange system to changes in the balance between bank transfer and throughput loads

morphology, compared to those associated with marginal and overbank accretion. However, a significant exception to this general rule occurs where the riparian corridor has been destroyed and/or the channel is disconnected from its floodplain by, for example, flood defence embankments. Under these circumstances the

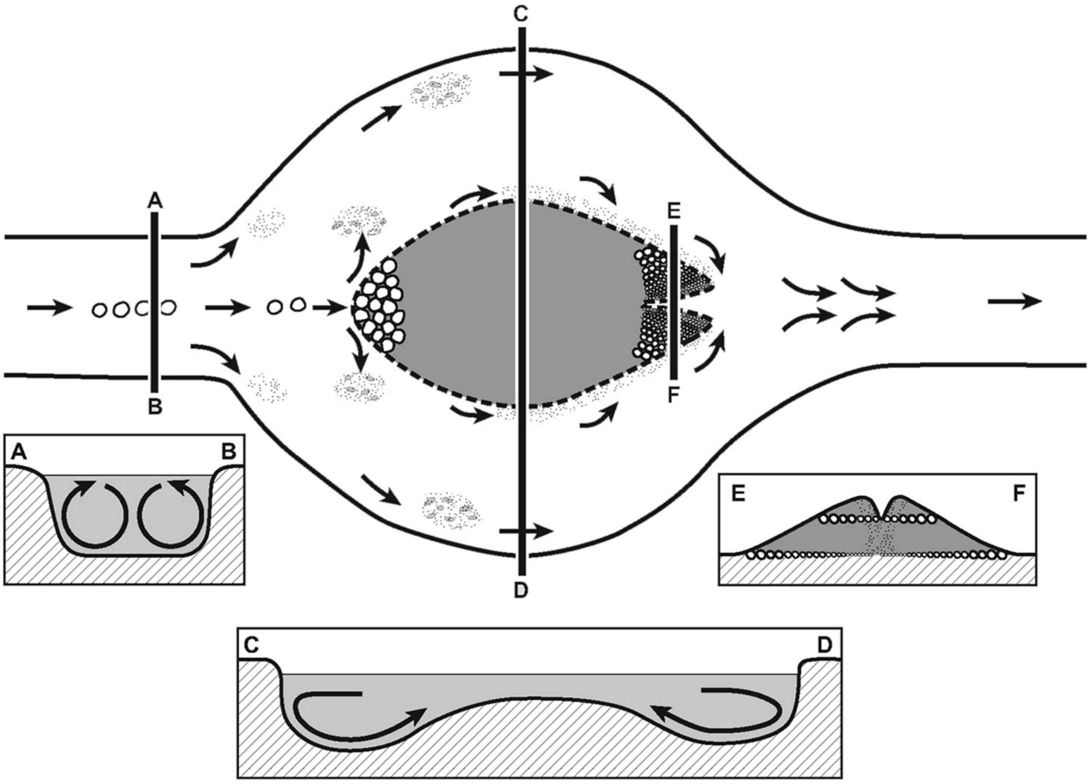

Fig. 3.11 Conceptualisation of flow around a braid bar as 'back-to-back meanders'. Modified, with permission, from Ashworth and Ferguson, 1992. © 1992 John Wiley & Sons Limited

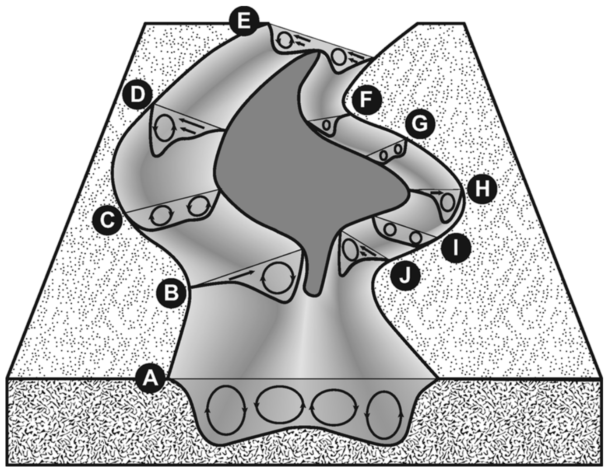

Fig. 3.12 Observed channel cross-sections and secondary flow cells around a braid bar in the Jamuna River, Bangladesh. Modified, with permission, from Richardson, 1997. © 1997 Roy Richardson

possibility for marginal and overbank storage is denied to the river and the deposition of fine sediments is restricted to the channel alone, producing exaggerated rates of sedimentation and prominent in-channel sediment features.

3.2.4.3 *Channel margin and floodplain deposition*

The capacity of the flow to carry sediment varies with approximately the sixth power of velocity. Hence, slowing down the flow even a little may produce a large reduction in its ability to transport sediment. Whether this actually leads to the deposition of material depends mainly whether or not flow is sediment-laden prior to its deceleration.

In rivers during in-bank flows, marked reductions in velocity occur at the channel margins, particularly in zones where the flow stalls or separates from the bankline – often termed areas of dead or slack water. It is therefore to be expected that in channels which are dynamically stable but posses areas of low or negative velocity, part of the fine sediment load is deposited to form 'slack water deposits'.

Characteristic locations for these deposits in sinuous rivers are at the inner bank of meander bends downstream of the bend apex (where main flow separates and recirculates) (Leeder and Bridges, 1975), and at the outer bank of very tight meander bends just upstream of the bend apex (where flow impinging against the outer bank forms a recirculating eddy) (Reid, 1984).

Marginal deposition is also a characteristic of morphological adjustment in channels that are over-wide. Slow velocities in the near-bank zones of excessively wide channels allow accumulation of debris derived from bank failures together with deposition of finer material in the sediment load to form a longitudinal sediment feature termed a *berm* or *bench*. Berm accretion represents a form of bank advance, particularly if colonisation of fresh deposits by vegetation increases bank roughness to further retard sediment-laden flows at the channel margin and accelerate channel narrowing (Schumm *et al.*, 1984).

During significant floods, the channel banks are overtopped and flow in the channel interacts with water stored or flowing on the floodplain. Research in flumes and observations in channels with complex cross-sections has revealed that large quantities of momentum are exchanged between channel and floodplain portions of flood flows, with vigorous mixing at the channel–floodplain interface.

While the details of flow structures and turbulent velocity fields are extremely complex – especially when flow in sinuous or meandering channels interacts with flow along a relatively straight floodplain (Wormleaton *et al.*, 2005) – the outcome is generally to generate complex flow fields with strong secondary currents that concentrate overbank deposition close to the banklines (Ervine *et al.*, 2000). While sedimentation also occurs on the floodplain remote from the channel due to the export of suspended load that accompanies the export of water and momentum, deposition decreases exponentially, both in terms of particle size and quantity, with distance from the bank edge (Pizzuto, 1987). Through time, the result of overbank deposition is to build up the elevation of the floodplain unevenly, with higher ground levels close to the channel forming *natural levees* formed in thicker layers of coarser sediments (Brierley *et al.*, 1997) and lower, backswamp areas in flood basins that are more remote from the river (Anderson *et al.*, 1998).

Innovative research using radioisotopes deposited during atmospheric testing of nuclear weapons in the 1950s and 1960s has established that recent and contemporary rates of floodplain deposition in the UK are not negligible. Typically, floodplain elevations in the south-west of England are increasing at average annual rates of 3–9 mm/year due to deposition of fine sediment derived primarily from catchment and bank erosion sources (Nicholas *et al.*, 2006). Taken over, for example, 50 years, this could raise the land surface around the channel by nearly half a metre – with obvious implications for floodwater elevations and risks to floodplain properties and infrastructure.

In other parts of the world, deposition rates are much higher. For example, field measurements made during the 2007 monsoon flood of the Jamuna River, Bangladesh made as part of doctoral research at Nottingham University revealed that this large event deposited an average of 4.6 cm of fresh sediment over the study area, ranging from more than 7 cm on the natural levee adjacent to the river to less than 2 cm in the backswamps (Islam, 2008). However, deposition within the system of distributary channels crossing the floodplain could be much greater, exceeding a metre in places. These observations attest to the dynamic and complex nature of contemporary floodplain sedimentation.

3.3 The sediment transfer system

3.3.1 Connectivity and breaks in the sediment system

Sediment being transported at a particular location in the river system may have arrived from a variety of sources and travelled via several different pathways over a range of time spans. Chapter 2 described in detail how the sediment transfer system comprises a series of sources, transfer links and stores extending throughout the drainage network. Consequently, changes to the catchment sediment yield or the stability of a reach midway between the headwaters and the sea may have marked ‘knock-on’ effects that are broadcast throughout the fluvial system through changes to processes and rates of sediment transfer and exchange. Impacts are transmitted downstream through either elevated or reduced sediment transfer that leads to enhanced sedimentation or sediment starvation, respectively. Impacts are transmitted upstream through adjustments to the channel slope (knick point migration or progressive slope reduction) and planform (changes in sinuosity or planform metamorphosis between straight, meandering, braided or anastomosed patterns) (Schumm, 1977; Schumm *et al.*, 1984; Simon and Thorne, 1996).

However, a change in catchment sediment yield or an episode of reach-scale instability does not necessarily trigger discernible morphological responses throughout the fluvial system. The intensity of morphological response tends to decrease rapidly with distance from the point of disturbance unless local factors act to perpetuate or amplify the impact or make the channel particularly sensitive (responsive) to destabilisation (Darby and Simon, 1999).

In fact, the fluvial systems of many British rivers are punctuated by natural and/or artificial controls that suppress or even prevent system-scale morphological changes. For example, bedrock outcrops, non-erodible substrate sediments (that is, those that are very coarse or strongly cohesive), and the inverts of weirs, culverts and bridge aprons all provide local base levels that prevent knick points from migrating past them and so limit the extent of bed level adjustments. Similarly, the sediment transfer system may be fragmented by sediment trapping at intermediate points along pathways linking the headwaters to the sea, or may be suppressed by dredging and de-silting that robs the fluvial system of its sediment. Typical breaks in the sediment transfer system include natural lakes and artificially constructed reservoirs, weir pools, sediment traps and heavily maintained flood defence channels with enlarged channel cross-sections.

It is vital to understand both connectivity and fragmentation of sediment transfer pathways when characterising the fluvial system, predicting system response to catchment change or selecting appropriate measures to deal with sediment-related problems. Only on the basis of a sound understanding of connectivity and fragmentation can sediment pathways between sources and storage areas be accurately identified. It is the ability to recognise the causal link between, for example, a lowland sedimentation problem and enhanced sediment production in an unstable, headwater stream that underpins the geomorphic approach to river management.

The insight necessary to apply geomorphological principles to real-world problems demands a thorough understanding of fluvial systems that possess rich histories of morphological change, punctuated sediment transfer systems and complex patterns of sediment erosion, transport and deposition. While the pace of change may at times be slow or imperceptible, the fluvial system *is* ever changing and recognition of the reality of channel adjustment and evolution is, in terms of developing sustainable goals for river management, the first step in applying geomorphological insights and approaches.

3.3.2 Timescales of channel adjustment and channel evolution

In the past, policy, planning, and operational horizons in river engineering and management were generally limited to project and budgetary timescales. The practice of discounting future costs and benefits effectively prevents adoption of longer-term strategies as the current values of the future financial impacts or benefits of a scheme or management strategy are discounted to practically zero over periods of a decade or two. Adoption of new approaches related to whole-life costs and sustainability has extended these horizons towards longer-term management goals and engineering solutions that recognise and accommodate channel evolution and adjustments in the river system. This requires appreciation of the dynamic nature of channel forms and processes and the potential for the river to change through time, either as a result of natural evolution or in response to climate change, altered catchment characteristics, engineering interventions for capital works or operational maintenance activities, at a variety of space- and timescales.

In this context, space- and timescales are linked in that the timescale for local cross-sectional adjustment triggered by a bank protection scheme is short, while meander planform response to a change of catchment land-use may take decades or centuries to be completed (see Fig. 1.4). At the millennium timescale, the long profile of the entire river system is evolving as basin topography is altered by changes to climate-driven weathering and erosion in the headwaters and deposition in the lowlands. Beyond this, over geological time, British rivers are known to be responding to eustatic (ice unloading) and relative sea-level changes associated with the end of the last ice age about 12 000 years ago.

The long timescales required for catchment-scale and system-wide adjustments mean that, once initiated, significant channel changes may continue long after the triggering event. It is, therefore, seldom possible to find the causes of contemporary change and instability in a river through inspection of the natural and anthropogenic phenomena that can be observed today. Consequently, a historical element is essential to any geomorphological investigation and explanation, with information obtained from historical maps, archives, remote sensing and narrative accounts of past events and channel forms. In the UK, the record of catchment and river development stretches back for over 1500 years and human occupancy of the landscape much longer than that. It is, therefore, vital to appreciate the extent to which contemporary channels are products of the rich tapestry of human artifice as well as natural processes. In this regard, Fig. 3.13 highlights some landmark periods in the long history of channel management in the UK.

While the accuracy of historical data may often be questioned and much of the information available is qualitative, the longer-term perspective gained from historical studies is crucial to the application of sustainable management approaches and engineering solutions that seek to cure the underlying and historical causes of current channel problems, rather than just treating currently observable symptoms.

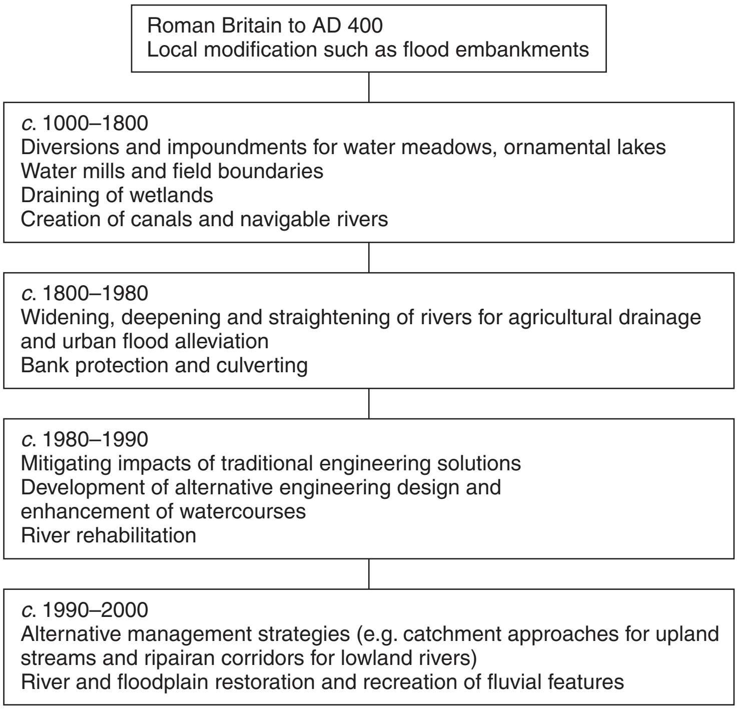

Fig. 3.13 Landmark periods in the history of channel management in the UK

3.3.3 *Extreme events*

There is a body of evidence obtained from long-term measurement and monitoring of fluvial processes which demonstrates that the dimensions and geometry of alluvial (self-formed) channels adjust to fluvial processes operating under a range of flows with low to moderate return periods (Knighton, 1998; Richards, 2004). It is generally accepted that the *dominant* or *channel forming* flow for a dynamically stable channel approximates to the bankfull discharge and has a return interval of 1 to 3 years in the annual maximum series (Soar *et al.*, 1999; Thorne *et al.*, 1999) although wide variations occur in nature and the return period alone does not provide an adequate basis on which to define the channel forming flow (Soar and Thorne, 2001). Notwithstanding this, extreme events of high magnitude but long return period certainly have significant and lasting impacts on the fluvial system (Macklin and Lewin, 2003). For example, an extremely large flood may alter channel form and floodplain topography directly through driving morphological changes that would not occur under lesser flows, while exceptional precipitation may destabilise slopes in headwater catchments (Reid *et al.*, 2008) to elevate catchment sediment supply not only during the event but for decades afterwards (Harvey, 2007).

For example, a geomorphological study of Shelf Brook, Derbyshire (National Rivers Authority, 1994a, 1994b, 1994c) illustrates the impact of extreme events vividly. A major flood alleviation scheme on Glossop Brook required frequent maintenance to prevent gravel shoaling. To mitigate the problem, gravel traps were proposed as a way of intercepting coarse bedload supplied by erosion in the Shelf Brook and Longclough Brook catchments. Archive and historical investigations established the importance of major flood events during the period 1930–1944 in disturbing the landscape (through landslides, slope erosion and channel instability) and so establishing copious sources of sediment supply to the fluvial system. This historical information was updated by ‘ground-truthing’ using field reconnaissance, to produce a map of sediment sources and sinks in Shelf Brook

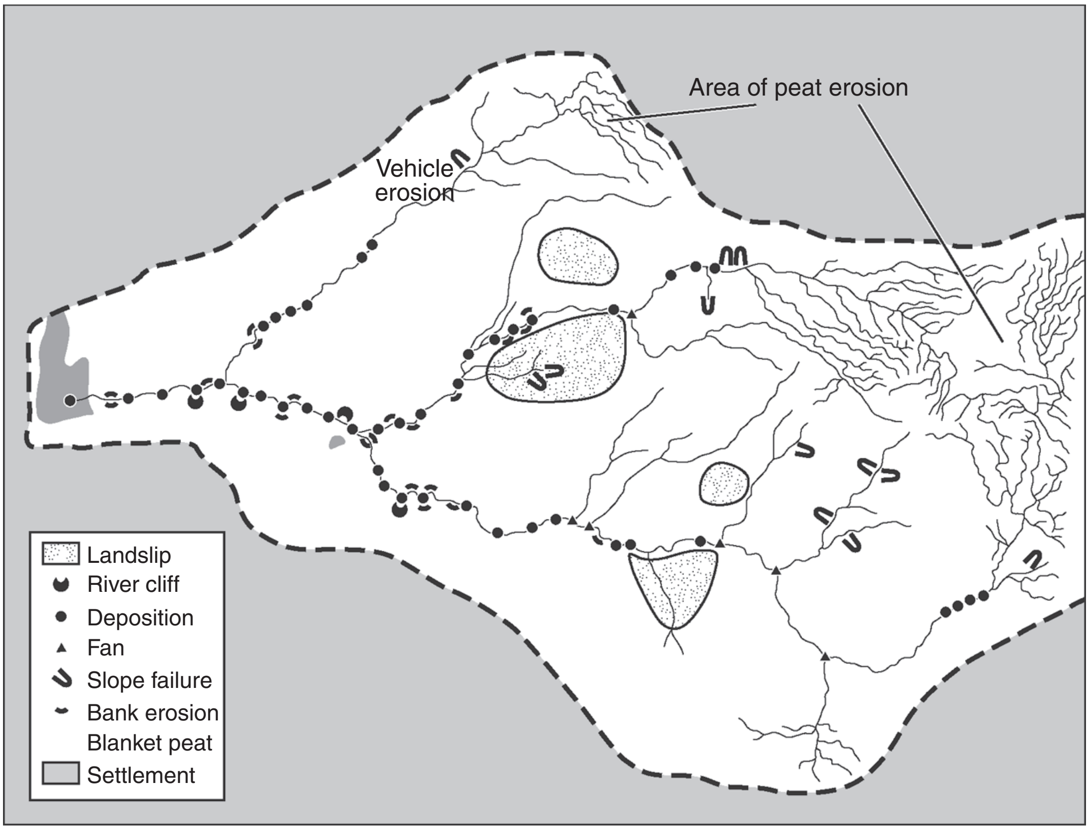

Fig. 3.14 Sediment sources and sinks in Shelf Brook, Derbyshire

(Fig. 3.14). The map, in turn, provided the basis for effective positioning of sediment traps that recognised the roles of both contemporary processes and the historic legacy of past extreme events, in conditioning the sediment transfer system. The Shelf Brook gravel traps have worked efficiently, although an incident in 2002 illustrates the need for regular maintenance. During summer of 2002 the traps had been allowed to overfill when a flooding event (*circa* 50 properties in Glossop) occurred.

3.4 System response to natural change and human impacts

3.4.1 Overview

The stability status and pattern of adjustment in the river system depend on changes in the driving variables of discharge regime and sediment yield. It is important to understand that the catchment and drainage channel network constitute a connected system in order to relate changes to natural processes and human activities in one part of the river basin to morphological responses in another. For example, Fig. 3.15 illustrates schematically how a wide variety of catchment and river activities may impact sediment transfer system to elicit morphological responses elsewhere in the river.

Understanding the dependence of channel form and process on catchment and upstream channel conditions and activities is vital to identifying and explaining causal factors responsible for morphological and sediment-related problems. For example, overgrazing in a headwater catchment can lead to increased surface runoff, soil deterioration and an elevated sediment yield (Henshaw, 2009). More quick-flow runoff from the hillsides due to soil compaction and reduced infiltration

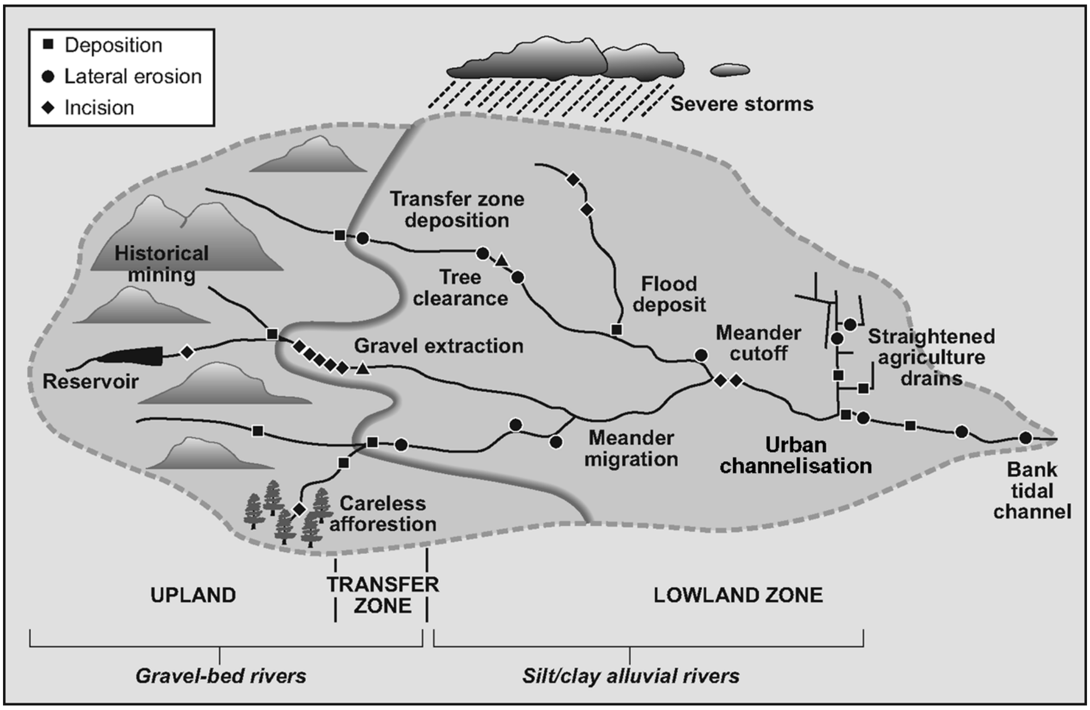

Fig. 3.15 Natural and anthropogenic catchment and river processes affecting sediment dynamics

increases peak discharges. It also increases the sediment input to headwater streams and elevates sediment loads supplied to the middle and lower courses to promote shoaling and accelerate rates of lateral shifting. Taken together, increased peak discharges, heavier sediment loads and associated channel adjustments usually increase the likelihood of flooding in the middle course, with serious implications for floodplain dwellers and users (Henshaw, 2009).

In this context, geomorphology can make a difference to practically all management functions through:

- Providing understanding of the factors that contribute to the stability of natural river channels (e.g. highlighting the importance of riffles, bars and islands acting as orderly stores of sediment in dynamically stable channels).
- Anticipating the environmental impacts of particular management decisions (e.g. downstream channel response to impounding flow and trapping sediment in a reservoir).
- Developing stable designs for flood defence, capital, maintenance and conservation projects (e.g. placement of gravel riffles that will not wash out during floods or become smothered by fine-grained deposition).
- Designing sustainable river restoration projects that possess the range of geomorphological features expected in an equivalent natural channel (e.g. pools, riffles, morphological variability, cross-sectional asymmetry).

3.4.2 *Catchment land-use change*

Channel morphology is sensitive to changes in the rainfall–runoff relationship and the catchment sediment yield that results from environmental change. The spatial distribution, rate of response and degree of morphological change triggered by a given catchment change are all system specific, but qualitative patterns of

Table 3.14 Qualitative predictors of morphological response to catchment change (modified from Schumm, 1977)

Increase in runoff alone, e.g. increased precipitation $Q^+ \sim w^+d^+F^+L^+S^-$	Decrease in runoff, e.g. reduced precipitation $Q^- \sim w^-d^-F^-L^-S^+$
Increase in catchment sediment yield alone, e.g. construction/overgrazing $Q_s^+ \sim w^+d^-F^+L^+S^+P^-$	Decrease in catchment sediment yield, e.g. soil conservation/reduced arable $Q_s^- \sim w^-d^+F^-L^-S^-P^+$
Both increase, e.g. afforestation/increased storminess $Q^+Q_s^+ \sim w^+d^{-/+}F^-L^-S^{-/+}P^+$	Both decrease, e.g. downstream of a reservoir $Q^-Q_s^- \sim w^-d^{-/+}F^-L^-S^{-/+}P^+$
Runoff increases and sediment yield decreases, e.g. urbanisation (after construction) $Q^+Q_s^- \sim w^{-/+}d^+F^-L^{-/+}S^-P^+$	Runoff decreases and sediment yield increases, e.g. water abstraction/reduced precipitation $Q^-Q_s^+ \sim w^{-/+}d^-F^+L^{-/+}S^+P^-$
Q = runoff Q_s = sediment yield W = width D = depth	F = width/depth ratio L = meander wavelength S = channel slope P = sinuosity

morphological response have been established through empirical studies (Table 3.14).

3.4.3 *River engineering*

River engineering, in the form of capital works and operational maintenance, is undertaken in order to solve problems related to flood defence, land drainage, navigation and channel instability that threaten infrastructure or flood defence assets. Although the precision of some of the data listed is no longer reliable due to changes in policy during the 1990s, the scale of river engineering and maintenance activities may be gauged from figures reported in the early 1990s (Table 3.15).

Many engineering interventions in the form of channel maintenance activities are designed specifically to mitigate problems associated with sediment and in this context Table 3.16 lists and defines some common sediment-related maintenance practices.

In the last three decades, evidence has accrued concerning the impacts of river engineering works on fluvial sediment transfer systems and the morphological adjustments of channels resulting from these impacts. The message that emerges is that local maintenance, such as that involving repeated gravel extraction, may trigger morphological responses and patterns of channel instability similar to those caused by larger-scale changes in climate and catchment sediment delivery processes (Wishart *et al.*, 2008). While recognising that river maintenance may be essential where this is necessary in terms of public safety, this finding does question the exent to which maintenance can ever be truly sustainable and it suggests that the

Table 3.15 Scale of engineering and maintenance activities in rivers in England and Wales

35 000	km of main river requiring periodic maintenance
17 450	km of main river maintained on average annually by the Environment Agency
27 000	km of channel maintained by Internal Drainage Boards (IDBs)
100 000	km of watercourses maintained by private landowners within IDB areas
7 850	km of channelisation along main rivers
2 400	km of bank protection on non-navigable rivers
1 025	km of sediment-related maintenance recorded in a 1991 R&D survey

Table 3.16 Engineering and maintenance procedures adopted to mitigate problems associated with sediment

Procedure	Description
Erosion control	Construction or reinstatement of measures to prevent bed scour and/or bank erosion where flood defence or land drainage assets are threatened
Gravel trap	Construction or cleaning out of structure designed to catch the coarse fraction of the sediment load and prevent sediment transfer to a flood control project downstream
Realignment	Relocating and straightening the channel to increase conveyance capacity and/or facilitate development of the floodplain. Usually accompanied by regrading and resectioning
Regrade	Large-scale (often grant-aided capital works) modification of channel slope and long-profile based on regime theory or one-dimensional hydraulic modelling (e.g. HEC-RAS)
Resection	Imposing or returning channel cross-section to design configuration, including reprofiling bed and banks. Usually based on regime theory or one-dimensional hydraulic modelling
Dredge	Removal of sediment that has accumulated in the channel to a degree that is considered (by Environment Agency staff and local stakeholders) to compromise flood defence or land drainage functions of the channel
De-silt	Removal of sediment (usually silt) that has accumulated in the channel within the last three years (often performed in conjunction with aquatic weed clearance)
Shoal removal	Removal of individual shoals (usually formed by gravel) where these are considered to compromise the flood control function of the channel

true costs and system-wide impacts of, for example, sediment removal for flood defence may have been underestimated (Lane and Thorne, 2008).

Historically, realignment has been a widespread channel improvement practice Initially, channels were straightened to form straight field boundaries and improve agricultural drainage (Brookes, 1988). More recently, the primary aim of realignment has been to improve flood conveyance and facilitate floodplain development. However, long-term impacts on the fluvial system locally and through upstream slope adjustment and downstream sediment transmission may be unfavourable. Locally, increased slope and reduced energy losses promote increased sediment transport. As local transport capacity exceeds the supply from upstream, the bed is scoured (degradation) to make up the difference (Lane, 1937). Bed lowering may lead to over-steepening of the banks, and serious bank retreat (widening) (Thorne, 1982). Through time, scouring leads to incision that progresses upstream as a knick point, to destabilise reaches upstream of the straightened reach. The excess sediment load produced by bed scour and channel widening is transmitted downstream where it is deposited to drive siltation that may destabilise the channel downstream (Lane, 1955; Schumm *et al.*, 1984; Simon and Hupp, 1986). Table 3.17 summarises the geomorphological impacts of channel straightening.

Table 3.17 Potential impacts of channel straightening

Upstream impacts	Local impacts	Downstream impacts
Nick-point migration	Steeper slope	Increased sediment input
Steeper slope	Reduced energy losses	In-channel deposition
Higher velocities	Higher velocities	Shoal and bar building
Increased sediment transport capacity	Increased sediment transport capacity	Aggradation
Bed scour	Bed scour	Reduced conveyance
Bank instability	Bank instability	Increased flood risk

Capital works may also impact the sediment system in a variety of ways, with implications for engineering performance, maintenance requirements, and geomorphological stability throughout the fluvial system, as well as in the project reach. These implications bear directly on the whole-life costs and sustainability of any river engineering scheme (National Rivers Authority, 1993).

Channel changes triggered in response to realignment and straightening in turn impact the river environment in general and in-stream and riparian habitats in particular. For example, bed scour destroys benthic habitats and washes out aquatic plants, while aggradation can smother spawning gravels and reduce pool-riffle variability. Even subtle changes at the bed, such as apparently minor changes in the particle size distribution or the ingress of fines into a cobble substrate, can have deleterious effects on the hyporheic zone, with catastrophic impacts on spawning redds and invertebrate habitats (Kondolf and Wolman, 1993; Lisle, 1989). Similarly, reach-scale bank retreat leads to destruction of the riparian corridor, with multiple detrimental effects on bank stability, ecology and aesthetics, and potentially damaging above- and below-ground impacts throughout the floodplain.

An example of wide-scale bank response to channel engineering may be drawn from capital works performed on the River Sence between 1973 and 1985 (NRA, 1994b; Newson and Sear, 1997). Extensive bank instability was reported in the engineered reaches immediately following the works, which had involved regrading and resectioning that produced high and steep banks surcharged by spoil taken from the channel (Fig. 3.16).

Following construction, erosion of the lower half of the bank profile occurred due to enhanced flow erosivity and decreased bank erosion resistance associated both with vegetation removal and the undetected presence of a weak sand layer low in the bank that was exposed by resectioning.

Erosion then brought the banks to a condition of limiting stability with respect to mass failure, with wet conditions subsequently triggering significant bank retreat through slumping. Further cycles of flow scour and slumping occurred for the next

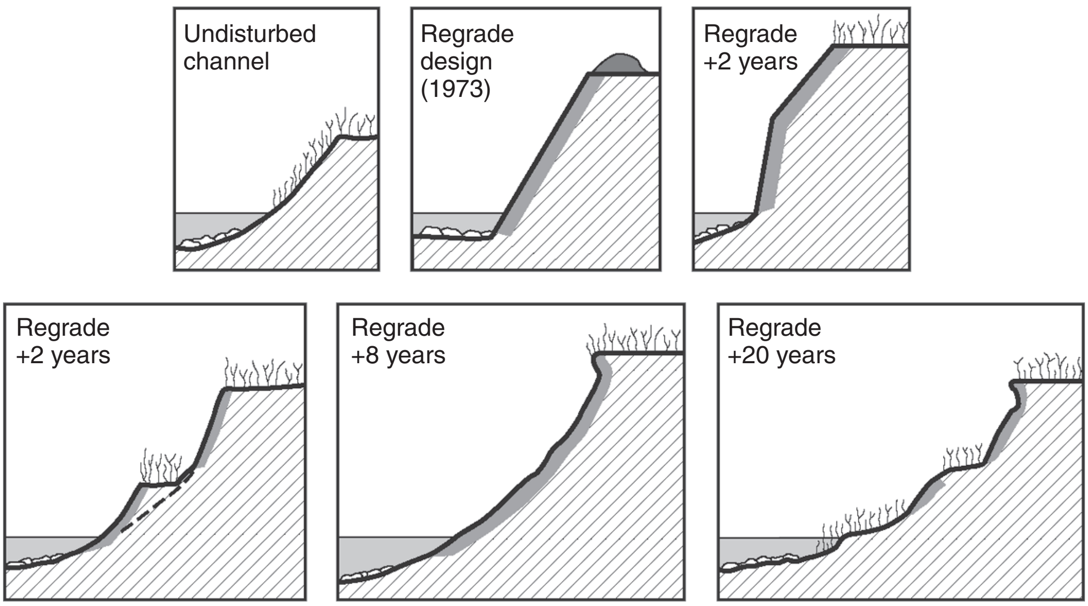

Fig. 3.16 Indicative bank profiles from an engineered reach of the River Sence, Leicestershire between 1973 and 1985. Modified, with permission, from Sear et al., *1995. © 1995 John Wiley & Sons Limited*

Table 3.18 Potential sediment impacts and morphological responses to engineering and possible geomorphological solutions

Engineering option	Impact on sediment system	Channel response W	D	S	D_{50}	C	Timescale	Possible solution
Straightening	Upstream: $T > Q_s = E$	+	+	+	+	+	After first transporting flood.	Upstream bed check weirs. Reinstate riffle/pool sequence, put shallow trap below straightened reach. Extend downstream floodway
	Downstream: $Q_s > T = D$	+	−	−	−	−	<1 to >50 years	
Dredging to grade	Upstream: $T > Q_s = E$	+	+	+	+	+	After first transporting flood	Upstream bed check weirs and gravel trap to prevent siltation. Plant trees on banks. Extend downstream floodway to allow meandering
	At site: $Q_s > T = D$	+	+	−	±	±	<1 to >50 years	
	Downstream: $T > Q_s = E$	+	+	+	+	+		
Shoal removal	Downstream: $T > Q_s = E$	+	+	+	+	+	After first transporting flood and +100 years	Accommodate shoals by extending floodway or two-stage channel
Weir removal	Upstream: $T > Q_s = E$	+	+	+	+	+	After first transporting flood.	Bed check weirs in blockstone. Sheet piling in upstream reaches. Downstream dredging or increased floodway
	Downstream: $Q_s > T = D$	+	−	−	−	−	<1 to >50 years	
Widening	Upstream: no change	nc	−	−	nc	nc	Siltation after first flood until channel recovers former size	Two-stage channel or upstream sediment trap and disposal of dredge spoil below over-wide reach
	At site: $Q_s > T = D$	−	+	−	−	−		
Gravel trap	Upstream: $T > Q_s = E$	+	+	+	+	+	After first transporting flood.	Do not overdig gravel trap. Protect upstream end with bed check weirs. Site trap at riffle. Underpin downstream lip. Do not site upstream of structures
	Downstream: $T > Q_s = E$	+	+	+	+	+	<1 to >50 years	
Bank protection	Downstream: $T > Q_s = E$	+	+	+	?	?	<1 year up to +20 years	Loosen opposite point bar to promote erosion and increase sediment supply downstream. Control upstream cause of erosion
Two-stage channel	At site: $T > Q_s = E$	+	nc	nc	?	?	After first flood	Protect berm margins in high stream power rivers. De-silt berms in rivers with high fine load. Reinstate pools, riffles and meanders

w = channel width; Q_s = sediment supply; D = channel depth; T = sediment transport; S = channel slope; E = erosion; D_{50} = median bed size; D = deposition; nc = no change; C = bed compaction six years, with bank conditions being further degraded by desiccation of exposed soil and poaching of low-angle bank profiles due to uncontrolled livestock access. Eventually, after 20 years of instability, the banks stabilised themselves through accumulation of slump debris on the lower bank. This occurred because the channel had over-widened to the extent that near-bank flows were no longer capable of removing failed material from the bank toe, illustrating the controlling influence of basal endpoint control on long-term bank retreat. However, by then bank erosion and failure had supplied literally hundreds of cubic metres of sediment per year to the River Sence which, in turn, generated deposition and further channel instability downstream in the fluvial system (Thorne and Easton, 1994).

In practice, during the mid- to late-twentieth century, the effects of system and morphological response to engineering were largely suppressed by heavy and frequent maintenance that allowed schemes to operate despite being out of synch with natural processes sediment supply, transport and deposition. However, during the 1990s, maintenance levels decreased due to reduced staffing levels, a drive for economic efficiency and the move to contracting work out. Reductions in maintenance, together with the fact that many schemes constructed in the mid-twentieth century were approaching the end of their useful lives, led to the introduction of geomorphological studies, performed to identify more sustainable solutions and to pilot schemes designed to investigate the feasibility of new management approaches.

Examples drawn from a variety of Environment Agency R&D projects are listed in Table 3.18 to illustrate the potential impacts of engineering activities and suggest how alternative options to heavy maintenance may be invoked to redress imbalances in the sediment transfer system.

References

Ackers, P. and White, W.R. (1973) Sediment transport: new approach and analysis. *Journal of the Hydraulic Division, American Society of Civil Engineers*, **99**, 2041–2060.

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment (1998a) River width adjustment. I: Processes and mechanisms. *Journal of Hydraulic Engineering*, **124**(9), 881–902.

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment (1998b) River width adjustment. II: Modeling. *Journal of Hydraulic Engineering*, **124**(9), 903–917.

Anderson, M.G., Walling, D.E. and Bates, P.D. (1998) *Floodplain processes*. Wiley, Chichester.

Andrews, E.D. and Parker, G. (1987) Formation of a coarse surface layer as the response to gravel mobility. In Thorne, C.R., Bathurst, J.C. and Hey, R.D. (eds) *Sediment transport in gravel-bed rivers*. Wiley, Chichester, pp. 269–300.

Ashworth, P.J., Ferguson, R.I. and Powell, M.D. (1992) Bedload transport and sorting in braided channels. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (eds) *Dynamics of gravel-bed rivers*. Wiley, Chichester, pp. 497–513.

Aslan, A., Autin, W.J. and Blum, M.D. (2005) Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi river, USA. *Journal of Sedimentary Research*, **75**(4), 650–664.

Bagnold, R.A. (1966) *An approach to the sediment transport problem from general physics*. US Geological Survey, Professional Paper 422-I, Reston, VA.

Bagnold, R.A. (1980) An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences*, **372**(1751), 453–473.

Ballantyne, C.K. (2002) Paraglacial geomorphology. *Quaternary Science Reviews*, **21**(18), 1935–2017.

Bathurst, J.C., Graf, W.H. and Cao, H.H. (1987) *Bedload discharge equations for steep mountain rivers in sediment transport in gravel-bed rivers*, (eds), Thorne, C.R., Hey, R.D. and Bathurst, J.C., Wiley, Chichester, 433–477.

Bathurst, J.C., Thorne, C.R. and Hey, R.D. (1977) Direct measurements of secondary currents in river bends. *Nature*, **269**, 504–506.

Bathurst, J.C., Thorne, C.R. and Hey, R.D. (1979) Secondary flow and shear stress at river bends. *Journal of the Hydraulics Division, ASCE*, **10**, 1277–1295, and Discussion **106**, 1710–1713 and Closure, **107**, 644–647.

Biedenharn, D.S., Hubbard, L.C., Thorne, C.R. and Watson, C.C. (2006a) *Understanding sediment sources, pathways and sinks in regional sediment management: wash load and bed-material load concept*. US Army Engineer Research and Development Center, Vicksburg, MS, Report ERDC TNSWWRP-06-3.

Biedenharn, D.S., Hubbard, L.J., Thorne, C.R. and Watson, C.C. (2006b) *Understanding sediment sources, pathways, and sinks in regional sediment management: application of wash load and bed-material load concept*. US Army Engineer Research and Development Center, Vicksburg, MS, Report ERDC TN-SWWRP-06-4. Available at: http://libweb.wes.army.mil/uhtbin/hyperion/TN-SWWRP-06-4.pdf.

Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (1992) *Dynamics of gravel-bed rivers*. Wiley, Chichester.

Blondeaux, P. and Seminara, G. (1985) A unified bar–bend theory of river meanders. *Journal of Fluid Mechanics*, **157**, 449–470.

Bluck, B.J. (1982) Texture of gravel bars in braided streams. In Hey, R.D., Bathurst, J.C. and Thorne, C.R. (eds) *Gravel-bed rivers, fluvial processes, engineering and management*. Wiley, Chichester.

Boardman, J., Poeson, J. and Evans, R. (2003) *Environmental Science Policy*, **6**, 1–6.

Bridge, J.S. (2003) *Rivers and floodplains: forms, processes, and sedimentary record*. Blackwell, London.

Brierley, G.J., Ferguson, R.J. and Woolfe, K.J. (1997) What is a fluvial levee? *Sedimentary Geology*, **114**(1–4), 1–9.

Brookes, A. (1988) *River channelization: perspectives for environmental management*. Wiley, Chichester.

Carling, P.A. (1984) Deposition of the fine and coarse sand in an open-work gravel-bed, *Canadian Journal of Fisheries and Aquatic Science*, **41**(2), 263–270.

Carling, P. (1989) Hydrodynamic models of boulder berm deposition. *Geomorphology*, **2**, 319–340.

Church, M. and Jones, D. (1982) Channel bars in gravel-bed rivers. In Hey, R.D., Bathurst, J.C. and Thorne, C.R. (eds) *Gravel-bed rivers*. Wiley, Chichester, pp. 291–338.

Cluer, B. (2004) *Sediment removal from freshwater salmonid habitat: guidelines to NOAA fisheries staff for the evaluation of sediment removal actions from California streams*. NOAA Fisheries, Southwest Region, Santa Rosa, CA.

Coulthard, T., Lewin, J. and Macklin, M.G. (2005) Modelling differential catchment response to environmental change. *Geomorphology*, **69**(1–4), pp. 222–241.

Cudden, J.R and Hoey, T.B. (2003) The causes of bedload pulses in a gravel channel: the implications of bedload grain-size distributions. *Earth Surface Processes and Landforms*, **28**(13), 1411–1428.

Cui, Y., Parker, G., Lisle, T.E., Gott, J., Hansler-Ball, M.E., Pizzuto, J.E., Allmendinger, N.E. and Reed, J.M. (2003) Sediment pulses in mountain rivers. *Water Resources Research*, **39**(9), 1239–1251.

Darby, S.E. and Simon, A. (eds) (1999) *Incised river channels*. Wiley, Chichester.

Dietrich, W.E. and Smith, J.D. (1983) Influence of the point bar on flow through curved channels. *Water Resources Research*, **19**(5), 1173–1192.

Dietrich, W.E. and Smith, J.D. (1984) Bed load transport in a river meander. *Water Resources Research*, **20**(10), 1355–1380.

Downs, P.W. (1994) Characterisation of river channel adjustments in the Thames basin, southeast England, *Regulated Rivers*, **9**, 151–175.

Downs, P.W. (1995) River channel classification for channel management purposes. In Gurnell, A.M. and Pets, G.E. (eds) *Changing river channels*. John Wiley & Sons, Chichester.

Environment Agency (1998) *Geomorphological approaches to river management*. Environment Agency, Bristol, Project record W5A/i661/1, prepared by Thorne, C.R., Downs, P.W., Newson, M.D., Clarke, M.J. and Sear, D.A.

Environment Agency (2004) *River sediments and habitats and the impact of maintenance operations and capital works*. HR Wallingford, R&D Technical Report FD1920/TR.

Environment Agency (2008) *Channel maintenance*: briefing note 1998469.

Ervine, D.A., Babaeyan-Koopaei, K. and Sellin, R.H.J. (2000) Two-dimensional solution for straight and meandering overbank flows. *Journal of Hydraulic Engineering*, **126**(9), 653–669.

Ferguson, R.I., Hoey, T., Wathen, S. and Werritty, A. (1996) Field evidence for rapid downstream fining of river gravels through selective transport. *Geology*, **24**(2), 179–182.

Goff, J.R. and Ashmore, P. (1994) Gravel transport and morphological change in braided Sunwapta River, Alberta, Canada. *Earth Surface Processes and Landforms*, **19**(3), 195–212.

Gomez, B. (2006) Typology of segregated (armoured/paved) surfaces: some comments. *Earth Surface Processes and Landforms*, **9**(1), 19–24.

Gomez, B. and Church, M. (1989) An assessment of bedload sediment transport formulae for gravel-bed rivers, *Water Resources Research,* **25**, 1161–1186.

Harvey, A.M. (2001) Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *Catena*, **42**(2–4), 225–250.

Harvey, A.M. (2007) Differential recovery from the effects of a 100-year storm: significance of long-term hillslope-channel coupling; Howgill Fells, northwest England. *Geomorphology*, **84**, 192–208.

Hemphill, R.W. and Bramley, M.E. (1989) *Protection of river and canal banks: a guide to selection and design*. Construction Industry Research and Information Association, London.

Henshaw, A. (2009) Impact of land use changes and land management practices on upland catchment sediment dynamics: Pontbien, mid-Wales. Unpublished PhD thesis. University of Nottingham.

Hey, R.D. and Thorne, C.R. (1975) Secondary flows in river channels. *AREA*, **7**, 191–196, and discussion, **8**, 235–236.

Hey, R.D., Bathurst, J.C. and Thorne, C.R. (1982) *Gravel-bed rivers: fluvial processes, engineering and management*. Wiley, Chichester.

Hoey, T.B. and Bluck, B.J. (1999) Identifying the controls over downstream fining of river gravels. *Journal of Sedimentary Research*, **69**(1), 40–50.

Hooke, J.M. (1979) An analysis of the processes of river bank erosion. *Journal of Hydrology*, **42**(1–2), 39–62.

Howard, A.D. and Knutson, T.R. (1984) Sufficient conditions for river meandering: A simulation approach, *Water Resources Research*, **20**, 1659–1667.

HR Wallingford (1990) *Sediment transport: the Ackers–White theory revisited*, Report SR **151**, Wallingford.

HR Wallingford (1992) *Morphological effects of the river improvement works*, Reports SR 151 and SR 300, Wallingford.

HR Wallingford (2008) *River sediments and habitats: impact of maintenance and capital works*. Main Report to the EA/Defra Joint Research Programme under FD1920, HR Wallingford Project No. MCS0839 (June).

Islam, M.N. (2008) Flow and sedimentation on the Jamuna floodplain in Bangladesh. *Proceedings of the BSG Conference*, Exeter, July.

Julien, P.Y. (1998) *Erosion and sedimentation*. Cambridge University Press, Cambridge.

Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B. (1995) *Gravel bed rivers in the environment*. Water Resources Publications, Littleton, Colorado.

Knighton, D. (1998) *Fluvial forms and processes: a new perspective*. Arnold.

Lane, E.W. (1937) Stable channels in erodible material. *Transactions of the American Society of Civil Engineers*, **102**, 123–194.

Lane, E.W. (1955) The importance of fluvial morphology in hydraulic engineering. *Proceedings of American Society of Civil Engineering*, **81**, 1–17.

Lane, S.N. and Thorne, C.R. (2007) River processes. In Thorne, C.R., Evans, E.P. and Penning-Rowsell, E. (eds) *Future flooding and coastal erosion risks*. Thomas Telford, London, pp. 82–99.

Lane, S.N. and Thorne, C.R. (2008) Fluvial systems and processes. In Evans, E.P. *et al*. (eds) *An update of the Foresight Future Flooding 2004 qualitative risk analysis*. Cabinet Office, London, Appendix A.

Lane, S.N., Reid, S.C., Tayefi, V., Yu, D. and Hardy, R.J. (2008) Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse. *Geomorphology*, **98**(3–4), 227–249.

Lane, S.N., Tayefi, T., Reid, S.C., Yu, D. and Hardy, R.J. (2007) Interactions between sediment delivery, channel change, climate change and flood risk and a temperate upland environment. *Earth Surface Processes and Landforms*, **32**, 429–446.

Lawler, D.M. (1992) Process dominance in bank erosion systems. In Carling, P. and Petts, G.E. (eds) *Lowland floodplain rivers: geomorpholgical perspectives*. Wiley, Chichester, pp. 117–143.

Lawler, D.M., Thorne, C.R. and Hooke, J.M. (1997) Bank erosion and instability. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 137–172.

Leeder, M.R. and Bridges, P.H. (1975) Flow separation in meander bends. *Nature*, **253**, 338–339.

Lisle, T.E. (1989) Sediment transport and resulting deposition in spawning gravels, north coastal California. *Water Resources Research*, **25**(6), 1303–1319.

Macklin, M.G. and Lewin, J. (2003) River sediments, great floods and centennial-scale Holocene climate change. *Journal of Quaternary Science*, **18**(2), 101–105.

Markham, A.J. and Thorne, C.R. (1992) Geomorphology of gravel-bed river bends. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. (eds) *Dynamics of gravel-bed rivers*. Wiley, Chichester, pp. 433–456.

Moore, R.J. and Newson, M.D. (1986) Production, storage and output of coarse upland sediments: natural and artificial influences as revealed by research catchment studies. *Journal of the Geological Society*, **143**(6), 921–926.

Mosley, M.P. (2001) *Gravel-bed rivers V*. New Zealand Hydrological Society, Wellington, New Zealand.

National Rivers Authority (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. NRA, Bristol, R&D Note 154, prepared by Hey, R.D. and Heritage, G.L.

National Rivers Authority (1994a) *Sediment and gravel transportation in rivers, including the use of gravel traps*. NRA, Bristol, R&D Project Record C5/384/2, prepared by Sear, D.A. and Newson, M.D.

National Rivers Authority (1994b) *Sediment and gravel transportation in rivers: a geomorphological approach to river maintenance. Policy and implementation recommendations*. NRA, Bristol, R&D Note 315, prepared by Sear, D.A. and Newson, M.D.

National Rivers Authority (1994c) *Sediment and gravel transport in rivers: a procedure for incorporating geomorphology in river maintenance*. NRA, Bristol, Project Record 384, prepared by Sear, D.A. and Newson, M.D.

Newson, M.D. (1986) River basin engineering – fluvial geomorphology, *Journal of the Institute of Water Engineers and Scientists*, **40**(4), 307–324.

Newson, M.D. and Bathurst, J.C. (1991) *Sediment movement in gravel bed rivers: applications to water supply and catchment management problem, River Dunsop, Forest of Bowland, Lancs*. Seminar paper no. 59. Dept. of Geography, University of Newcastle.

Newson, M.D. and Sear, D. (1997) The role of geomorphology in monitoring and managing river sediment systems. *Journal of the Chartered Institution of Water and Environmental Management*, **11**(4), 264–270.

Nicholas, A.P., Walling, D.E., Sweet, R.J. and Fang, X. (2006) Development and evaluation of a new catchment-scale model of floodplain sedimentation. *Water Resources Research*, **42**(10), 1–13.

Oldmeadow, D.F and Church, M. (2006) A field experiment on streambed stabilization by gravel structures. *Geomorphology*, **78**(3–4), 335–350.

Pizzuto, J.E. (1987) Sediment diffusion during overbank flows. *Sedimentology*, **34**(2), 301–317.

Proffit, G.T. and Sutherland, A.J. (1983) Transport of non-uniform sediments. *Journal of Hydraulic Research*, **21**(1), 33–43.

Quine, T.A. and Walling, D.E. (1991) Rates of soil erosion on arable fields in Britain: quantitative data from caesium-137 measurements. *Soil Use and Management*, **7**(4), 169–176.

Reid, I., Frostick, L.E. and Brayshaw, A.C. (1992) Microform roughness and the selective entrainment and entrapment of particles in gravel-bed rivers. In Billi, P. and Reid, J.B. (1984) Artificially induced concave bank deposition as a means of floodplain erosion control. In Elliott, C.M. (ed.) *River meandering*. ASCE Publications, New York, pp. 295–305.

Reid, I., Frostick, L.E. and Layman, J.T. (1985) The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channels. *Earth Surface Processes and Landforms*, **10**(1), 33–44.

Reid, S.C, Lane, S.N., Berney, J.M. and Holden, J. (2008) The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river. *Geomorphology*, **83**(1–2), 152–182.

Richards, K.S. (2004) *Rivers: form and process in alluvial channels*. Blackburn Press, Caldwell, NJ.

Richardson, W.R.R. (1997) *Secondary flow and channel change in braided rivers*. Unpublished dissertation, University of Nottingham.

Sarker, M.H. and Thorne, C.R. (2006) Morphological response of the Brahmaputra–Padma–Lower Meghna river system to the Assam earthquake of 1950. In Sambrook Smith, G., Best, J., Bristow, C. and Petts, G.E. (eds) *Braided rivers*. Blackwell, London, ISBN 9781405151214, pp. 289–310.

Schumm, S.A. (1977) *The fluvial system*. Wiley-Interscience, New York.

Schumm, S.A., Harvey, M.D. and Watson, C.C. (1984) *Incised channels: morphology, dynamics, and control*. Water Resources Publications, Littleton, CO.

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment related river maintenance: the role of fluvial geomorphology. *Earth Surface Processes and Landforms*, **20**(7), 629–647.

Sechet, P. and le Guennec, B. (1999) The role of near wall turbulent structures on sediment transport. *Water Research*, **33**(17), 3646–3656.

Simon, A. and Hupp, C. (1986) Channel evolution in modified Tenessee channels. *Proceedings of the 4th Interagency sedimentation Conference*, Las Vegas, Nevada, **2**, 5-71–5-82.

Simon, A. and Thorne, C.R. (1996) Channel adjustment of an unstable coarse-grained stream: opposing trends of boundary and critical shear stress, and the applicability of extremal hypotheses. *Earth Surface Processes and Landforms*, **21**(2), 155–180.

Simon, A., Curini, A., Darby, S.E. and Langendoen, E.J. (2000) Bank and near-bank processes in an incised channel. *Geomorphology*, **35**(1–2), 93–217

Smith, J.D. (2004) The role of riparian shrubs in preventing floodplain unravelling along the Clark Fork of the Columbia River in the Deer Lodge Valley, Montana. In Bennett, S.J. and Simon, A. (eds) *Riparian vegetation and fluvial geomorphology*. Water Science and Application 8, AGU, Washington DC.

Soar, P.J. and Thorne, C.R. (2001) *Channel restoration design for meandering rivers*. Final Report ERDC/CHL CR-01-1, Vicksburg, US Army Research and Development Center, 416 pp. plus appendices. Available at http:// libweb.wes.army.mil/uhtbin/hyperion/CHL-CR-01-1.pdf.

Soar, P.J., Thorne, C.R., Fripp, J. and Copeland, R. (1999) Effective discharge calculation for channel restoration design: application. *Proceedings of the International Water Resources Engineering Conference*, Seattle, August, Walton, R. and Nece, R.E. (eds), EWRI-ASCE, CD ROM.

Thorne, C.R. (1982) Processes and mechanisms of river bank erosion. In Hey, R.D., Bathurst, J.C. and Thorne, C.R. (eds) *Gravel-bed rivers: fluvial processes, engineering and management*. Wiley, Chichester, pp. 227–271.

Thorne, C.R. (1998) *Stream reconnaissance guidebook: geomorphological investigation and analysis of river channels*. Wiley, Chichester.

Thorne, C.R. and Easton, K. (1994) Geomorphological reconnaissance of the River Sence, Leicestershire for river restoration. *East Midlands Geographer*, **17**(1–2), IBG Special Issue, 40–50.

Thorne, C.R. and Osman, A.M. (1988) Riverbank stability analysis: II Applications. *Journal of Hydraulic Engineering, ASCE*, **114**(2), 151–172.

Thorne, C.R. and Hey, R.D. (1979) Direct measurements of secondary currents at a river inflexion point. *Nature*, **280**, 226–228.

Thorne, C.R., Bathurst, J.C. and Hey, R.D. (1987) *Sediment transport in gravel-bed rivers*. Wiley, Chichester.

Thorne, C.R., Biedenharn, D.S., Hey, R.D., Soar, P.J. and Watson, C.C. (1999) Effective discharge calculation for channel restoration design: calculation. *Proceedings of the International Water Resources Engineering Conference*, Seattle, August, Walton, R. and Nece, R.E. (eds), EWRI-ASCE, CD ROM.

Thorne, C.R., Hey, R.D. and Newson, M.D. (1997) *Applied fluvial geomorphology for river engineering and management*. John Wiley & Sons, Chichester.

Thorne, C.R., Newson, M.D. and Hey, R.D. (1997) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester.

Thorne, C.R., Russell, A.P.G. and Alam, M.K. (1993) Planform pattern and channel evolution of the Brahmaputra River, Bangladesh. In Best, J.L. and Bristow, C.S. (eds) *Braided rivers*. Geological Society of London Special Publication No. 75.

Thorne, C.R., Zevenbergen, L.W., Pitlick, J.C., Rais, B., Bradley, J.B. and Julien, P.Y. (1985) Direct measurements of secondary currents in a meandering sand-bed river. *Nature*, **316**(6030), 746–747.

Tooth, S., Rodnight, H., Duller, G.A.T, McCarthy, T.S., Marren, P.M. and Brandt, D. (2007) Chronology and controls of avulsion along a mixed bedrock-alluvial river. *Geological Society of America Bulletin*, **119**(3–4), 452–461.

Walker, J. (2001) The use of sediment modelling techniques to address the differing needs of management on the river Eden, UK, *Water and Environment Journal*, **15**, 252–257.

Whiting, P.J. and King, J.G. (2003) Surface particle sizes on armoured gravel streambeds: effects of supply and hydraulics. *Earth Surface Processes and Landforms*, **28**(13), 1459–1471.

Whittaker, J.G. and Jaeggi, M.N.R. (1982) Origin of step-pool systems in mountain streams. *Journal of the Hydraulic Division, American Society of Civil Engineers*, **108**(HY6), 758–773.

Wiberg, P.L. and Smith, J.D. (1987) Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. *Water Resources Research*, **23**(8), 1471–1480.

Wishart, D., Warburton, J. and Bracken, L. (2008) Gravel extraction and platform change in wandering gravel bed river. *Geomorphology*, **94**, 131–152.

Wormleaton, P., Hey, R.D., Sellin, R. and Bryant, T. (2005) Behaviour of meandering overbank channels with graded sand beds. *Journal of hydraulic Engineering,* **131**, 665–681.

4

Driving processes II. Investigating, characterising and managing river sediment dynamics

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4.1 Using geomorphology to investigate and characterise sediment dynamics

4.1.1 Background

Geomorphology can contribute to river channel engineering and management across a range of applications and river functions (Thorne *et al.*, 1997). Inclusion of geomorphology in project-related investigations and adoption of geomorphic principles in the planning, design and post-project management of schemes is now commonplace in the UK, particularly when addressing problems concerned with erosion, sedimentation, instability, channel rehabilitation and the design of environmentally-aligned channels and maintenance regimes (Gilvear, 1999).

Geomorphology also contributes significantly to river restoration and recent environmental legislation, coupled with growing awareness of the need to properly understand the catchment context for reach-scale restoration schemes, means that the degree of involvement of geomorphologists is expanding. Project proponents become increasingly reliant on geomorphic analyses to produce improvements in hydromorphology and the geomorphic predictions necessary to demonstrate that the benefits of proposed projects are likely to be sustainable (Newson and Large, 2006).

During the 1990s, growing application of geomorphic principles, methods and analyses led to demand for approaches that were transparent, repeatable and auditable, and for which there was standardised guidance that could be referred to in briefing notes, tender documents, proposals and project reports. In the UK, a framework for geomorphological investigations was developed, involving a series of nested activities that would run in parallel with development of the hydrological, engineering and environmental aspects of a proposed project, as outlined in Chapter 1.

In this first section of Chapter 4, the procedures, methods and techniques applied in studying the driving processes of morphological change for project-related purposes are examined and illustrated in more detail. Coverage stems from a suite of methods developed through research sponsored by the National Rivers Authority (NRA) and Environment Agency during the 1990s and summarised in R&D reports by the Environment Agency (1998a, 1998b). However, coverage also incorporates later developments that have, or may soon, become accepted as 'standard approaches'. It does not, however, extend to techniques that are currently in development but which are not yet close to acceptance as being standard approaches. For example, geo-RHS has enormous promise, but is yet to be made available for general

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uptake by practitioners (Geodata Institute, 2004). It would, therefore, be premature to include it with the more widely tried and tested approaches described here. However, reference is made to the early findings of several new and innovative methods in Chapters 5 and 6.

4.1.2 *Approaches*

While it is now generally recognised that river channel sediment dynamics must be taken into account in river engineering, management and restoration, the breadth of sediment-related problems that may be encountered and variety of practical contexts within which it is necessary to account for sediment dynamics rule out the possibility of any single, universal approach being capable of dealing with all the situations where sediment investigations are required. While it is, therefore, appropriate that a range of approaches is available, responsibility rests with practitioners to select the approach(es) appropriate to the level of risk associated with the sediment problem being addressed, the resources available to support geomorphic studies, and the need for stakeholders to understand and have faith in the outcomes of the sediment study and the reliability of the science that underpins it.

To assist with selection of approaches suitable to the purpose for which they are to be applied, this section describes a suite of tools and methods that progresses from catchment-wide surveys that are, necessarily, broad and qualitative, to reach and site-scale investigations that are detailed and quantitative. The resulting framework for geomorphic studies spans a range of requirements in terms of data input, technical knowledge and costs (time and money), and is capable of generating output resolutions which extend from indicative to diagnostic over spatial scales from whole catchments to short river reaches.

While the scope and purpose of a geomorphic study are project-specific, when framing up any investigation of sediment dynamics practitioners should keep sight of the over-arching need to:

1. establish the nature of catchment-wide linkages in the sediment transfer system
2. explore those linkages qualitatively and, if possible, quantitatively
3. identify natural events, engineering interventions and management actions likely to disrupt sediment dynamics in the fluvial system, with the potential to trigger morphological and sediment-related problems that require costly and environmentally damaging solutions
4. promote selection of management and project design options that improve connectivity, continuity and balance in the sediment transfer system.

4.1.3 *Catchment Baseline Survey*

A Catchment Baseline Survey (CBS) provides a strategic overview of the geomorphological ‘state’ of a drainage network. Its purpose is to develop a broad understanding of the geology, hydrology, and geomorphology of the entire catchment and its river system, in order to inform holistic approaches to the solution of any morphology and/or sediment-related problems and provide the basis from which to define the catchment context for reach- or site-scale sediment management projects and actions. A CBS may be a stand-alone investigation or it may be undertaken in preparation for a Fluvial Audit.

While a CBS recognises the value of viewing the fluvial system as a single entity for broad-scale investigation, planning and management, it also allows the study team to divide the river network into geomorphic reaches. Reaches are defined primarily on

Fig. 4.1 Reach with high geomorphological conservation status. This reach might be prioritised for protection from capital works or heavy maintenance based on the outcome of a CBS

the basis of their geomorphological conservation status – that is, the degree to which they retain their natural morphological forms, sediment features and fluvial processes. However, other attributes, such as the reaches dominant function in the sediment transfer system (that is, whether it acts predominantly as a sediment source, sink, transfer or exchange) and its morphological stability status (e.g. statically stable, incising, aggrading, widening, narrowing or dynamically stable) may also be taken into account when identifying and delineating reaches. These aspects of morphological status are considered further when conducting a Fluvial Audit.

A CBS provides a broad, catchment-wide evidence base with which the proponents of projects, catchment stakeholders and government regulators can make informed decisions concerning catchment and river management as well as proposed development activities. Importantly, this evidence base identifies those reaches in the system that are particularly vulnerable to degradation and deserve special protection due to their high geomorphological conservation status (Fig. 4.1). Further, it also highlights those reaches that have been adversely impacted by past actions, but which hold the greatest restoration potential based on their current status, catchment context and suitability for restoration that is both feasible and effective at the system scale (Fig. 4.2). Both these outcomes are extremely important in terms of ensuring that: (i) the hydromorphological capital of the system is conserved (as required under the Water Framework Directive), (ii) conservation efforts are targeted on protecting the most valuable and vulnerable reaches, and (iii) restoration priorities consider restoration potential at both the reach and catchment scales.

A Catchment Baseline Survey has two main components: a desk study and a field survey. The desk study involves compilation of existing, baseline information relevant to the study catchment and CBS. Information that should be included in this study includes catchment geology, topography, soils, land-use, management, development and flood risks. It must further obtain copies of all current and historical maps, aerial photographs and satellite imagery relevant to the study catchment.

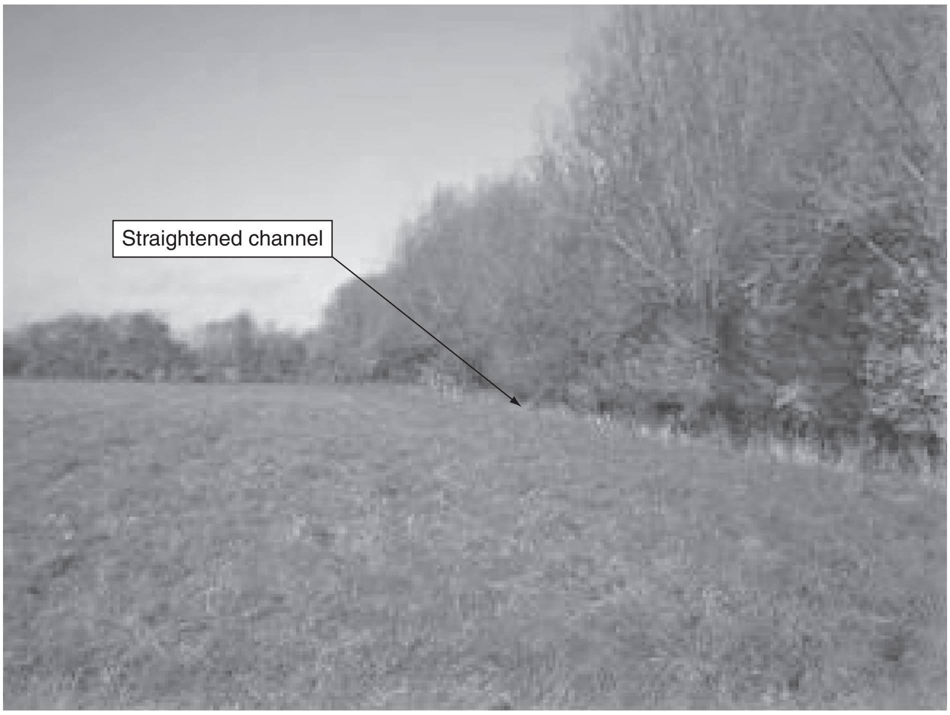

Fig. 4.2 Reach with low geomorphological conservation status but high restoration potential. This reach might be prioritised for restoration based on the outcome of a CBS

This baseline material should be supplemented by additional information obtained through consultation with the relevant catchment authorities and statutory agencies. While a CBS is by definition a broad-scale, catchment-wide survey, local knowledge of the catchment and the current issues that exist within it are still invaluable and can provide insights essential to identifying 'hot spots' and 'key reaches' while contextualising river problems with respect to the views and beliefs of non-expert stakeholders and communities. In a similar vein, within the UK, a great deal of information relevant to CBS investigations exists in the form of the River Habitat Survey (RHS) database. While RHS study sites extend over only 500 m in length, there may be multiple sites distributed throughout the study catchment and it is strongly recommended that data and observations available for all existing RHS sites in the study catchment are obtained as a matter of course when conducting a CBS (Raven *et al*., 1998).

The knowledge obtained through the desk study is not only of value in itself but it also underpins and informs the design of the field survey component of the CBS. The fieldwork methodology centres on using stream reconnaissance to collect information and record it on suitable survey sheets during a walkover survey of the drainage network, or a selected component thereof. The extent of the walkover survey is decided on the basis of the desk study. An experienced surveyor can be expected to cover 5–6 km of channel during an 8-hour working day. This figure can be used to estimate the time and financial resources needed to perform the field component of the CBS. It is often necessary to undertake the walkover survey in a team of two to meet health and safety requirements.

A wide range of stream reconnaissance sheets suitable for application to CBS surveys now exist. While they are broadly similar, they have usually been developed for particular types of survey or geographical areas and not all are equally transferable. The best sheets are those that can be adapted to fit the particular survey

Table 4.1 Areas covered in generic river reconnaissance sheets that may be adapted for use in a Catchment Baseline Survey

Heading	Broad information detailed
Details of survey	River name, reach number, date of survey, grid reference (start and finish), conservation status
Valley overview	Valley form, land use, riparian corridor, floodplain, tree lining, terraces, levees
Channel geometry	Planform description, channel gradient, modification, channel cross-section form
Boundary conditions	Bed and bank material and form, bank modification, vegetation (bank and in-channel)
Management operations	Management operations observed in the channel
Channel flow types	Channel flow types observed in the reach
Sediment dynamics	Sediment sources and sinks
Channel dynamics	Evidence of incision, widening, aggradation, stability, adjustment and narrowing
Photograph locations	Grid references for all of the photographs taken

requirements of the study catchment and project. The general headings that are covered by the survey sheets are detailed in Table 4.1.

Stream reconnaissance sheets record observations and measurements of the physical form of the channel, its riparian corridor and (in some cases) its floodplain. Some sheets place particular emphasis on the physical biotopes and functional habitats, while others focus on the condition of the banks or the risks posed by channel instability at bridges and other in-stream structures. In general, however, the aim is to add detail to the information gathered in the desk study in ways relevant to the problem or project being investigated. This involves updating and supplementing the knowledge gained from archive and remote sensing sources in order to validate and further develop the insights and understanding developed during the desk study. In this respect, fieldwork is essential to support accurate delineation and classification of geomorphic reaches according to their ‘geomorphological conservation value’, which is a measure of the channel’s ‘naturalness’ that is relevant to environmental standards for river management (Table 4.2).

Table 4.2 Summary of Environment Agency (1998a, 1998b) scheme for classifying geomorphological conservation value

Susceptibility to disturbance	Score	Description
High	8–10	Conforms most closely to natural, unaltered state and will often exhibit signs of free meandering and posses well-developed bedforms (point bars and pool–riffle sequences) and abundant bank side vegetation
Moderate	5–7	Shows signs of previous alteration but still retains many natural features, or may be recovering towards conditions indicative of higher category
Low	2–4	Substantially modified by previous engineering works and likely to possess an artificial cross-section (e.g. trapezoidal) and will probably be deficient in bedforms and bankside vegetation
Channelised	1	Awarded to reaches whose bed and banks have hard protection (e.g. concrete walls or sheet piling)
Culverted	0	Totally enclosed by hard protection
Navigable	–	Classified separately due to their high degree of flow regulation and bank protection, and their probable strategic need for maintenance dredging

Once established and validated, reach-by-reach mapping of conservation value provides the basis for planning future management and restoration efforts designed to work at the system as well as the reach scale, which increases their effectiveness and sustainability while representing a move away from the types of reactive management and catchment-blind restoration efforts that have characterised past projects. Reach-by-reach assessment and classification of the fluvial system also facilitates design of the field campaign necessary to collect data on sediment dynamics and morphological changes in the river as part of a Geomorphological Dynamics Assessment (GDA) that may subsequently be required to support selection and design of the preferred management or restoration option.

When the results of the desk study and field survey components of the CBS have been compiled and reconciled, they are used to produce catchment-wide maps of geomorphological conservation values, dominant reach functions and other notable features (such as constraints on morphological channel adjustments and barriers to fish migration), backed by commentaries and narrative interpretations within a Geographical Information System (GIS).

As with all classification systems there is potential for ambiguity and misunderstanding in the use of the system. For example, in some applications it can be difficult to differentiate between channels that should score 8, 9 or 10 in Table 4.2. However, when undertaking a CBS, rigorous quality control (by a suitably experienced geomorphologist) should be performed to ensure that scoring is consistent and that each reach is classified correctly, at least in relation to the others in the study system. This can account for uncertainties in the scoring and classification method and will guarantee that the results of the geomorphological classification provide a sound basis from which to prioritise the selection of reaches to be conserved or restored. The classification can also be used alongside other maps of channel status (such as those in River Basin Management Plans produced under implementation of the EU Water Framework and Floods Directives) to identify reaches that have been heavily modified by past engineering and management and which present particular restoration challenges in terms of achieving good ecological potential.

The approach espoused in Table 4.2 is useful in defining how much a river has been modified in the past and gaining an idea of its ‘naturalness’. As well as highlighting reaches of particularly high or low status, and so helping to identify the ‘key’ reaches in the system, this also provides insights regarding the spatial distribution of geomorphological conservation values through the drainage network and a broad overview of the geomorphic status of the river as a whole. The classification itself is relatively simple, effectively scoring reaches relative to a ‘natural’ reference reach with the broad assumption being that if a channel has been modified, its conservation value will be reduced. However, even modified systems have some conservation value and thus proposed actions that may result in reductions of conservation value cannot be ignored in low-scoring reaches.

Other geomorphic limiting factors, such the channel’s sediment type and susceptibility to disturbance, also vary throughout the catchment, though they are not taken into account within this particular classification system. In this context, the information collected during the CBS field survey should be sufficiently broad to support further classification and mapping initiatives. In this way, a single set of CBS survey sheets can be a useful aid to understanding process–form linkages and process–response mechanisms at both the reach and catchment scales – which adds value to the CBS and provides the basis for initial assessment of geomorphological dynamics in the fluvial system. Reconnaissance-level surveys of the type performed in a CBA rarely, however, provide a sufficient basis for the design of channel management or restoration measures, especially if structures or channel resectioning is involved. More advanced methods and techniques are required to do this, for example, a Fluvial Audit being performed to place a reach-scale sediment problem in its catchment context and a geomorphological dynamics assessment being employed to assess localised morphological response to proposed engineering or maintenance actions.

The outputs of a CBA should be substantial. The main report should summarise and synthesise all the information gained from the desk study and field survey and demonstrate how this led to classification and delineation of the geomorphologically defined reaches shown in the catchment maps. A description of each reach should be provided, which should comment on its geomorphological conservation value and discuss important aspects of reach-scale geomorphology such as the dominant fluvial processes, sediment features, physical biotopes and functional habitats. GIS-based maps should be included to show the distribution of conservation status throughout the catchment and other notable features such as barriers to fish passage (this is increasingly required as removal of fish barriers is an important mitigation measure related to implementation of the Water Framework Directive). The report should close by identifying key or critical reaches in the fluvial system, current and potential issues related to geomorphology, examples of inappropriate management or engineering activities, and opportunities for improved river management (including conservation of high-status reaches and restoration of reaches with good restoration potential).

4.1.4 Fluvial Audit

4.1.4.1 History of the Fluvial Audit

The term *Fluvial Audit* was coined in a report on sedimentation problems in two upland catchments in north-west England in the early 1990s (see Newson and Bathurst, 1997). It was subsequently adopted and defined by the Environment Agency (1998a) as being 'a technique that examines the sediment conditions in a particular problem reach in relation to those in the catchment as a whole'.

Through this examination of sediment conditions, the original Fluvial Audit (FA) sought to identify the credits (sources), debits (storage) and transfers (transport paths) of sediment in the catchment, in order to support interpretation of problems related to sediment and/or channel instability within the broader context of sediment dynamics in the fluvial system. It did so by establishing either a qualitative or semi-quantitative sediment budget for the problem reach, developing a sound understanding of the fluvial processes operating in the river locally and identifying the root causes of the sediment-related problems. The methods and techniques applied in fluvial auditing were developed and refined during early applications in a series of NRA R&D projects (see, for example, Sear *et al.*, 1995), resulting in a standardised procedure for sediment investigations related to Flood Alleviation Schemes and operational maintenance (Environment Agency, 1998a; Sear *et al.*, 2004).

Consequently, in its initial form, the Fluvial Audit was developed to answer specific questions relating to channel sedimentation and/or bed and bank erosion in so far as they caused specific problems related to flood risk management, channel stabilisation and channel maintenance. In this context, the method was founded on the principles that:

1. It is better to treat the cause of a sediment problem than its symptoms. For example, in the case of siltation in a flood control channel that exposes people and property in the protected area to an unacceptable level of flood risk, rather than operational or responsive dredging to treat the symptom (unacceptable shoal development) it is better to identify *why* the supply of sediment to the reach exceeds its transport capacity and then deal with this imbalance either by managing the source of the excess sediment, or modifying the design of the channel to match its transport capacity to the supply from upstream.
2. Sustainable flood risk management and channel maintenance requires a holistic understanding of the connected systems through which water, sediments and debris are transported.
3. Connectivity operates over a range of timescales related to: the spatial scale of the system, the dominant geomorphological processes, the nature of the transfer pathways, natural and artificial constraints on sediment transfer and the magnitude and sequence of hydrological events responsible for driving and disturbing the fluvial system.
4. When attempting to manage or mitigate sediment-related problems, the value of natural, self-regulating geomorphic functions and process–response mechanisms inherent to the fluvial system is at least as great as those of capital works and maintenance operations.

In early applications, these principles were invoked in Fluvial Audits designed for three main functions:

1. Analysing a sediment-related problem specific to a given reach (at scales of around 1–10 km).
2. Developing an overview of catchment sediment production and connectivity in the fluvial system (at the catchment scale, typically 10–1000 km^2 in the UK).
3. Assessing historical disturbance to the fluvial system and its effects at the catchment or reach scales, typically over the last 500 years.

The results of these early investigations were used to identify the causes of sediment-related river management problems and to guide the development of sustainable solutions that might involve using allowed morphological adjustment/recovery, channel rehabilitation or structural interventions to manage erosion, sediment transfer or deposition (for examples, see Sear *et al.*, 1994, 1995).

However, starting in the mid-1990s, the role for the FA expanded from assisting in the solution of specific, sediment-related problems in flood control channels to encompass strategic investigations at the catchment scale in support of a wider range of river management activities, particularly including natural conservation. The aim of fluvial auditing evolved to encompass not only mapping sediment sources and sinks in the river network and surrounding catchment but also gaining an understanding of how the sediment transfer system supports and interacts with the physical biotopes and functional habitats present in the channel, riparian zone and floodplain (Newson and Newson, 2000). The output from fluvial audits of this type was an interpretation of channel form and behaviour over time, together with an inventory of geomorphological and physical biotope features in the study reaches. An implicit assumption in many of these studies was that they incorporated a Catchment Baseline Survey that could be re-evaluated in the future as part of a wider evaluation of river response to management and engineering. Data were, therefore, increasingly collected in digital format, accurately geo-referenced and stored within a GIS and linked database.

A third period of development and evolution of the fluvial audit has taken place during the last 5 years in support of the restoration of degraded river habitats. Much of this development has been driven by the legislative requirements of the European Union Habitats Directive (92/43/EEC). In England, work has been commissioned by the Environment Agency and Natural England, while similar initiatives have taken place in both Scotland (initiated by the Scottish Environmental Protection Agency and Scottish Natural Heritage) and Wales (by the Countryside Council for Wales). The aims of these modern Fluvial Audits have expanded to include:

1. Developing the sound understanding of geomorphological processes, sediment dynamics and hydromorphology that is required to support the development of favourable conditions for in-stream habitats protected under the Habitats Directive at Sites of Special Scientific Interest (SSSI) and Special Areas of Conservation (SAC) in, or connected to, rivers.
2. Determining the extent and location of human modifications and their impact on favourable conditions.
3. Using the information from items 1 and 2 above to identify reach-scale management actions necessary to move the river towards a favourable condition.

Achieving these aims has required both further refinement of the methods and techniques used in fluvial auditing and the development of new data analysis techniques, including multi-criteria analysis (Sear *et al.*, in press).

The history of the FA has also featured technical innovation and the adoption of emerging methods and models. The FA provides a framework for developing an understanding of sediment dynamics and morphological responses in a catchment context but, in applying that framework, auditors have taken advantage of improvements in our capability to model fluvial erosion, deposition and the resulting changes in channel morphology (see, for example, Darby and van de Wiel, 2003; Coulthard and van de Wiel, 2006). To take advantage of current developments when selecting the investigative approaches to be employed for a particular audit, consideration should be given to the application of tools that are now available and that are relevant to fluvial auditing including:

- aircraft-mounted remote sensing: to support catchment-scale assessment of point and diffuse sediment sources and, in particular, soil erosion
- geomorphological/soil erosion models: to refine the understanding of the sediment system developed from the desk study and field reconnaissance elements of the audit
- 1-D sediment transport models: to validate classification of geomorphological reaches as sediment sources, transfers or stores
- novel techniques for collecting bed grain size data: to add quantitative definition of the bed material to the qualitative description provided by field reconnaissance
- MImAS field technique: to define reach-scale hydromorphological status and so link the Fluvial Audit methodologically to implementation of the Water Framework Directive (Environment Agency, 2007)
- river channel typologies: to cross-tabulate the geomorphological reaches identified in a Fluvial Audit to the reach classification performed when developing a River Basin Management Plan.

4.1.4.2 *Current status of the Fluvial Audit*

To understand the current status of the Fluvial Audit it is necessary not only to know something of its historical evolution but also to recognise that, although it is presented as a standard procedure, in practice it is performed differently by different practitioners, even though its principles and aims remain the same. Thus, some Fluvial Audits are just desk-based investigations supporting limited interpretation of a specific sediment-related problem, while others include extensive fieldwork and data collection to support sediment modelling and sophisticated interpretation of sediment issues at the catchment scale. The scope of work in a Fluvial Audit is determined by the contractor performing the study in consultation with the client, and usually represents the minimum levels of resourcing and effort required to deliver the information necessary to meet the requirements of the project. However, best practice recommends that a Fluvial Audit should be preceded by (or incorporate) a detailed Catchment Baseline Survey (CBS) and that, where necessary, it should be followed by a Geomorphological Dynamics Assessment (GDA).

It follows that in tender documents, best practice guides and project briefs, the specification for a Fluvial Audit is crucial and must be based on the specific requirements of the investigative study. It is, therefore, critical to understand the reason for undertaking the work in the first place, so that the scope, nature and purpose of the FA can be accurately defined. The levels of time, effort and resourcing necessary to perform an FA will vary significantly depending on its scope, nature and purpose and this has implications for the timescale and overall cost to the project. It is therefore vital that the reason for performing an FA is discussed and agreed by all those involved in the project before embarking on the work, to ensure that the Fluvial Audit is fit for purpose, while still being feasible and affordable given the resources available.

Table 4.3 Documentary/historical sources used in Fluvial Auditing

Source	Timescale	Location
Maps		
Estate	C16th +	British Library and
Enclosure	C18th–19th	National Library of Wales
Tithe	1840s	County Archivist
County	1853–1923	Ordnance Survey
Ordnance Survey	1948 +	British Geological Survey
1 : 10,560 County Series	106 years	Soil Survey
National Grid Series	106 years	
Drift geology 1 : 50,000 Series		
Soil Survey 1 : 50,000 Series		
Remotely sensed imagery		
Aerial photographs	1930s +	NERC/Cambridge University
Satellite images	1970s +	NERC/National Remote Sensing Centre
Documents		
Estate papers	C16th +	British Library/NLW
Local newspapers	C19th +	Archives/newspaper offices
Court of Sewers records	C15th–18th	Archives/British Library
Catchment Board records	1930 +	Archives/Environment Agency files
River Board records	1946 +	Archives/ Environment Agency files
Water Authority records	1973 +	Environment Agency files
NRA reports	1989 +	Environment Agency files
Scientific journals	C20th +	British Geomorphological Research Group/CIWEM/CEH

4.1.4.3 Elements and outputs of the Fluvial Audit

The historical element of a Fluvial Audit is important because the causes of contemporary, sediment-related problems are often rooted in the past. In this context, catchment changes and river management actions that occurred years, decades or even centuries ago, and which cannot be detected through fieldwork, may be important. Consequently, historical and archive studies are an important element of the Fluvial Audit and these involve accessing sources of information that may be unfamiliar to many river managers, scientists and engineers. Typical historical documentary sources are listed in Table 4.3.

In addition to historical and documentary studies, fluvial auditing employs geomorphological fieldwork and stream reconnaissance to characterise the problem reach or reaches and identify the relevant channel forms and sedimentary features. An important component of stream reconnaissance is accurate classification of the vertical stability status of the reach (incising, aggrading or stable), based on recognition of indicative channel, infrastructure and floodplain features. In this regard, Table 4.4 lists some of the attributes commonly used to assess channel stability in upland, mid-course and lowland contexts.

The primary output of a Fluvial Audit consists of three major constituents:

1. time chart of catchment changes and management actions that may have impacted fluvial geomorphology

Table 4.4 Indicators of channel stability status

Category	Upland (source)	Middle (transfer)	Lower (sink)
Evidence of incision	Perched boulder berms Old channels in floodplain Old slope failures Undermined structures Exposed tree roots Narrow/deep channel Bank failures (both banks) Armoured/compacted bed Thick gravel exposure in the banks overlain by fines	Terraces Old channels in floodplain Undermined structures Exposed tree roots Tree collapse (both banks) Trees leaning towards channel (both banks) Downed trees in channel Bank failures (both banks) Armoured/compacted bed Thick gravel exposure in the banks overlain by fines	Old channels in floodplain Undermined structures Narrow/deep channel Exposed tree roots Tree collapse (both banks) Trees leaning towards channel (both banks) Bank failures (both banks) Thick gravel exposure in the banks overlain by fines Compacted bed sediments
Evidence of aggradation	Buried structures Buried soils Many uncompacted 'overloose' bars Eroding banks at shallows Contracting bridge openings Deep fine sediment overlying coarse particles in bed/banks Many unvegetated bars	Buried structures Buried soils Large, uncompacted bars Eroding banks at shallows Contracting bridge openings Deep fine sediment overlying coarse particles in bed/banks Many unvegetated bars	Buried structures Buried soils Large, uncompacted, 'overloose' bars Eroding banks at shallows Contracting bridge openings Deep fine sediment overlying coarse particles in banks Many unvegetated bars
Evidence of stability	Vegetated bars and banks Compacted, weed-covered bed Bank erosion rare Old structures in position No evidence of change from old maps Well-established trees on banks Little large woody debris	Vegetated bars and banks Compacted, weed-covered bed Bank erosion rare Old structures in position No evidence of change from old maps Well-established trees on banks Little large woody debris	Vegetated bars and banks Compacted, weed-covered bed Bank erosion rare Old structures in position No evidence of change from old maps Well-established trees on banks Little large woody debris

Table 4.5 Commonly encountered potentially destabilising phenomena (PDPs)

	Increased sediment supply	Decreased sediment supply
Catchment factors	Climate change (>rainfall)	Climate change (<rainfall)
	Upland drainage	Dams/river regulation
	Afforestation	Reduced cropping/grazing
	Mining spoil inputs	Cessation of mining
	Urban development	Vegetation of slopes/scars
	Agricultural drainage	Sediment management
Channel factors	Upstream erosion	Upstream deposition
	Agricultural runoff	Sediment traps
	Tributary input	Bank protection
	Bank retreat	Vegetation on banks
	Tidal input	Dredging (shoals and berms)
	Straightening	Channel widening upstream
	Upstream embanking	Upstream weirs/bed controls

2. map of catchment and drainage network indicating sediment sources, pathways and sinks
3. geomorphological map of the channel system indicating geomorphological reaches, key locations and current stability status.

These outputs form the basis for identifying the cause(s) of sediment-related problems and identifying sustainable solutions and project design approaches capable of treating these causes, rather than just treating their symptoms.

Based on the understanding of sediment dynamics and geomorphological adjustments (past and present) gained through a Fluvial Audit, a number of secondary products may then be derived. First among these is a table listing all the factors that significantly affect channel stability – including those that have operated in the past, those that operate currently and those that may be activated or reactivated in the future. These factors, are collectively termed potentially destabilising phenomena (PDPs). A list of commonly encountered PDPs is given in Table 4.5.

4.1.4.4 *Core aims of a Fluvial Audit*

While the objectives of a modern fluvial audit must necessarily be project-specific, there remain a set of core aims that provide points of reference with respect to national policies and EU directives relevant to the management of rivers and other water bodies. These may be summarised as to develop and present:

1. a conceptual model of the historical evolution of the channel and floodplain geomorphology, highlighting how catchment form and runoff processes control the flow regime, sediment regime and valley form that constitute the boundary conditions for the contemporary river system
2. a qualitative or semi-quantitative description of the current functioning of the sediment transfer system within the river network and surrounding catchment, including reach-scale delineation of supply, transport and storage zones
3. a sound understanding of the specific impacts of historical and contemporary river and land management activities (PDPs) on fluvial forms, sediment dynamics, channel stability, and the quality and diversity of habitats present in the river, riparian corridor and floodplain, on a reach-by-reach basis
4. a synthesis of the knowledge, understanding and insights gained through items 1 to 3 above that is used to identify specific channel and catchment engineering or

management actions capable of mitigating any negative impacts identified in item 3 as part of a river restoration plan, and which relates these to the expected ecological benefits

5. a catchment-scale sediment management plan designed to restore connectivity and facilitate the operation of natural geomorphic processes and channel forms so that habitat may achieve a favourable condition, degraded rivers can regain good ecological status and heavily modified watercourses can achieve good ecological potential.

4.1.4.5 Planning and performing a Fluvial Audit

Clearly, the scope of the Fluvial Audit has expanded since its original inception, to the point that the tasks involved in a Fluvial Audit may best be planned and performed through a series of linked work packages. In the case of a full Fluvial Audit, the work packages involved should cover:

1. Investigation and interpretation required to develop a scientifically robust, conceptual model of the long-term geomorphological evolution of catchment, channel and floodplain.
2. Investigation, data collection and analysis required to develop a scientifically robust, qualitative or semi-quantitative model of the current sediment transfer system and how this is connected to the wider catchment.
3. Archive studies and field data collection to document the types, locations and chronology of river channel and land management actions that may have influenced the current form and process within the river network (PDPs).
4. Classification of the river network in terms of the severity of disruption to the fluvial system, accounting for discontinuities in the sediment transfer system (e.g. dams, weirs, culverts) as well as divergence from natural form and process identified in the conceptual models and evaluation of the impacts on the channel, riparian and floodplain ecologies.
4. Classification of each geomorphic reach in terms of the degree of channel 'naturalness' relative to the conceptual model of channel form and function in such a way that the assumptions and limitations to the classification are transparent.
5. Development of outline proposals for engineering and management actions based on removing or mitigating the constraints to 'naturalness' identified using the conceptual and sediment transfer models as part of a river restoration plan that fully recognises the catchment context for the project reach(es).
6. Ecological assessment of the proposed actions to identify potential ecological risks and benefits.

Figure 4.3 illustrates a proposed framework for an advanced Fluvial Audit and how its outputs relate to the development and appraisal of alternative options for river management and restoration. In this context, the power of the Fluvial Audit lies in its capability to accurately define the catchment context for reach-scale management and restoration while at the same time contributing to the advanced stages of the development of a strategic restoration plan for an entire fluvial system or catchment.

Many practitioners will view the core aims set out herein as aspirations, pointing out that they may not be all achievable, or even essential, in many applications. Similarly, the scope illustrated in Fig. 4.3 is unlikely to be met in perhaps 90% of FAs with, for example, many applications lacking the justification and/or resources necessary to support broad-scale sediment modelling. Nevertheless, the core aims

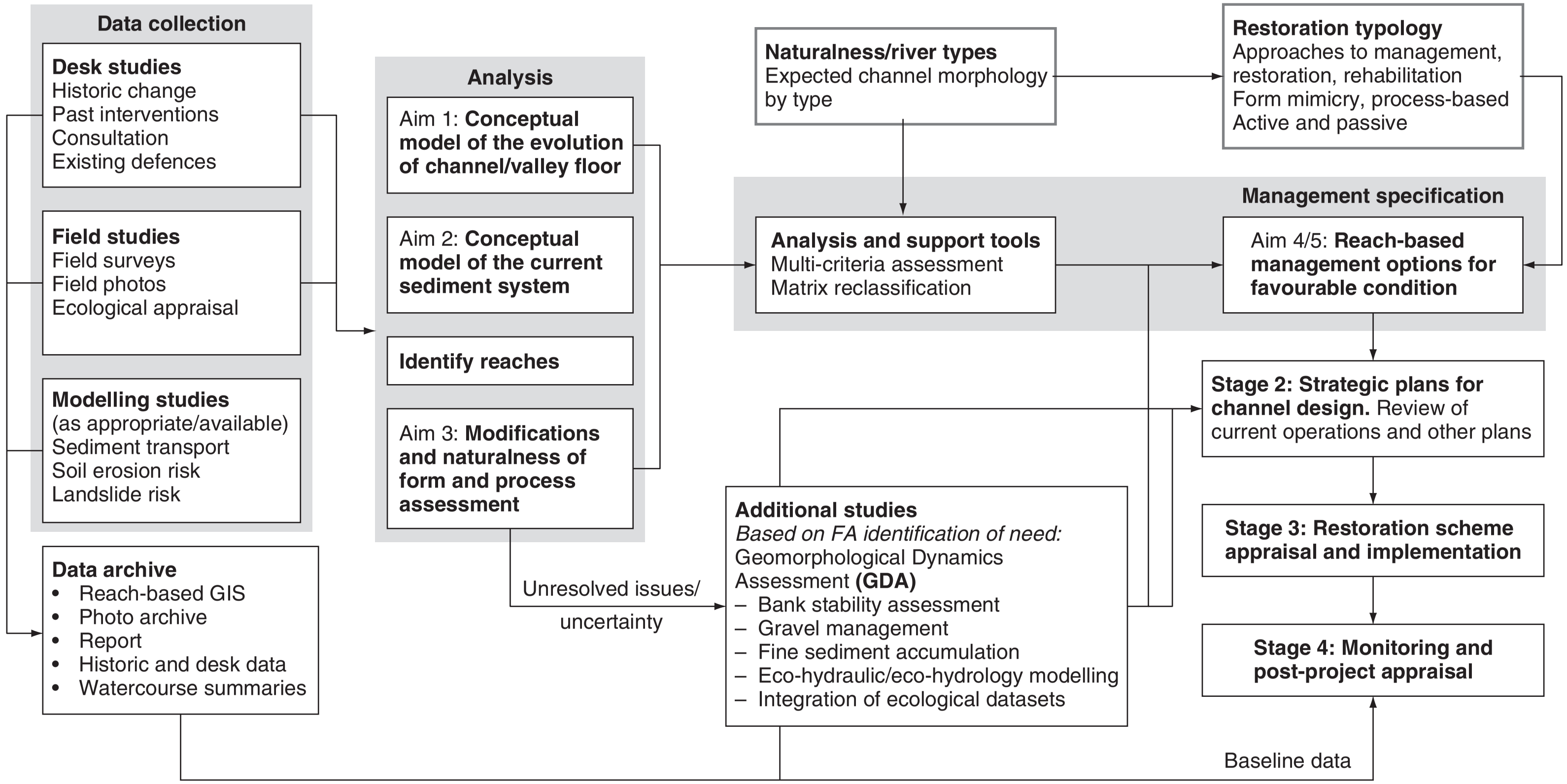

Fig. 4.3 Proposed framework for a Fluvial Audit performed as part of geomorphological investigations to support planning of management actions and/or restoration projects designed to achieve a favourable condition for habitat. Grey areas are external to the auditing process

and planning framework presented here are useful in setting standards for what a Fluvial Audit may *seek* to achieve, increasing the ambitions of stakeholders responsible for commissioning and designing river projects, demonstrating best practice and 'raising the bar' in terms of the standards expected by regulators responsible for reviewing and permitting management and restoration proposals.

4.1.4.6 *Assumptions underpinning a Fluvial Audit*

While the utility of the Fluvial Audit has been demonstrated in numerous applications and is no longer open to question, it is nonetheless important to remember that an FA cannot cover all of the possible causes of environmental and/or ecological degradation at the reach and catchment scales. For example, the aims and specifications for an FA set out above are sufficiently extensive in scope to be regarded as infeasible by many practitioners, yet they still implicitly assume that sediment-related problems may be identified and dealt with on the basis of investigation and modelling of sediment dynamics as controlled by fluvial processes. The implication is that sediment loads are transport limited and that finer sediment, that constitutes wash load in the study reach, either does not contribute significantly to the problem being dealt with, or is a pressure that has already been identified and accounted for through related studies performed to develop a catchment-wide sediment budget. Dealing with wash load requires more advanced studies using an approach such as the Sediment Impact Assessment Method (SIAM) described in Section 4.1.6 below or sediment routing by size fraction using iSIS Sediments or HEC-RAS version 4.0. The point is that, while the scope and purpose for which an FA may be undertaken have expanded in the two decades since it was conceived, it still constitutes no more than a component (albeit a powerful and versatile one) of the suite of studies that constitute a complete geomorphic investigation.

4.1.5 *Stream power analysis as a screening tool*

While it is possible to predict the type and direction of morphological adjustment likely to occur in response to a given river engineering or management action on the basis of a purely qualitative assessment of the type of intervention and the pre-project form of the channel, confidence is increased if a quantitative element can be introduced to the investigation and deliberation. Geomorphological theory, as well as Bagnold's approach to the sediment transport problem based on the physics of the process (Bagnold, 1980; Ferguson, 2005), demonstrate that the capacity of a river to do geomorphological work, and so change the position or morphology of the channel, may be characterised by the availability of stream power to entrain and transport sediment. In this context, the total stream power is defined by:

$$\Omega = \rho g Q S$$

where, Ω = total stream power per unit channel length, ρ = density of water, g = gravity, Q = discharge, and S = energy slope (usually approximated by water surface slope). However, total stream power is highly scale dependent, with larger rivers routinely having much higher powers than smaller ones, and a more widely used index of stream power that is much less strongly scale dependent is the specific stream power, or stream power per unit area of the bed, defined by:

$$\omega = \frac{\rho g Q S}{w}$$

where, w = a representative channel width and the units of stream power are watts per square metre (W/m^2). This represents the stream power used by Bagnold (1966) in his sediment transport analyses, although he omitted the gravitational constant, g, in order that the units of specific stream power should match those of unit sediment transport (kg/m/s). When using Bagnold's bedload transport equation, the relevant value of width is the 'active width' of the bed – that is, the width of that part of the bed over which the bed is potentially mobile. In other applications, either the bed, water surface or bankfull width may be used, as appropriate to the selected value of discharge.

In a wide-ranging study of British rivers, Ferguson (1981) found the median specific stream power at bankfull stage displayed by alluvial rivers with actively meandering channels to be approximately 30 W/m^2, although the range of observed values was large, extending from 5 to 350 W/m^2. Ferguson further identified that geomorphologically moribund rivers had bankfull stream powers between 1 and 60 W/m^2, with a median value of around 15 W/m^2.

Further research on stream power and channel type used early results from the RHS database, combined with estimates of bankfull discharge, to calculate specific stream power for a large number of reaches with contrasting topographic and geomorphological settings (NRA, 1995). The results showed that values of specific stream power in British rivers to range from 2 to 1815 W/m^2. It is clear then that the energy levels and capabilities for responding to natural or artificial perturbations through dynamic channel adjustment vary enormously across the UK.

The finding that streams with adjustable channel boundaries display a very wide range of specific stream powers has been corroborated by observations in other countries. For example, working on the Colorado river during controlled releases from Glen Canyon Dam in 1996, Schmidt *et al.* (2001) calculated specific stream powers ranging between 260 and 2150 W/m^2 for a discharge of 250 $m^3 s^{-1}$ at ten rapids in the Grand Canyon.

As well as providing the basis for sediment transport prediction, stream power has also been promoted as a tool with which to: predict planform pattern (van den Berg, 1995); explain the occurrence of channel incision (Schumm, 1977); evaluate the performance of river engineering and restoration projects (Brookes, 1988; Brookes and Shields, 1996); and classify floodplains (Nanson and Croke, 1992).

However, while the theoretical basis for specific stream power is strong, its use in practical applications depends on identification of thresholds, or at least threshold bands, of stream power capable of discriminating between rivers or reaches likely to display different types of morphological behaviour in response to disturbance.

In this context, Brookes (1983, 1987a, 1987b) found the post project readjustment of straightened river channels to be related to particular levels of specific stream power, with straightening schemes in rivers possessing less than 15–25 W/m^2 of specific stream power at the bankfull stage likely to respond morphologically through processes led by deposition and those in streams with powers in excess of 25–35 W/m^2 likely to respond through erosion (Fig. 4.4). These thresholds are broadly in line with the earlier work of Ferguson (1981).

A later study by the National Rivers Authority (NRA, 1995) attempted to relate channel instability to specific stream power by bed material type (silt, gravel, gravel/cobble, cobble). The findings revealed a tendency for the stream power associated with instability to increase with increasing bed material size (Table 4.6).

However, error margins in the data were too high to support the analyses necessary to establish predictive relationships between stream power, bed material calibre

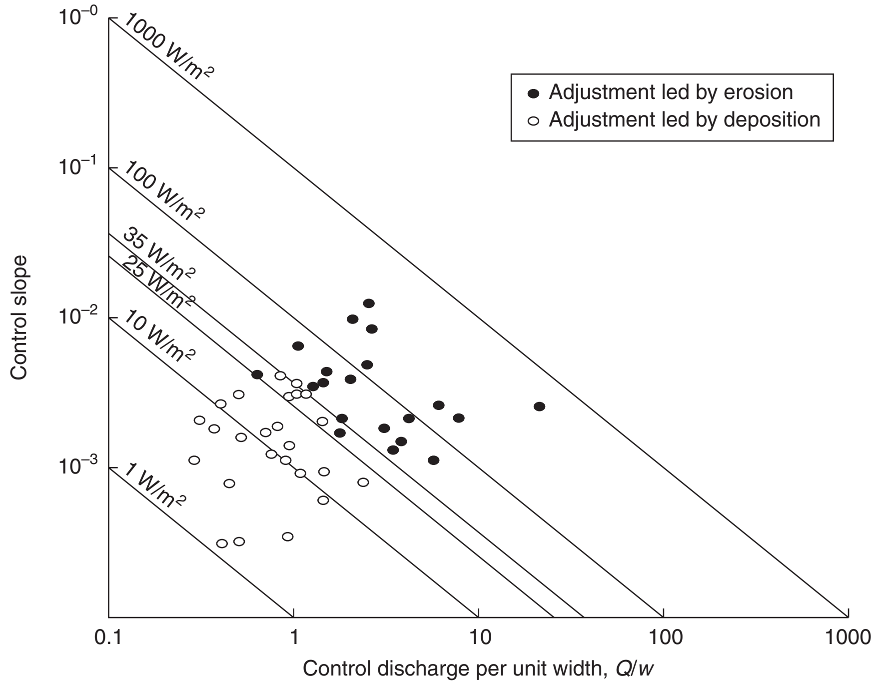

Fig. 4.4 Specific stream power plot showing channel response to disturbance for several British rivers. Modified, with permission, from Brookes, 1987b. © 1987 John Wiley & Sons Limited

and channel stability or adjustment. Also, it was noted that there was a tendency for the lowest values of stream power in most of the sediment size groups to be associated with a higher incidence of instability, while stable conditions were observed at some sites with stream powers in excess of 1000 W/m^2.

Lack of a simple relationship between channel instability and stream power should be expected because by no means all of the stream power expended by a river is actually available to perform geomorphic work through sediment entrainment and transport. In fact, most stream energy is consumed in overcoming:

- internal friction through flow shearing and turbulence (related to velocity gradients and the presence of large eddies and secondary flow structures)
- boundary friction due to the roughness of the bed (related to sediment size, particle size distribution and clustering) and banks (related to bank profile and stratigraphy)

Table 4.6 Stream power values associated with stability/instability in UK rivers with different calibres of bed material from National Rivers Authority, 1994b. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

	Bed stable			Bed unstable		
Size group	No. of obs.	Median stream power: W/m^2	Range of stream power: W/m^2	No. of obs.	Median stream power: W/m^2	Range of stream power: W/m^2
Silt	2	48	14–81	6	38	8–105
Gravel	9	107	12–1766	27	73	4–490
Gravel/cobble	4	136	59–269	6	79	58–482
Cobble	1	n/a	n/a	13	142	7–427

- form drag due to bed topography (related to bedforms such as sand ripples/dunes, pools and riffles, and channel bars/islands) and irregularities in the banklines
- bend losses due to flow curvature effects in meandering and braided channels (related to the sinuosity of the channel and tightness of the bends)
- retardance by submerged and emergent vegetation (related to abundance and stiffness of stems and therefore highly seasonal for flexible plants, and the abundance and size of woody debris jams).

In natural channels, these processes of flow resistance consume all but a fraction of the total stream power, moderating the ability of the flow to erode its channel boundaries and transport additional sediment. However, the proportion of energy consumed by the processes listed above varies widely through time and space, depending mostly on the size of bed sediment, the occurrence of bedforms (ripples, dunes, etc.), the presence of sediment features (bars, shoals, riffles, etc.), the cross-sectional morphology and its spatial variability, the channel planform pattern, the frequency of woody debris jams and, very importantly, the types and densities of vegetation occupying the channel, riparian corridor and floodplain (see Chapter 2 for details).

It is highly significant that many channels that have been heavily modified through engineering or maintained through vegetation clearance and/or desilting lack some or all of the morphological, sedimentary and vegetational features responsible for energy dissipation listed above. The initially high hydraulic efficiency of newly constructed and recently maintained channels makes them particularly vulnerable to instability because reduced power consumption in overcoming energy losses leaves a greater proportion of stream power available for eroding the bed and banks and transporting away the additional sediment load so gained. This is true not only of channelised rivers but also of some restoration designs. Although the proportion of the total stream power available to erode and transport sediment may still be very small in such modified channels, it may have doubled or tripled compared to the pre-disturbance value.

Conversely, channels that have been significantly oversized for land drainage or flood defence purposes may experience extremely low values of specific stream power due to their excessive active widths, making them prone to siltation because they lack the capacity to transport the sediment load supplied from upstream.

Recognising these principles, and drawing on the results obtained from engineered river reaches in England and Wales by Ferguson (1981), Brookes (1983, 1987a, 1987b, 1988) and Brookes and Sear (1996), the National Rivers Authority (1994b) reported general rules linking the type of post-project channel adjustment to specific stream power:

Low energy streams ($\omega < 10\,\mathrm{W/m^2}$) – are likely to experience sedimentation that obscures constructed features

High energy streams ($\omega > 35\,\mathrm{W/m^2}$) – are likely to erode constructed features

Laterally dynamic streams ($\omega > 100\,\mathrm{W/m^2}$) – are likely to recover their sinuosity after straightening.

During the late 1990s and the early part of the twenty-first century, this oft-quoted guidance become almost a mantra in stream power and river restoration circles, but experience has shown that specific stream power cannot be used in isolation to infer either the potential for post-project adjustment, or the type of instability likely to occur in British rivers (for recent evidence, see River Restoration Centre, 2008). Further, they are definitely *not* transferable to other rivers in different morphodynamic regions of the world.

However, careful reading of the source documents makes it plain that the original authors at no time suggested that these findings were either prescriptive or transferable, or that stream power analysis could constitute a stand-alone predictor of channel response to disturbance. What seems to have happened is that, following their publication, some end users saw these general rules as a way of answering difficult questions simply and cheaply, and their application got ahead of the science base that underpins them.

Lack of a simple correlation between predicted and observed stream power values in many studies may be attributed to local variability of the type identified by Schmidt *et al.* (2001). Hence, the complexities of stream morphology at the cross-sectional scale are best avoided when using the approach (Worthy, 2005). Indeed, Brookes (2007) gives clear guidance on collecting data on bankfull discharge and slope and, in this context, it is important to remember that stream power analysis is best applied at the reach scale or greater.

When using stream power analysis to investigate likely types and patterns of channel change, additional knowledge of the fluvial system is required to identify non-alluvial reaches that are highly resistant to change or which may effectively be non-adjustable. This knowledge may be gained through a Detailed Catchment Baseline Survey, Fluvial Audit, or some other form of broadly based stream reconnaissance (Thorne, 1998; see Chapter 1). Even in alluvial reaches, stream power thresholds depend on the sediment properties of the bed and, particularly, bank materials. This means that, in addition to the specific stream power, knowledge of calibre of the bed material and the erodibility of the banks is essential to establishing locally relevant stream power bands and thresholds. Finally, while a stream power analysis can indicate whether channel adjustments are more likely to be led by erosive or depositional processes, it cannot in itself be used to predict the types and patterns of morphological change that result. This requires a sound understanding of the geomorphology of the reach in question:

1. in relation to the local balance between upstream sediment supply and local transport capacity
2. with respect the history of channel disturbance, and
3. with regard to PDPs and constraints,

as each of these factors influence the nature of morphological changes involved in channel adjustment. The information required can be obtained from a Detailed Catchment Baseline Survey coupled with a Fluvial Audit.

While recent experience has highlighted significant limitations to stream power analysis when used in isolation, it has also demonstrated that, when taken together with the appropriate information gathered from, for example a Fluvial Audit, stream power analysis constitutes a useful *screening tool* when attempting to predict channel evolution and response to engineering or management interventions in the fluvial system (Brookes and Wishart, in prep). Specifically, stream power analysis may be used during the early phases of research and project-related studies in order to establish the degree of broad-scale variability in the fluvial system, screen out reaches likely to be in equilibrium, and identify reaches liable to be adjusting through either erosion or deposition-led fluvial processes. This is not only useful in itself but it also helps establish the catchment context for more detailed, reach or site-scale investigations performed as part of a Geomorphological Dynamics Assessment. In theory, sediment modelling could fulfil the same purpose, but the results of stream power screening may obviate the need for broad-scale sediment modelling, and it has the great advantage of requiring fewer resources of time, money and specialist expertise than those required to build, calibrate, run and interpret a complex sediment model.

In addition, specific stream power has also proven useful as a means of estimating the likely travel distance for bed material grains carried by the flow as bed material load. This is useful in establishing the distance-scale for event-related transport steps that link up sediment sources and stores in the sediment transfer system. For example, in R&D Project Record C5/384/2 (NRA, 1994b), data for upland streams in different parts of the UK were combined to define relationships between the excess specific stream power during the peak of a flood event and the mean travel distance for bed particles of different sizes (Fig. 4.5).

While considerable scatter is present in the data, the upper envelope for gravel transport distance serves as a useful guide to the maximum distance over which coarse bed material particles may be expected to move between erosional sources and depositional stores or sinks during a single transporting flow event. This effectively scales the step length for coarse sediment moving through the system episodically as bed material load, which is difficult to achieve using conventional sediment transport equations or sediment models.

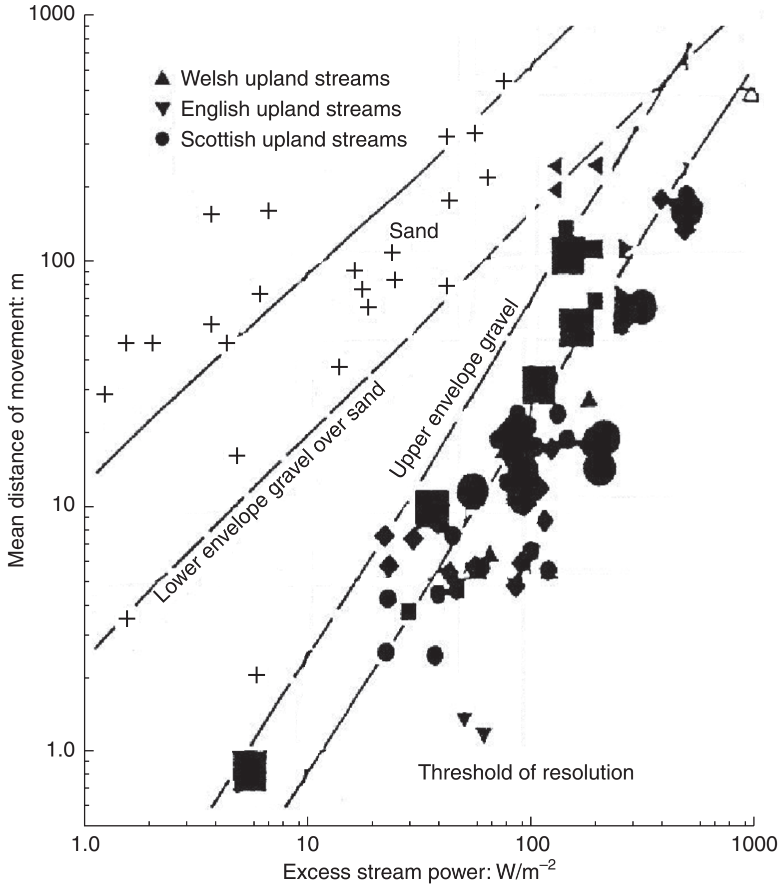

Fig. 4.5 Movement distances for bed material particles as a function of excess specific stream power above the value required to initiate motion

4.1.6 Sediment Impact Assessment Method (SIAM)

4.1.6.1 Background

Where river sediment dynamics are considered in river engineering and management projects in the UK, the Fluvial Audit. approach described in Section 4.1.4 above is currently the most widely employed approach used in investigating and characterising catchment-scale sediment dynamics and identifying geomorphic reaches as being sediment sources, transfers or sinks. While the Fluvial Audit has proven useful in river conservation and restoration projects, it cannot support the quantitative outputs required to interface effectively with the engineering components of project planning and design integral to, for example, a flood alleviation scheme. Also, the utility of the Fluvial Audit in options appraisal and selection is limited because it is not predictive and cannot simulate system response to alternative engineering or management actions.

Conventionally, quantitative analysis and simulation of sediment movement in rivers is performed through application of the equations of fluid flow, sediment transport and sediment continuity in hydraulic or hydrodynamic models that have a sediment module, such as iSIS Sediment (Mikoš *et al.*, 2003) or HEC-RAS 4.0 (Gibson, 2006). However, the resources and data required to apply these models restrict their use to the reach rather than the catchment scale, while extended run times mean that they cannot readily be used for the types of long-term, continuous simulations required to investigate sediment dynamics over long periods or through long reaches. Also, accurate sediment modelling demands both specialist training and prior experience on the part of the modeller, not only in modelling the flow of water but also in the applicability and appropriate use of different sediment transport equations. At present (2009) there are probably less than 100 academics and rather fewer practitioners in the UK who are fully competent and confident in sediment modelling.

In light of these issues, the Flood Risk Management Research Consortium (FRMRC) (see http://www.floodrisk.org.uk/) created a Work Package in the Research Priority Area concerning Geomorphology, Sediments and Habitats tasked with developing a quantitative tool which would build on the existing qualitative Fluvial Audit to derive an approach capable of:

- characterising sediment source, transfer and sink areas on a reach-by-reach basis (where reaches are defined as geomorphically consistent sub-units of a river drainage network)
- representing sediment flux divergences between reaches resulting from differences between the supply of sediment and local transport capacity, and
- predicting the reach-scale response in the sediment transfer system to alternative engineering interventions and/or management actions proposed for flood risk management purposes.

4.1.6.2 SIAM: *principles and applications*

One of the main objectives of geomorphic investigations performed as part of project-related studies is to inform selection of the most sustainable option for solving a sediment-related problem during the pre-feasibility and options appraisal stages of project planning. Usually, this will be the option that cures the site or reach-scale problem at hand within the context of the wider sediment transfer system. In doing so, such solutions avoid or at least minimise the risks associated with unintentionally triggering sediment imbalances elsewhere in the fluvial system. SIAM was developed through joint research between Colorado State University and the University of Nottingham, under funding from the US Army Corps of Engineers, specifically to facilitate this decision-making process by providing a method for rapid assessment of the impact of alternative sediment management actions on sediment balances throughout the river network. It does this by comparing sediment supply from user-defined sediment sources to sediment transport capacity on a reach-by-reach basis and so evaluating local sediment imbalances and downstream sediment yields under existing and 'with project' conditions, for different proposed sediment management options.

SIAM is embedded within the 'Hydraulic Design' module of version 4.0 of the US Army Corps of Engineers' Hydrologic Engineering Center, River Analysis System (HEC-RAS) (Biedenharn *et al.*, 2006; Gibson and Little, 2006). It works by taking hydrological and hydraulic information from the HEC-RAS, one-dimensional hydrodynamic model and using it to calculate reach-averaged bed material load transport rates by grain size under the range of recorded discharges. The computed transport rates are integrated with flow duration data to compute an annualised bed material load transport capacity for each user-defined geomorphic reach, in tonnes per year. The capacity to transport bed material load is then compared to the annualised input of bed material load from upstream and a range of user-defined, local sediment sources (e.g. bank erosion, gullies, field erosion) to estimate the balance between bed material load supply and transport capacity in the reach for each size class. In performing the calculations, it is assumed that the movement of wash load is supply (rather than transport) limited throughout the fluvial system.

Grain size accounting allows SIAM to track the wash load and bed material load components of the total load separately as they move downstream through the fluvial system. Each size fraction is treated either as wash or bed material load on a reach-by-reach basis, following Einstein's (1950) convention that wash load is sediment in transport that is not found in significant quantities in the bed. In SIAM, the threshold between wash and bed material loads may be set by the user, but the default value is the D_{10} of the bed material. Downstream changes in the threshold diameter mean that sediment that is wash material in one reach may become bed material load in the next reach downstream, and *vice versa* (Fig. 4.6).

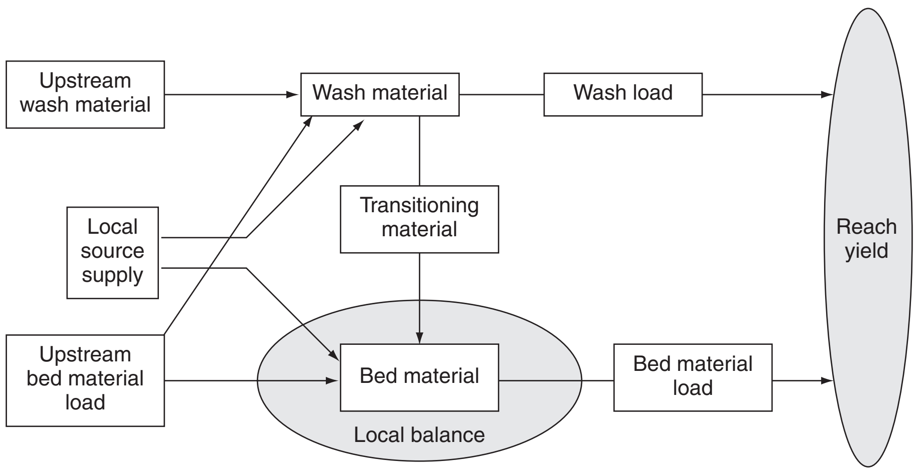

Fig. 4.6 Flow diagram illustrating how SIAM accounts for bed material and wash load dynamics in the sediment transfer system

The advantage of treating the movement of wash load as being supply limited while that of bed material load is transport limited may be illustrated by considering a channel where the upper course is steep and the channel bed material is correspondingly coarse, but the lower reaches have lower slopes, the bed material is correspondingly finer and flood control channels are prone to siltation. In such a system, sand supplied by bank erosion in the headwaters would travel as wash load in the upper course as it is finer than the D_{10} of the bed material, but in the downstream reaches it would be treated as bed material load due to the smaller size of the bed material there. In SIAM, sand would move through the upper reaches but would not reside there as there is unlimited capacity to transfer it downstream. However, in the lower reaches, the movement of sand as bed material load would be limited by the locally low transport capacity, resulting in problems due to siltation. In its predictive mode, further SIAM runs would then demonstrate that stabilising the eroding banks that are the source of the sand would not impact the balance of bed material load supply and transport capacity in the upper course, so that no morphological response to bank stabilisation would be predicted there. This would not be the case in the lower reaches, however. Here a reduction in the supply of sand from upstream would reduce the surfeit of bed material load supply over transport capacity, reducing sand deposition and sediment-related problems in the lower course. This demonstrates how SIAM can be used to make causal links between an upstream sediment source and a downstream sediment sink and so promote selection of options that promote sediment management based on using source control to address the cause of a sediment-related problem rather than its symptoms locally by, for example, dredging.

4.1.6.3 *Data inputs and outputs*

The input data required to run SIAM (Fig. 4.7) define for each geomorphic reach the:

- annual hydrograph (discharges and durations: to support calculation of hydraulic parameters in HEC-RAS)
- channel parameters (geometry and roughness: to support calculation of hydraulic parameters in HEC-RAS)
- bed material properties (particle size distribution: to support calculation of bed material transport capacities by size fraction in HEC-RAS)
- sediment supply from local sources (volumes and particle size distributions: to support calculation of annualised sediment inputs in SIAM).

In this context, local sediment sources exclude the bed but include diffuse catchment erosion, landslides, eroding channel banks, gullies, and anthropogenic sources such as arable fields, ditches, and mines. It should be noted that where sediment is removed from a reach by, for example, gravel extraction, the impact on sediment transfer can be represented in SIAM as a negative input.

SIAM delivers a table and bar charts listing and illustrating annualised transport capacities, downstream bed material and wash loads, local sediment inputs and the local balance between the supply of bed material load and the capacity of the reach to transport that load, for each sediment reach. A negative local balance indicates excess bed material transport capacity and thus the potential for scour in a reach, whereas a positive local balance indicates excess supply of bed material load and the potential for deposition. All outputs are given in terms of grain size fractions as well as totals for each sediment reach. It should be noted that while SIAM

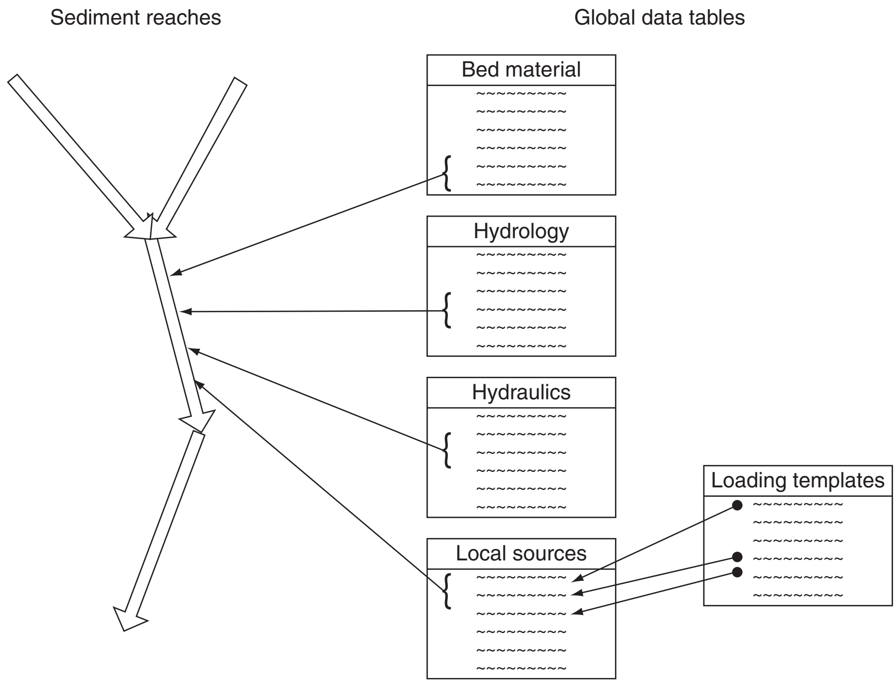

Fig. 4.7 Input data requirements to run SIAM

indicates whether sediment is likely to be removed from or accumulate in a reach, it does not predict the types of morphological changes likely to be driven by sediment imbalance. This requires consideration of the results of a SIAM study in conjunction with the findings and insights gained from other types of geomorphological investigation that might include stream reconnaissance, a Fluvial Audit or a Geomorphic Dynamics Assessment.

4.1.6.4 *Capabilities and limitations*

SIAM provides a means of accounting for sediment in the fluvial system that sits between the qualitative evaluation of a Fluvial Audit and quantitative sediment routing using a sediment transport model. It has practical utility because it can provide quantitative outputs at the catchment scale. While its results are indicative and are certainly not as precise as those of a sediment routing model, the limited resources available for geomorphic investigations often preclude the use of complex numerical models, making SIAM an attractive alternative to purely qualitative analysis.

SIAM can be used to appraise options for sediment management to screen out those that are either ineffective or risk creating new sediment-related problems in other reaches in the river that may be remote from the project reach. This is the case because the data input structure of SIAM is designed so that the sediment inputs from different sources can easily be changed, allowing the user to alter sediment loadings and investigate the impacts of various sediment management options and possible future ‘with and without project’ scenarios. Identifying which in a long list of options deserve more detailed investigation provides cost savings to the project and promotes adoption of sediment management actions that are preferable in the catchment context and which, therefore, are more likely to be permitted by regulators.

Embedding SIAM within HEC-RAS 4.0 makes the method available to the end-user community as part of a tried and tested model that is available worldwide at no cost to the user. However, it must be borne in mind that, in SIAM, the channel geometry is not updated based on the scour or deposition predicted in a reach, and so the results are only indicative of trend of morphological change due to sediment imbalance in a representative year. Since SIAM is a reach-based model that uses reach-averaged parameters and produces reach-averaged results, information on the distribution of erosion or siltation within a reach cannot be determined and the impacts of local scour or deposition cannot be simulated.

SIAM implicitly assumes that the bed in each reach is alluvial – that is, free to adjust to scour driven by an excess of bed material transport capacity over supply from upstream and local sources. Hence, it is essential for users to identify any reaches where scour is limited by bedrock or other resistant materials on the basis of the results of stream reconnaissance or bed material sampling surveys.

4.1.7 Geomorphological Dynamics Assessment (GDA)

4.1.7.1 Overview

The ultimate and most intense level of geomorphological investigation employs a series of approaches to evaluate fluvial processes, mechanisms of morphological adjustment, river channel dynamics and sensitivity to change at the scale of the individual problem site or project reach. The overall aim of a Geomorphological Dynamics Assessment (GDA) is to provide a comprehensive understanding of the three types of geomorphological data discussed in Chapter 1, pertaining to river morphology, materials and processes (and their interactions) over a range of time-scales relevant to the problem or project being investigated.

The GDA provides a framework to support decision making when balancing competing goals in river management and facilitates the identification and selection of solutions to sediment-related problems and river channel stability issues that are both effective and sustainable in terms of economy, engineering, social equity and environmental quality. A GDA requires the application of geomorphological skills and insights as well as sound field craft and technical design knowledge. Consequently, its planning, execution and interpretation demand the attention of one or more experienced fluvial geomorphologists with wide-ranging experience in applying geomorphological principles and methods to solve river management problems.

The techniques employed are generally undertaken as part of research-style investigations and involve a combination of detailed, desk-based studies together with intensive fieldwork using specialised instrumentation. As the nature of the work is highly specialised and often labour and equipment intensive, for all but the largest and most well-funded projects, these investigations can only be performed for one or two study sites, with data collection sustained for, at best, one or two years. It is, therefore, crucial to correctly identify the most appropriate sites at which to deploy the resources needed to support a GDA and this requires a thorough understanding of the fluvial system and the catchment scale sediment dynamics. Consequently, access to the results of a competently conducted Fluvial Audit (especially including any relevant GIS files and databases) is recommended as a prerequisite for planning a GDA.

In designing and performing a GDA, it is desirable to match the techniques and duration of the underpinning investigations to the nature and spatial scale of the problem being addressed. In many cases, however, the scope of the study will be constrained by the timescale of the project, the funding allocated to support geomorphological studies and the availability of people with the necessary experience in applied fluvial geomorphology. This is especially likely to be the case when the project is being undertaken by professional consultants, as the resource and management constraints intrinsic to commercial practice tend to severely limit the duration, equipment and level of effort that can be devoted to the fieldwork component of any study. As a result, many GDAs take the form of a rapid Geomorphological Assessment that is used to support sediment modelling and a range of other environmental assessments and which is deemed adequate to meeting the needs of the client and the requirements of the agencies responsible for scrutinising and/or permitting the project. Typically, assessments of this type rely heavily on historical analyses, desk studies and modelling of river flows and sediment transport using industry standard software that is supported by a single field visit or targeted visits to a small number of sites rather than a substantial fieldwork programme. However, it should be emphasised that, if the results of a GDA are to support the selection of a sustainable management solution, quantitative measurement and, if possible, monitoring of key channel forms and processes are essential for matching the solution correctly to the cause, severity and extent of the problem.

For example, when diagnosing and selecting the appropriate solution to a bank erosion problem, different study methods and equipment are appropriate to different scales of time and space (Fig. 4.8). To investigate bank erosion at a single problem

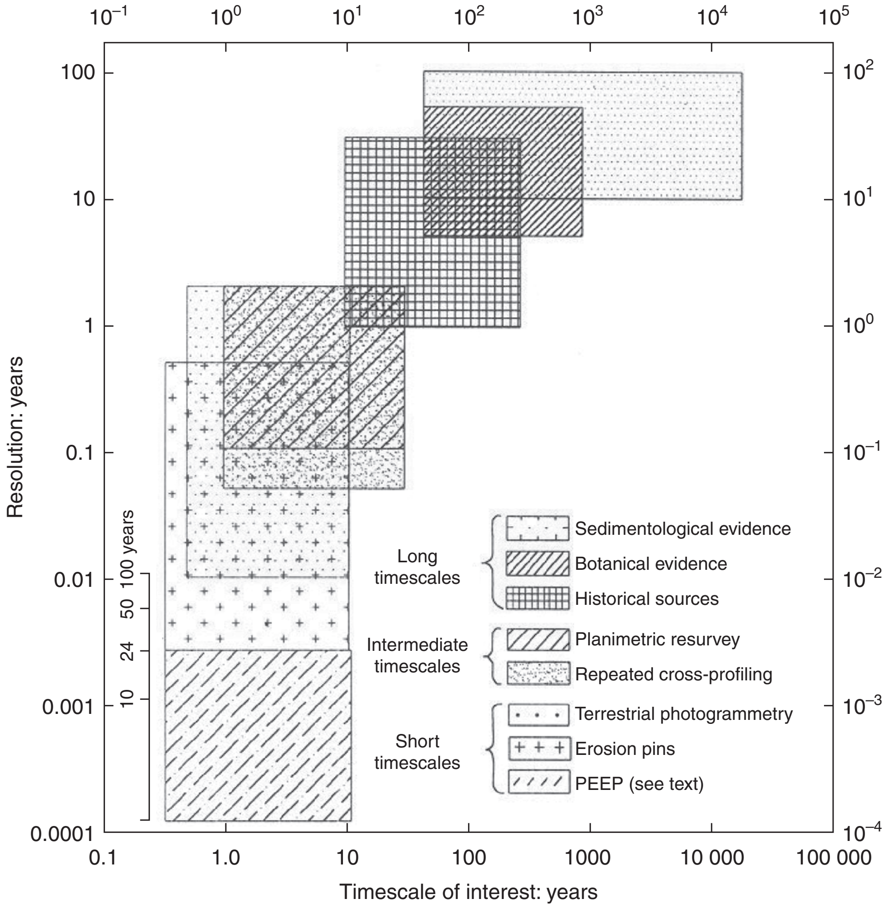

Fig. 4.8 Timescales and techniques appropriate to the assessment of bankline change at a variety of spatial scales. Modified, with permission, from Lawler, 1993. © 1993 John Wiley & Sons Limited

site, ground-based photogrammetry perhaps supported by the use of erosion pins would yield useful information on the spatial distribution of erosion, event effectiveness and the average rate of retreat provided that measurements were conducted for at least one year or, ideally, a few years. Conversely, a meaningful assessment of bankline changes at the reach scale would require evidence collected over a wider area and a longer period, probably necessitating the use of archive sources (historical maps, aerial photographs, etc.), plus interpretation of the spatial distribution of floodplain age and landform configuration, based on interpretation of the spatial distributions of plants, elevations and sediments (Fig. 4.8).

The general point here is that there are a wide range of practical methods that can be employed in a GDA and it is absolutely vital to select the appropriate techniques when designing the investigations. In a book of this breadth it is only possible to provide a brief review of some of the main techniques, and these have been grouped into the following categories of approaches.

4.1.7.2 *Geomorphological reconnaissance and morphological mapping*

Stream reconnaissance for geomorphological applications is an assessment technique frequently employed when addressing a wide range of sediment-related problems. The methodology centres on completing a series of recording sheets, mainly through field observation, together with the compilation of a photographic record of the condition of the channel. The strengths of the approach are that it can easily be adapted to the investigation of different types of river-related issue and provides a comprehensive inventory of morphological features that can support multiple forms of analysis, prediction and impact assessment. The method also provides a vehicle for progressive morphological studies through its employment in a Catchment Baseline Survey and/or Fluvial Audit and then GDA, albeit at a decreasing spatial scale of scope and analysis. A detailed commentary of stream reconnaissance is given by Thorne (1998), following earlier studies by Downs and Thorne (1996) and Thorne *et al.* (1996), with guidance on completing the relevant sections describing and illustrating through sketches the features (and processes) of the channel, river banks, floodplain and valley.

In general, the type of stream reconnaissance performed within a GDA is relatively detailed, being limited to the problem site, project reach and the reaches immediately up- and downstream. However, in many cases the relevant morphological changes and impacts may extend more widely and a series of reconnaissance surveys must be performed to provide a more complete understanding of the problem. Stream reconnaissance is particularly suitable for the assessment of a variety of river-related problems including:

- excessive or unnatural bank erosion/instability
- channel instability triggered by inappropriate river regulation or management
- morphological responses to bank protection or channel modifications for flood defence or land drainage
- local erosion/sedimentation associated with instream structures (e.g. jetties, intakes, outfalls, weirs)
- issues at river crossings (bridges, culverts)
- the impacts of sediment management, such as desilting.

However, the technique is also used more in the context of Fluvial Auditing, and is a practical method to analyse river channel change through repeated surveys as part of a monitoring programme (see below).

The results of a stream reconnaissance survey can be presented as a morphological map, illustrating the geomorphological forms, features and processes observed in the field. The map can be extended to include indicators of incision, aggradation and stability (see section 4.1.4 above and for an overview of the types of data that can be illustrated on Geomorphological maps, see Randle *et al.*, 2006).

4.1.7.3 *Historical analysis of river channel change*

Historical maps, aerial photographs and satellite imagery can be invaluable when establishing and interpreting past trends of channel change and morphological response to natural or human impacts in a problem reach, particularly in large rivers (see Gurnell *et al.*, 2003 for an overview of using historical data in studies of fluvial geomorphology). As a component of a GDA, a site-specific, historical analysis is usually undertaken in conjunction with a detailed stream reconnaissance survey. A frequently employed technique is serial cartography, which involves superimposing past channel bank lines on successive editions of large-scale historical maps to enable distributions, styles and rates of change to be ascertained (Hooke and Kain, 1982; Hooke and Redmond, 1989; Hooke, 1997; also see Lawler *et al.*, 1997 for a summary of the method). Analyses of this type can prove to be extremely informative, although they are subject to a degree of uncertainty depending on the sources accessed and the techniques used to process the historical information (see Downward, 1995). It should be noted however that the utility of historical maps is limited when attempting to relate channel changes to recent human activities (say over the past 20 to 30 years), due to the relatively long periods between map updates in the UK.

Where suitable sources are available, channel change maps can also be produced using historical aerial photographs and other remotely sensed images, such as satellite imagery (Gilvear and Bryant, 2003), although sets of repeat images are rare and digitising river features is not a straightforward task, being especially challenging where dense riparian vegetation obscures the banklines. A particular value of historical imagery, however, is in identification of floodplain features, such as meander scrolls and terrace features that are indicative of previous channel positions and adjustments. Through targeted field sampling, the floodplain sediments within these palaeofeatures can be analysed and dated, providing useful information on historical rates of lateral channel migration to validate and support the archive studies.

Despite their undoubted value in illustrating planform changes, information from maps, aerial photographs and satellite images cannot be used effectively to identify instream and vertical adjustments of river form. Establishing the spatial distribution and rate of change in the elevation and configuration of the channel bed requires repeat surveys of channel cross-sectional and longitudinal profiles and these are very rarely available unless the reach has previously been monitored in a research project or as part of a long-term flood modelling study. Given this limitation, a search should be made for alternative sources of historical information that may shed light on vertical adjustments in the project reach. For example, inspection of fixed and dated structures may reveal evidence of changes in bed level related to past morphological adjustments (see Trimble, 2008). Similarly, examination of historical discharge and stage records from a gauging station in or near a problem reach can reveal temporal trends in the stage–discharge relationship (a technique known as specific-gauge analysis) that are indicative of vertical morphological adjustments triggered by, for example, instream channel modifications, land-use or climate change.

4.1.7.4 Measurement and characterisation of channel forms and processes

Essential components of the GDA process include measuring, monitoring, characterising and analysing river channel forms and processes. However, as noted previously, unless the GDA is part of a university-led, research-level investigation, project management and resource constraints usually severely limit the opportunity for field measurements to be undertaken. A wide range of field methods are available (see Simon and Castro, 2003), and selection of those to be employed should match the field study to the scale and nature of the problem being investigated. Measurements typically include:

- channel planform mapping
- surveys of bed and water surface topography
- sedimentary surveys of the bed, substrate and bank materials
- volumetric measurements of in-channel sediment storage in bars and changes therein, within or between geomorphic reaches
- bank stratigraphy, hydrology and failure mechanics
- measurement of velocity fields in one, two or even three dimensions using an electromagnetic current meter, or acoustic Doppler velocimeter (or current profiler) to indicate areas susceptible to deposition or scour and show the presence of secondary currents that might be related to bank erosion (see Bathurst, 1997) and Whiting (2003) for further discussion on measuring stream flow and using measurements to support calculation of flow resistance and other hydraulic parameters).

The best approach to performing a detailed topographic survey is to use a Total Station or a differential GPS to construct a Digital Elevation Model (DEM) that covers the channel, riparian corridor and as much of the floodplain as necessary to provide the basis from which to identify and interpret fluvial forms and features relevant to the problem and/or project in hand. Survey points should be distributed randomly throughout the surveyed area, with additional points along edges such as bank lines, to pick out abrupt changes of slope that are otherwise lost in the triangulation procedure used to construct the DEM. If it is not feasible to produce a DEM, cross-sections should be surveyed at relatively close intervals along the channel (ideally, every one to three times the channel width) to capture local variability in channel form, with additional intermediate points surveyed in to support plotting of an accurate thalweg long profile. In addition to defining the channel geometry and its fluvial forms and features, DEM or channel cross-section data can also be used to support hydraulic geometry and regime analyses (see below), compute stream power and model sediment transport.

Sedimentological surveys should include sampling of both surface and subsurface bed materials, as well as the bar and bank materials. Standard approaches are available and should be adopted when collecting and analysing river sediment data (e.g. Wolman, 1954; Hey and Thorne, 1983; Bunte and Abt, 2001; Kondolf *et al.*, 2003) so that results are sufficiently accurate, repeatable and comparable to those of other studies. The composition and characteristics of channel boundary materials and sediments found in bars usefully supplement information gathered through stream reconnaissance, support assessment of fluvial erosion and deposition processes, provide insights into the origin(s) of sediment in the fluvial system (particularly through comparing particle size distributions at points along the channel), and supply the input data needed for sediment transport calculations and regional sediment budget/management models. In addition, sediment and channel geometry data may be used together to estimate the flow conditions at which bed and bank particles are on the point of entrainment (threshold of motion). Identifying the threshold of motion has several practical applications, for example in the examination of bed stability and for scour assessments (see discussion on channel bed scour in Chapter 2 and, for a general overview of incipient motion and sediment transport, see Reid *et al.*, 1997).

The Environment Agency of England and Wales has derived a standard bank assessment methodology that can be applied as a component of a GDA. The *Waterway Bank Protection* manual (Environment Agency, 1999) is a practical approach that advises users of the measurements needed (bank and channel sediment, morphology and flow properties) to identify dominant bank erosion processes and mass failure mechanisms, select appropriate management solutions and set up post-project monitoring arrangements (see also the overview of channel bank erosion in Chapter 3).

Measuring, mapping and characterising the physical biotopes and functional habitats in the channel from morphological, sedimentological and velocity data can be undertaken as part of a GDA to provide an overview of the conditions to which the instream ecology is exposed (see Clifford *et al.*, 2006). On this basis, an informative dataset can be developed that is of assistance when selecting appropriate management solutions to problems related to lack of habitat quantity, poor quality and/or limited diversity. In many cases, the percentage channel area occupied by riffles, pools, runs and glides can be ascertained relatively quickly to indicate the richness of biotopic conditions and so guide efforts to restore in-channel habitats.

4.1.7.5 Hydraulic geometry and regime analysis

Regime analysis is a method that can be applied to predict the three-dimensional shape of alluvial channels in dynamic equilibrium, and is, therefore, a means for quantifying differences between channel geometries in unstable and stable river channels. In regime channels, the channel dimensions, planform configuration and slope are adjusted to the prevailing flow and sediment regimes so that the sediment load supplied from upstream can be transmitted downstream without net aggradation, degradation or width change through time. In most cases, and following the hydraulic geometry approach introduced by Leopold and Maddock (1953), the main independent variable is the dominant discharge or ‘channel forming’ flow. This is generally taken to be the bankfull discharge and often found to correspond to the effective discharge or flow that transports most sediment (for example, Andrews, 1980). In gravel-bed rivers, the bankfull discharge, on the annual maximum series, is often found to have a return period of about 1.5 years (Hey, 1975), although there is considerable scatter about this value. Most regime-type equations predict bankfull width, depth and velocity, with slope generally found to be too poorly correlated with discharge for practical use. In addition, equations predicting meander wavelength from bankfull width with high degrees of correlation have been reported widely in the literature (Soar and Thorne, 2001).

The American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modelling of River Width Adjustment (1998b) recommends employing regime theory as a simple assessment of equilibrium conditions and to provide a rapid indication of the present morphological status of disturbed river channels. For example, in a quantitative analysis of the impact of flood control measures on the River Blackwater, UK, Thorne *et al.* (1996) compared the cross-sectional dimensions of the constructed channel, measured from field survey, with those derived from the regime equations of Hey and Thorne (1986). They showed that the imposed width and depth were almost double the values expected for an undisturbed river, while the bankfull channel capacity was approximately four times the dominant discharge. Their analysis also revealed that, notwithstanding the enlarged condition of the channel, the low stream power and the limited availability of sediment for transport were likely to severely restrict natural recovery, justifying active restoration of the channel to recover lost habitat quality and diversity.

A range of regime equations have been developed and there is a wealth of literature on the subject (see Chapter 2 for a review of downstream hydraulic geometry, and for summaries see Hey and Thorne, 1986; Hey, 1997; Soar and Thorne, 2001). As with all empirical equations, however, caution must be exercised in their use as they are derived from specific ranges of conditions and exhibit a degree of uncertainty that reflects the natural variability of stable, equilibrium conditions found in natural channels.

Soar and Thorne (2001) present a comprehensive analysis of regime equations for both sand-bed and gravel-bed rivers that are considered to be undisturbed and in dynamic equilibrium. Different equations are presented for riverbanks characterised as either erosive or resistant due to the presence of riparian vegetation. Practical design equations for predicting the stable bankfull width, W, in UK gravel-bed rivers and US sand-bed rivers as a function of bankfull discharge, Q, within 95% confidence limits on the mean response are given by:

Sand-bed rivers $$W = (3.38 + 1.94V)Q^{0.5}\,\mathrm{e}^{\pm 0.083} \tag{1}$$

where e is exponential and the binary variable V has a value of unity if tree cover over the banks is less than 50%, and a value of zero if tree cover over the banks is equal to or greater than 50%.

Gravel-bed rivers $$W = (2.48 + 1.27V)Q^{0.5}\,\mathrm{e}^{\pm 0.051} \tag{2}$$

where V has a value of unity if banks are 'grass lined' and/or tree/shrub cover over the banks is less than 5% and a value of zero if banks are 'tree-lined' with at least 5% tree/shrub cover.

In some cases, it may be possible to derive regional regime relationships from measurements taken at undisturbed reference sites on the river system that is the subject of the GDA, or from sites in neighbouring catchments exhibiting the same types of hydrological and physiographic conditions, and apply them to the project reach (see Harrelson *et al.*, 1994 for a guide to identifying reference reaches). While the number of sample sites might be insufficient to develop regression equations, plotting the stable channel dimensions from just a few locations can still provide a useful visual guide for use in channel design or to support locally referenced investigations of channel instability.

4.1.7.6 *Assessment of sediment yield and effective flows*

To gain a general understanding of the sediment transfer system in a GDA it is often useful to estimate and compare annual sediment yields at selected points in the drainage network. The annual bed material load at a particular location can be predicted by applying a suitable sediment transport equation over the range of flows experienced at that location. Guidance on the choice of transport equation is given by Gomez and Church (1989) and Yang (2006) and a review of equations used in applications is provided in Chapter 3. In estimating the annual bed material load, the 'effectiveness' of individual discharge classes in transporting sediment over the period of flow record can also be examined (see Biedenharn *et al.*, 2000; 2001 for practical guidance). Applications for this type of analysis include examining disparities between sediment supply and transport capacity for a problem or project reach, providing input data with which to construct a catchment sediment budget (see Reid and Dunne, 2003) and supporting closure between sediment supply and transport capacity when designing channel restoration works intended to ensure equilibrium in sediment transfer within the fluvial system (Soar and Thorne, 2001).

In this context, it must be noted that application of conventional sediment transport formulae requires detailed information on channel geometry, discharge and bed material sediment size gradation – information that is seldom available from archive sources and which is likely to be too expensive to collect to support the design of any but the best financed project investigations. In practice, the data necessary to calibrate a sediment transport equation are generally unavailable in the UK and it is neither cost-effective nor time-efficient to propose that a field campaign be mounted to validate the accuracy of conventional sediment transport calculations. When applied uncalibrated, uncertainties in calculated sediment transport rates are large and the results can only be taken to be indicative of actual transport rates. This is the case because research studies have shown that even the best bed material load equations produce predictions that are only within a factor of 2 of measured loads for 70% of the time. In addition, the load of sediment that is finer than that found in the bed and which constitutes 'wash load' is supply limited rather than transport limited, and it cannot be predicted using any sediment transport equation that relies on parameters describing the stream hydraulics, channel morphology and bed sediment characteristics to predict the capacity of the flow to transport bed material. This is unfortunate as the 'wash load' commonly makes up more than 80% of the total sediment load carried by a river.

Under circumstances where it is necessary to estimate the sediment load routinely as part of a GDA, an approach developed by the Environment Agency (1998a) has proven particularly useful in situations where physically-based equations cannot be applied as data are limited. This involves predicting sediment load as a function of catchment area. Based on the observed data in Fig. 4.9 (National Rivers Authority, 1991), equations have been developed for the annual yields of bedload and suspended sediment load in both source areas (headwater catchments) and larger catchments (Environment Agency, 1998b).

Small catchments (especially headwater basins) with drainage areas less than $\sim 100\,\mathrm{km}^2$:

$$(r^2 = 0.31) \qquad \Psi_{\mathrm{bed}} = 5.85A^{1.08} \tag{3}$$

$$(r^2 = 0.63) \qquad \Psi_{\mathrm{susp}} = 11.64A^{1.16} \tag{4}$$

Large catchments with areas greater than $\sim 100\,\mathrm{km}^2$:

$$(r^2 = 0.41) \qquad \Psi_{\mathrm{bed}} = 2.50A^{1.16} \tag{5}$$

$$(r^2 = 0.48) \qquad \Psi_{\mathrm{susp}} = 31.04A^{1.04} \tag{6}$$

where Ψ_{bed} = annual bedload yield (tonnes/year), Ψ_{susp} = annual suspended load yield (tonnes/year) and A = drainage area of the contributing catchment (km^2).

Clearly, the limited empirical database underpinning these formulae, taken together with the relatively low coefficients of determination for the regression equations, indicates that they should be applied with a degree of caution and that the predictions they produce are purely indicative and subject to a degree of uncertainty. Nevertheless, the robust form and minimal data required to apply these equations

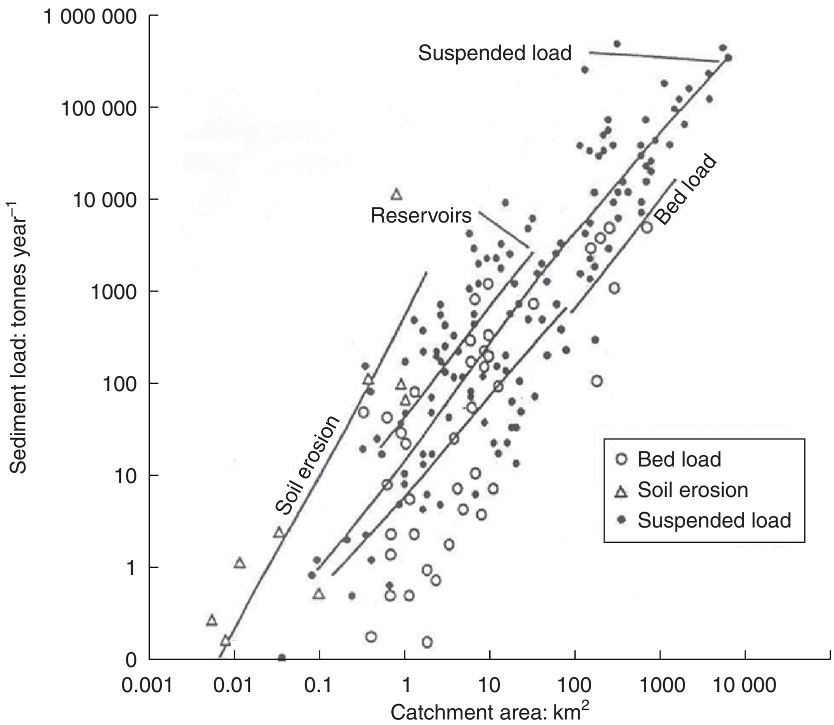

Fig. 4.9 Observed data for sediment yield (bedload and suspended load) as a function of catchment area in UK rivers from the National Rivers Authority, 1991. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

makes them useful when initial estimates of sediment yield are required. In this respect, they present a preferable alternative to ignoring sediment entirely when characterising a study reach in the context of the problem investigation or initial design steps in a river management or restoration project.

4.1.7.7 *Sediment transport and bank stability modelling*

Differences in the utility, data requirements and modes of application of different modelling tools mean that the selection of appropriate tools is project-specific, being determined primarily by the nature of the problem to be investigated. When all that is required is an estimate of sediment transport at a given cross-section, software is available to compute both event-specific and annualised transport rates and yields based on a user-selected sediment transport equation. A good example of this type of functionality is the SAM (Stable Alluvial Method) Hydraulic Design Package, originally developed by the US Army Corps of Engineers (USACE) Waterways Experiment Station, Vicksburg, Mississippi and now managed by Ayres and Associates, Inc., Fort Collins, Colorado. (http://www.ayresassociates.com/Web_ SAMwin/overview.htm).

More commonly, however, sediment transport analysis must account not only for sediment transport into and out of the study reach but also bed level changes through aggradation or degradation that result from imbalance between sediment input and output. This requires application of a hydraulic or hydrodynamic flow model with a sediment transport function. Examples of the models that can be employed for this type of analysis include iSIS Sediments, which is a module of the iSIS software developed through a joint venture between Halcrow Group Ltd (http://www.halcrow.com/isis/sediment.asp) and HR Wallingford Software Ltd (http://www.wallingfordsoftware.com/products/isis/sediment. asp) and HEC-RAS 4.0, which has been developed by the Hydrologic Engineering Center of US Army Corps of Engineers (http://www.hec. usace.army.mil/software/hec-ras/). These models are suitable for the study of sediment transport and associated bed level changes in a range of fluvial environments, being particularly useful in the study of sediment problems related to significant channel modifications, flood defence assets, bridges, pipeline crossings, impoundments and sediment management activities such as dredging, desilting or aggregate/mineral extraction. However, both models simulate flow and sediment movement in just one dimension and, where it is required to account for complex flow patterns, multidimensional models must be used. An example of a two-dimensional flow and sediment transport model is MIKE-21, developed by the Danish Hydraulics Institute (DHI) (http://www.dhigroup.com/Software/Marine/MIKE21.aspx), which has been used successfully in many investigations of sediment dynamics in rivers and estuaries.

While these computer models allow sediment transport computations to be performed accurately, problems related to model stability and excessive run times limit their capability to perform long-term, continuous simulations and the skills of an experienced modeller with a sound knowledge of sediment transport mechanics are essential to ensure reliable operation of the model and sensible interpretation of its results. Furthermore, as noted earlier, collection of the datasets necessary to support sediment modelling requires a considerable investment in archive and field data collection and preprocessing. The resources needed to build and operationalise a sediment transport model are also non-trivial. Currently, the performance of any sediment modelling is the exception rather than the rule in project-related investigations, while modelling that extends to two and, especially, three dimensions remains a research-related activity beyond the scope of most project investigations.

Bank stability modelling yields insights into the causes of bank retreat, provides a quantitative basis for the identification of key geomorphic thresholds such as the critical bank height for mass failure, and allows predictions to be made concerning bank stability response to toe scour and/or over-steepening. Simple spreadsheet-based, geotechnical analyses for shear failures in steep river cliffs formed in well-drained cohesive soils (Osman and Thorne, 1988; Thorne and Osman, 1988) may be used to perform indicative calculations in scoping studies. More advanced models that account for excess pore water pressures generated by rapid drawdown in poorly drained banks provide the basis for more detailed investigations as well as allowing a probabilistic approach to be adopted (Darby and Thorne, 1996). Where it is required to account for the effects of bank stratigraphy, pore water pressures/suctions and the presence of plant roots that reinforce the soil, the BSTEM model developed by the US Department of Agriculture may be applied (http://www.ars.usda.gov/Research/docs.htm?docid=5044; Pollen and Simon, 2005). A useful overview of processes, mechanisms and modelling of river bank erosion and geotechnical failure is provided by the American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics, and Modelling of River Width Adjustment (1998a, 1998b) and a review of bank retreat parameterisation and modelling is given by Parker *et al.* (2008). However, as in the case of sediment modelling, reliable modelling of bank stability depends as much on the capability of the modeller as the sophistication of the selected computer model. The fact is that regardless of the model selected, the skills of an experienced modeller with a sound knowledge of soil mechanics are essential to ensuring reliable operation of the model and sensible interpretation of its results.

4.1.7.8 *Monitoring programmes*

The decision to monitor river form and process represents a serious commitment to fieldwork and is seldom possible unless the project team have access to a directed research programme funded by a research council or government agency. Monitoring programmes that might be employed in a GDA under these circumstances can be divided into two types: repeat surveys and continuous measurement. Different types of repeat surveys are available, including those based on: stream reconnaissance; planimetric mapping aided by geographical information system (GIS) methods; repeat cross-section profiling; bed and substrate sampling; and fixed point photography. Repeat surveys should be performed at regular intervals, with additional surveys undertaken following each event (natural or anthropogenic) that has a significant impact on channel morphology. Repeat surveys have been shown to be generally applicable to the investigation of a wide-range of issues related to channel stability and change, and to be useful in establishing the geomorphological impacts of all kinds of natural and management-related phenomena.

Monitoring that involves continuous measurement may include: discharge and/or water surface elevation; suspended sediment and, exceptionally, bedload transport rates; and rates of vertical and/or lateral erosion. Continuous monitoring of discharge or stage usually requires the setting up of a hydrological station with dedicated measurement and data logging equipment. Continuous monitoring of sediment transport is only meaningful if related to flow monitoring at a hydrological station and is sufficiently challenging to be considered beyond the scope of all but the best funded projects. Measuring and monitoring techniques in general have been reviewed by Reid *et al.* (1997) and Hicks and Gomez (2003), while detailed treatments of suspended and bedload monitoring are provided by Wren *et al.* (2000), and Ryan and Troendle (1997) and Bunte *et al.* (2004), respectively. Hassan and Ergenzinger (2003) provide a useful commentary on the use of tracers as an alternative to fixed bedload samplers. Continuous monitoring of vertical channel changes may be accomplished using a bathymeter attached to a fixed structure such as a bridge, while lateral erosion rates on an eroding bank might be monitored by installing photoelectronic erosion pins (PEEPs) (Lawler, 1992). Monitoring techniques for bank erosion more generally have been reviewed by Lawler (1993) and Lawler *et al.* (1997).

Reviews of some of the above techniques in the context of impact assessment, modelling and monitoring are provided by Skinner and Thorne (2005) and Randle *et al.* (2006).

When designing a monitoring programme, the practical strategy should be carefully tailored to the problem being investigated, must be achievable given management and resource constraints of the project, and should be designed to maximise the utility of the dataset generated for multiple applications. The frequency and duration of sampling are crucial considerations and, ideally, the time span should be sufficiently long to detect seasonal fluctuations in process–form relationships and observe the processes operating under a range of geomorphologically-significant flows, up to and including bankfull discharge. Hence, it is recommended that the duration of a GDA-related monitoring programme should be at least one year.

4.1.7.9 *Brief for a GDA*

It is not possible to write a definitive methodology for performing a GDA as the assessment should employ techniques that are suited to a specific problem, within recognised operational constraints. However, when addressing a significant, sediment or channel instability related problem, it is recommended that the following steps be taken.

1. Assess the problem within the context of the fluvial system in terms of fluvial processes, morphological change/evolution, human activities, operational maintenance and catchment management plans/goals. It is recommended that this contextualisation be informed on the basis of the results of a Catchment Baseline Survey and/or Fluvial Audit performed earlier in the project, and developed through examination of historical maps and archival information, interviews with relevant river management agency staff and the completion of a detailed geomorphological stream reconnaissance for the problem reach.
2. Perform an intensive programme of surveys and measurements to characterise reach-scale geomorphological processes and forms, followed, if feasible, by a sustained period of monitoring to elucidate the types and scales of sediment dynamics operating within the reach, the nature of morphological adjustments occurring in response to natural events and human impacts, and evolutionary trends operating within the fluvial system.
3. Use the results of items 1 and 2 above to predict future morphological change within the problem reach under a ‘do nothing’ scenario. If it is determined that the problem is likely to persist and that the risks this poses to people or infrastructure are unacceptable, identify possible solutions based on active channel management approaches. Active channel management might involve:
   i. changing the maintenance regime or usage of the reach if identified to be causing or contributing to the problem
   ii. allowing adjustment of channel morphology if change is occurring naturally, or
   iii. relocating, realigning or modifying existing assets (for example, footpaths, fishing pegs, bank protection structures and flood embankments) to reduce the risk posed by sediment-related processes or channel instability.

   Where there is no feasible solution through active channel management, structural measures may be considered.
4. For both active management or structural measures, use the results of items 1 to 3 above to predict the nature and scale of ‘with project’ morphological response to the alternative management actions or engineering works, with a view to identifying those alternatives that do not trigger additional problems either on site or elsewhere in the river system.
5. For active channel management or structural measures, use the results of items 1 to 4 above to match the scope, strength and length of channel covered by the preferred alternative to the cause(s), severity and extent of the problem. In some cases, where a site-scale problem is associated with reach or system-scale instability, this may involve management actions or engineering works located beyond the immediate site.

4.1.7.10 Outcomes of a GDA

The outcome of a GDA should be a report detailing the investigations and assessments performed and recommending alternatives as described above. This should include the following:

1. Assessment of the sediment-related or channel instability problem within the context of wider catchment issues.

2. Characterisation of the problem in terms of its extent, severity, processes and mechanisms.
3. Identification of the underlying cause(s) of the problem (supported by the findings of an existing Catchment Baseline Survey and/or Fluvial Audit, where available).
4. Justification for allowed morphological adjustment, active channel management or structural measures.
5. Recommendation of the alternative that best matches the solution to the nature and scale of the problem, with active management preferred, where feasible, to structural works. In the case of solutions involving structural measures, soft engineering using natural materials should be considered in preference to hard solutions using artificial materials, wherever possible.

4.1.8 Geomorphological post-project appraisal

4.1.8.1 Overview

Post-project appraisal (PPA) should be integral to the planning, design and implementation of all capital works and significant maintenance operations that affect a river or floodplain. This often neglected part of a project is actually essential for two main reasons. First, it is necessary when verifying that the work was performed in compliance with the proposal and the relevant permit or statutory approval. Second, it provides the basis for assessing the performance of the works or actions, identifying the need for any adaptive management, appraising the success of the project and disseminating experience gained. The PPA process further offers the opportunity to evaluate the applicability of key components of the works, such as specific design approaches or restoration measures, to the particular conditions encountered at the project site. In addition, PPA is the only way that the unanticipated side-effects of a project or maintenance operation can be identified, and experience shows that there always are unintended consequences to any river management or engineering action. In essence, the philosophy underpinning PPA is to enable practitioners to learn from experience (both good and bad) and facilitate post-project management and to feed back the knowledge gained in order to improve design guidance and professional best practice.

Planning the PPA procedure appropriate to a project or maintenance operation should form an integral component of project planning and design, with pre-project conditions established prior to implementation and an 'as-built' survey performed immediately following completion of the works (Fig. 4.10). There is considerable debate concerning how soon after completion post-project monitoring should commence, but generally it is considered that once monitoring begins it should continue for at least 3 to 10 years (Skinner *et al.*, 2008). This is necessary to allow time for the river to respond to post-project conditions at the site and reach scales and so enable trends of channel adjustment towards a new equilibrium morphology to emerge and be identified.

It is critical to successful PPA that baseline data on pre-project conditions and trends of change are assembled, that the aims and objectives of the project can be accurately defined, and that the project design principles are known and properly documented (including design drawings where appropriate). It is therefore necessary in any river project to collect baseline data at the site and reach scales in order that changes in morphology, environment, habitats and ecosystems that occur following the implementation of a scheme can be compared to the pre-project condition and evaluated accordingly. Similarly, the aims and objectives of the project must be

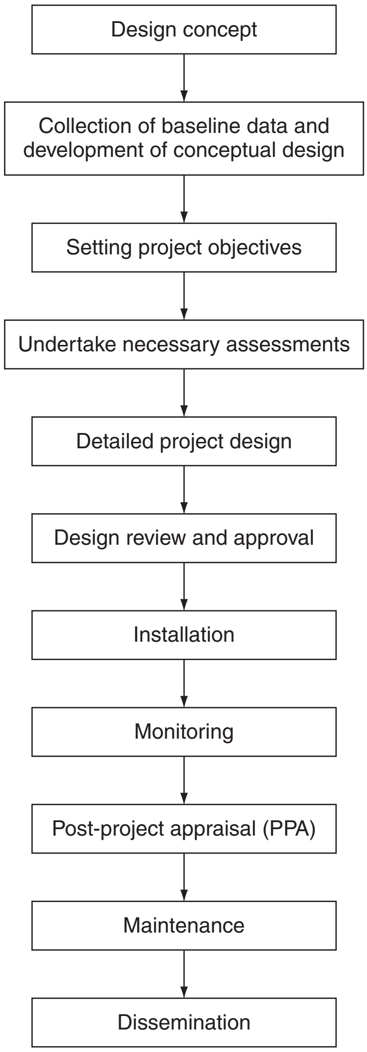

Fig. 4.10 Project execution procedure. Adapted, with permission, from Skinner and Bruce-Burgess, 2004. © CIWEM

known so that its actual outcomes can be appraised with respect to the project's documented goals. Historically, lack of clearly stated aims and objectives has limited the potential for PPA to assess the success of many projects by their own terms, making it necessary to appraise schemes relative to generic criteria, such as standard indices of sustainability. Ideally, objectives should be measurable so that quantitative as well as qualitative measures of the project's success can be derived. In the case of projects that involve channel resectioning, realignment and/or the installation of structures, it is important that the design drawings that the contractor used to implement the works are documented and made available for PPA.

It is also especially useful if a set of 'as-built' drawings is also created to record any intended or unintended differences between the project as designed and as built. This is important when appraising the project for a number of reasons. First, it allows appraisers to determine whether the project was actually built according to the design that was produced by its proponents: in practice on-site changes are often made for perfectly good reasons to do with site conditions, unforeseen construction issues and/or ease of construction. Second, it supports a 'compliance audit' to check whether the project was built in compliance with the permissions granted by the relevant regulatory authorities. Third, it provides a sound basis on which to monitor change or deterioration in any structural elements and evaluate post-construction responses more widely in the fluvial system. Once the 'as built' survey has been completed, monitoring must be continued for years or even decades in order to accrue the body of evidence necessary to support appraisal of the performance of the project and to establish trends of morphological adjustment occurring in response to its installation and operation.

Clearly, the methodological basis for a PPA must be sound if its findings are to be credible. In the late-1990s, a Geomorphological Post-Project Appraisal (GPPA) methodology was developed at the University of Nottingham (Skinner, 1999). However, uptake of this and other standardised approaches to GPPA has been slow, due largely to lack of appreciation of the potential benefits of using a standard approach, coupled with difficulties in securing funding to support monitoring that extends much beyond the period of project implementation. Encouragingly, recent best practice in river projects and, particularly, river restoration has increasingly involved incorporation of GPPA into project planning, while recognition that post-project appraisal presents the potential for 'future-proofing' projects designed with adaptive management in mind has strengthened the case for monitoring and after-care. In Europe, the requirements of the Habitats and Water Framework Directives further promote GPPA, as once restoration or rehabilitation has allowed a water body to achieve 'Good Ecological Status' through recovery of a more natural hydromorphology in the river, the stakeholders responsible for it must 'take the necessary measures to prevent deterioration of status' (Commission of European Community (CEC), 2000). The effect is to impose a duty to monitor the performance of any rehabilitation or restoration scheme, appraise whether its impacts are being sustained and, if not, take the steps necessary to prevent deterioration in the ecosystem through, for example, adaptive management.

4.1.8.2 *Methodological approach*

In essence, GPPA represents a particular type of environmental assessment (Sadler, 1988) and its methodology should be capable of being adapted to appraise any aspect of a variety of river management actions and engineering interventions. In this context, the main steps in the procedure developed by Skinner (1999) and illustrated in Fig. 4.11 are to:

- collect the documents and information necessary to support GPPA (desk study)
- determine whether the project was constructed as planned and whether the 'as-built' condition is in compliance with the relevant permits (compliance audit)
- monitor whether the project is performing as intended by comparing its outcomes to the detailed objectives and design criteria stated in the original planning and design documents (performance audit)
- survey whether any unanticipated/unintended responses are occurring in the fluvial system that may either jeopardise or add value to the performance of the project
- flag any particularly successful techniques applied in the project and promote them in order to improve 'best practice'
- appraise the short-term success of the project against the goals and aims stated in the project proposal and provide an indication of whether success is likely to be sustainable over the longer term
- identify any requirements for maintenance work or adaptive management.

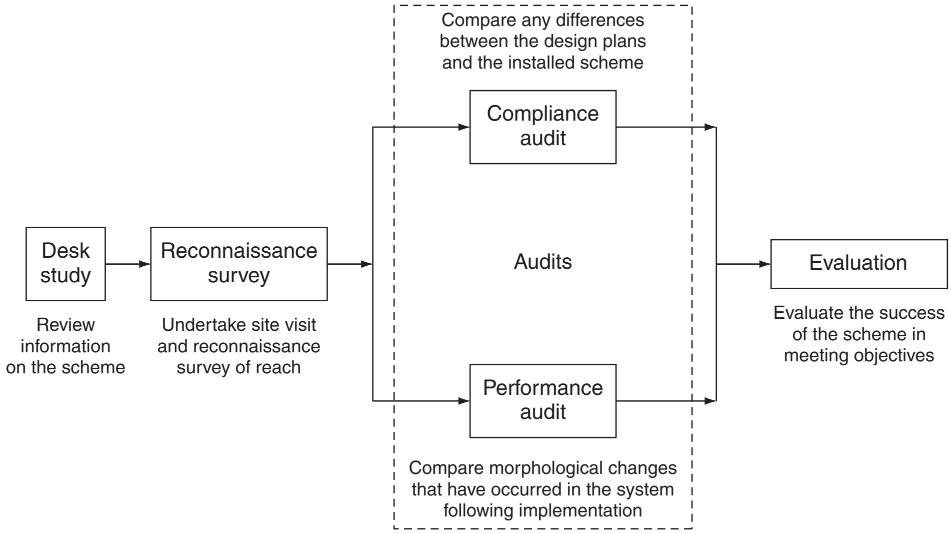

Fig. 4.11 Geomorphological post-project appraisal procedure. Adapted, with permission, from Skinner, 1999. © Kevin Skinner

4.1.8.3 Desk study

The desk study is an important starting point for GPPA, with the overarching aim being to collect all the information necessary to establish the morphological goals, objectives and design criteria of the project and characterise the pre-project state of the river in the contexts of both the project reach and the wider catchment. The information that must be obtained comes from project-related documents dealing with: project planning, goals and objectives; options evaluation; hydrologic, geomorphic, hydraulic and biological investigations; design (including drawings); and implementation (including 'as-built' drawings). Useful additional sources of information on the river and its environment include documents relating to the catchment in general and reports related to previous works undertaken in the project or adjacent reaches. This information is used, along with the project's stated goals and objectives, to define the scope of the GPPA and the area to be monitored. It must be recognised that the compilation of a substantive and comprehensive body of information in the desk study provides the foundation from which a GPPA may meet its objectives.

4.1.8.4 River reconnaissance survey

The river reconnaissance survey is important for three reasons. First, a qualitative reconnaissance survey can help establish the geomorphological conditions in the project reach prior to project implementation (see Section 4.1.7.2). The information collected is similar to that compiled in a Fluvial Audit, focusing on understanding sediment dynamics in the project and adjacent reaches and based on observation of sediment features, river morphology and morphological changes involving channel incision, lateral shifting, aggradation or planform metamorphosis. The reconnaissance record sheets and geomorphic map that are produced from the field survey provide the basis for interpreting process–form relationships operating in the river before the project was constructed. Second, many projects fail to provide funding to support a post-construction survey and comparison of geomorphic record sheets and maps derived from river reconnaissance performed prior to and immediately following construction can enable differences between the pre-project 'as-designed' and 'as-built' conditions to be established. Third, in the case of projects that make no provision for a formal programme of post-project monitoring, periodic reconnaissance surveys can provide a preferable alternative to 'doing nothing' by generating information and supporting the interpretation of geomorphological process–response changes in the project and adjacent reaches.

4.1.8.5 *Compliance audit*

The compliance audit should be undertaken as soon as possible after construction of the scheme. The objective of this element of GPPA is to identify and characterise any differences between the project 'as designed' and 'as built'. In practice, the project actually constructed often differs significantly from that designed due to miscommunication between the design team and the contractor, contractor error and/or unforeseen site conditions or circumstances that must be accommodated through on-site changes. It is important to identify and document these differences for two reasons.

First, while they may or may not be reasonable and allowable in terms of the relevant contract documents, it is still necessary to demonstrate that the project was built in compliance with the permits governing its design and construction. Second, differences between project design and build may be responsible for unexpected performance attributes and outcomes or, in extreme cases, failure of the project. Significant deviation from the design must, therefore, be detected to avoid attributing poor performance or failure to what was actually a sound approach. Key parameters to be checked in the compliance audit include the dimensions, slope, cross-sectional geometry and bed materials of constructed channels, and the positioning, dimensions and materials used in any structural elements. However, a raft of other variables may also be important and these too should be checked, on a case-by-case basis. For example, where a project involves the use of vegetation it is important to check that the *taxa*, quality, density and assemblages used in each of the plantings conform to those specified in the design documents.

The output of the compliance audit is a document that records any differences between the project as designed and as constructed, as well as the reasons why any differences occurred. The compliance audit should be retained on the project file so that subsequent performance audits can take these differences into account and so that they are factored in when evaluating the project's success as a whole.

4.1.8.6 *Performance audit*

The performance audit compares the morphological outcomes of the project to those intended when it was proposed, planned and permitted (with due allowance made if the project was not constructed as designed). This audit therefore requires that the morphological goals of the project are expressed in the form of measurable objectives against which the actual outcomes of the project can be compared. Ideally, the project planning process also should extend to designing the monitoring strategy necessary to check if the objectives have been achieved and so support a performance audit (see Fig. 4.10), though this is still rarely achieved in practice.

The first step in a performance audit is to establish, from the desk study, what pre-project data are available. If pre-project data are unavailable, qualitative (and any quantitative) information from a reconnaissance survey can be used to help establish the condition of the river prior to project implementation, although this is a weak substitute for the hard data that should be available from a pre-project monitoring programme. The second step is to determine, from the compliance audit, how the project 'as built' differed from that planned and designed. Having established the condition of the channel prior to and immediately following construction, performance auditing next requires determination of the nature and distribution of morphological changes that have occurred since installation. This is best achieved through a programme of post-project monitoring designed to elucidate the temporal and spatial performance of the scheme and the responses it has triggered in the fluvial system. As noted earlier, if monitoring is impossible, periodic reconnaissance surveys may be employed instead as a less than ideal substitute.

A particular issue arises when GPPA is applied to audit the performance of a river restoration or rehabilitation project that invokes 'prompted recovery' rather than structural measures or channel reconstruction to achieve the intended morphological outcomes. In schemes that employ prompted recovery, the timescale required for the recovery of more natural forms and features in the channel is indeterminate as recovery relies on the occurrence of morphologically-significant runoff events that are weather-related. Consequently, the timing and duration of monitoring programmes or reconnaissance surveys required to establish project performance cannot be accurately specified in advance and the commitment to monitoring must be, to a degree, open ended. Experience indicates however that in the UK a reasonable assessment of trends of morphological adjustment through 'prompted recovery' in response to a restoration project can be meaningfully audited between 3 and 10 years after implementation.

4.1.8.7 Geomorphic evaluation

Geomorphic evaluation is the last stage of the GPPA methodology. It draws together the results of the compliance and performance audits to support evaluation of the success of the scheme in meeting its stated goals and objectives. Provided that the necessary information is available, the project can be evaluated not only in terms of its geomorphological response to implementation of the project but also with respect to the likely trajectory morphological adjustments into the future – allowing the appraisal team to comment on the longer-term sustainability of the morphological improvements gained from the project. This is the case because detailed monitoring and geomorphic interpretation provide a sound basis from which to identify causal links between process–response mechanisms inherent to the river and adjustments triggered not only by the project but also by other potentially disturbing phenomena (PDPs) that perturb dynamic stability in the river network. Hence, the findings of the geomorphic evaluation should be factored into any wider post-project appraisal of the project as a whole to allow consideration of its success within the context of the catchment, fluvial and ecosystems.

4.1.8.8 Outputs

The output from a Geomorphic Post-Project Appraisal is a substantive report (20–30 pages) detailing the results of the desk, reconnaissance, compliance, performance and evaluation stages described above and appraising the performance of the project with respect to fluvial processes, river morphology and habitats. If the GPPA is being undertaken within 3–5 years of project completion then the results of the appraisal can only evaluate impacts and geomorphological responses in the short term. It follows that appraisal of the degree to which the project has been successful in meeting its objectives is, likewise, limited to a short-term assessment, although a 'forward look' may be included in the appraisal based on emerging trends of morphological recovery and adjustment to the project. Short-term appraisal is still important however as stakeholders are always interested in the immediate effects of a river project and early identification of adverse responses in the fluvial system is vital to scheduling the adaptive management actions necessary to limit or reverse deterioration in the morphology and/or habitats.

However, only by continuing GPPA for a considerable period (5 or more years) can the longer-term impacts and morphological responses associated with a project be revealed and the sustainability of its success be established. Added benefits of continuing appraisals for 5 to 10 years after implementation include determining how the channel in the project reach has adjusted to the direct impacts of the scheme and how the channel in the project and adjacent reaches has evolved through time as an integral part of the wider fluvial and catchment systems. A GPPA report based on desk, monitoring and reconnaissance surveys performed over a decade or more should also be able to comment on how resilient the project (and its success) has been to the impacts of extreme events, providing a sound basis from which to comment with increased confidence on channel stability and the likely future trajectory of any ongoing morphological change. It follows that the outputs of an authoritative GPPA can inform discussion of the long-term performance of the project as well as establishing the sustainability of its outcomes and success.

In summary, the outputs of a GPPA should be useful first in establishing the degree to which a project has been successful, second in supporting adaptive management of the project in question and third in contributing to improved project designs for future projects.

Hence, the report should include a section synthesising the lessons learned during the GPPA and providing pragmatic advice that could be used to guide and improve future GPPA exercises. Additionally, suggestions for adaptive management, such as changes to the maintenance regime or other actions designed to reduce the adverse impacts and/or improve the performance of the project should be presented, always bearing in mind the agreed success criteria for the scheme.

Wider dissemination of the outputs of GPPAs is critical to improving best practice and ensuring that lessons learned from the project are brought to the attention of academics and professionals involved in river engineering, management and restoration. In this context, the report should close with a section outlining modifications to the design approach adopted in the project that would enhance the performance and/or sustainability of future projects employing that approach. This facilitates continued development of successful techniques and improvement or abandonment of unsuccessful ones, offering the likelihood that an increasing number of projects will achieve geomorphological sustainability – maximising the habitat benefits while minimising maintenance requirements.

4.2 Managing sediment dynamics

4.2.1 Overview

The major types of sediment-related management activities undertaken in the UK are listed in Table 4.7 and are divided into managing sediment erosion, transfer and deposition. While a range of measures is available, until recently most solutions adopted 'traditional' methods. For example, questionnaire surveys reported by the NRA and, later, the Environment Agency found that, during the 1990s, 90% of channel maintenance activity comprised dredging, regrading and resectioning,

Table 4.7 Measures commonly used to manage sediment-related problems

Sediment-related problem	Measure	Description
Erosion	Bed control	Weir, sill or grade control structure installed in an incising channel to prevent continued lowering of the bed. May be constructed from artificial (concrete, sheet pile) or natural (wood, stone) materials
	Bank protection	Stabilisation of a retreating bank where a flood defence structure or other asset is threatened. May employ a variety of materials/techniques ranging from biotechnology (soft) to hard, structural engineering
Sediment transfer	Bed regrading	Large-scale (often grant-aided capital works) modification of the bed profile to alter the reach-scale slope. Usually based on regime theory or hydrodynamic modelling (HEC-RAS or iSIS)
	Channel resectioning	Large-scale modification of channel cross-section including resizing of the area, changing the geometry and reprofiling of the banks. Usually intended to increase channel capacity to convey floods or, if part of a restoration scheme, to improve habitat
	Gravel trapping	Installation of structures (usually low weirs) to prevent downstream movement of coarse sediment transported as bedload. Widely used to maintain the design capacity or stability of a flood defence channel or land drainage asset
Deposition	Dredging	Removal of sediment that has accumulated on the bed and/or banks in order to maintain the channel's flood defence, navigation or land drainage functions. Capital dredging may involve 'over-dredging' that lowers the bed elevation generally or at selected locations
	Desilting	Removal of fine sediment that has accumulated in the channel within about the last three years. This action is often performed in conjunction with weed clearance to maintain the capacity of the channel to convey flood water
	Shoal removal	Selective dredging to remove individual sediment features such as bars or riffles where these are perceived to be compromising the flood defence or navigation functions of a channel
	Groynes/deflectors	Structures installed to promote the spatial organisation of sediment storage in a reach that is a net accumulator of sediment. May be used to maintain a clear thalweg for navigation or to create or conserve habitat diversity

while 78% of all cases of siltation were solved by dredging and 62% of bank erosion problems were treated using a hard engineering structure. Only a third of operations involved any consideration of environmental or geomorphological issues at the design or implementation stages.

However, in the twenty-first century, conserving channel form and process is increasingly recognised as an essential component of all sediment management actions. While the Environment Agency continues to spend around £3 million on dredging and a further £8 million on controlling aquatic and riparian vegetation (Environment Agency, 2008), activities are being promoted that take a broader view of the fluvial system and attempt to work with natural processes of sediment erosion, transport and deposition to achieve geomorphological sustainability. This is most clearly expressed in Scotland, where there is a presumption against removing sediment from a water body unless this can be shown to be essential to the public good and is done in a way that avoids degrading its hydromorphological condition and ecological status (SEPA, 2005). In England and Wales, the Environment Agency cautions that maintenance activities, including dredging and weed cutting, must comply with the requirements of the Habitats and Water Framework Directives (Environment Agency, 2008) and notes that, while neither directive entirely rules out sediment management activities, they do promote the reinstatement of natural river channels. It follows that the Environment Agency will seek and require, as far as possible, a reduction in interference in natural river processes. Hence, although dredging will continue in future in England and Wales, it will only be permitted where it can proven to be essential to the public interest.

The outcome is that, when proposing a sediment management project or action in the UK, proponents must not only make an unanswerable needs case in terms of the public interest, they must also demonstrate that the work will produce sustainable benefits and can be performed in a manner that, first, minimises the potential for locally adverse impacts on habitats and ecosystems and, second, avoids disrupting the sediment transfer system in ways likely to trigger further, sediment-related problems elsewhere in the fluvial system. It is in this context that site- and reach-scale options for managing sediment-related problems are prefaced here by consideration of the case for sediment management to be planned and coordinated at the catchment scale.

4.2.2 *Catchment sediment management concept*

The current condition of practically every river system in the UK is the outcome of natural processes and events coupled with the local history of anthropogenic interventions in the fluvial system and human activities in the catchment. At various times during the last 300 years, the construction of weirs and dams, diversion and abstraction structures, flood embankments, channel reprofiling, resectioning and straightening, and the clearance of natural vegetation from the channel, riparian corridor and floodplain have been employed to greater or lesser degrees in all main rivers for water power, water supply, flood control, navigation, channel stabilisation, recreation and conservation purposes. The cumulative impacts of these interventions, combined with catchment activities such as deforestation, reforestation, agricultural intensification, mineral extraction and urbanisation have significantly disrupted the dynamics of water, sediment and woody debris in British rivers, as well as the range and quality of habitats they provide and the ecosystems they support.

Growing realisation that site- and reach-scale sediment problems are often symptomatic of disruption to the sediment transfer system by human actions, past and present, strengthens the case for managing sediment dynamics at the catchment scale. The underlying concept is that channel instability in one reach drives complex process-response through generating an excess or paucity of sediment supply to the reaches downstream and channel slope adjustments that migrate headwards to affect the reaches upstream (Schumm, 1977). For example, the additional sediment liberated by erosion in one reach is carried downstream where it may cause sedimentation problems in flood control channels, damage wetlands and lakes, adversely impact fish and wildlife habitats, degrade water quality, and adversely impact infrastructure. Simultaneously, bed lowering in the eroding reach creates a headcut or nick point that migrates upstream where it may cause channel incision that destroys bedforms and benthic habitats, disrupts hyporheic flow, undermines instream structures and, in extreme cases, disconnects the channel from its floodplain. Conversely, excessive deposition of sediment in reaches that have been over-widened or over-deepened for flood defence may starve the next reach downstream of sediment, triggering scour and further instability there, while promoting siltation upstream through backwater effects.

Historically, sediment management in British rivers has employed capital works together with responsive and operational maintenance performed at the site and reach scales to suppress the morphological symptoms of sediment imbalances (Table 4.7). The effect was to 'censor' sediment and sediment features out of the riverscape while failing to address the root cause of the problem: imbalance in the catchment sediment transfer system. However, the modern focus on river management at the catchment scale, particularly through Catchment Flood Management Plans (http://www.environment-agency.gov.uk/research/planning/33586.aspx; Evans *et al*., 2002) and draft River Basin Management Plans (http://www.environment-agency.gov.uk/research/planning/33250.aspx; Griffiths, 2002) highlights the need for sediment management actions to be coordinated at the basin or regional scales.

While the concept of catchment sediment management is still viewed widely as being novel in the UK, the strategic need to manage sediment at the catchment or regional scales has been accepted for some years in morphogenetic regions of the developed world where sediment yields are higher and sediment-related problems more acute. This has led to research initiatives aimed at producing approaches to representing sediment dynamics that are reliable and fit for purpose. For example, *SedNet* (http://www.clw.csiro.au/publications/general2002/managing_regional_water_quality.pdf) has been developed in Australia, while in the US the Army Corps of Engineers has developed *Regional Sediment Management* (see http://www.wes.army.mil/rsm/).

While the needs case for catchment sediment was comparatively weak in the UK during the late-twentieth century due to naturally lower catchment sediment yields and decades of well-organised capital works and maintenance, it was massively strengthened at the turn of the century by passing of the EU Water Framework Directive (WFD) (EU, 2000) with its requirement that all EU water bodies achieve good ecological status or, in the case of those that have been heavily modified, good ecological potential by 2015. The directive refers specifically to sediment issues through use of the term 'hydromorphology', which is defined in the directive as: 'The physical characteristics of the shape, the boundaries and the content of a water body.'

For the WFD to be implemented, this definition must provide the basis for:

- developing a method for hydromorphological classification
- identifying reference sites representative of high hydromorphological status (i.e. the 'natural' condition of the water body)
- setting of environmental standards consistent with good ecological status, and
- designing programmes of measures through which failing watercourses can achieve good ecological status or potential by 2015.

Hydromorphology and the draft standards based on it tend to stress the importance of channel *form* rather than *process*. In this regard, the European Committee for Standardisation (CEN, 2004) suggests reference conditions for 'high status' hydromorphological quality in rivers as:

- reflecting totally, or nearly totally, undisturbed conditions
- lacking any artificial instream and bank structures that disrupt natural hydromorphological processes, and/or unaffected by any such structures outside the site
- bed and banks composed of natural materials
- planform and river profile: not modified by human activities
- lateral connectivity and freedom of lateral movement: lacking any structural modification that hinders the flow of water between the channel and the floodplain, or prevents the migration of a channel across the floodplain

- lacking any instream structural works that affect the natural movement of sediment, water and biota
- having adjacent natural vegetation appropriate to the type and geographical location of the river.

It is, however, clearly implied that sediment transport processes should be unimpeded, a view endorsed and expanded upon by Newson and Large (2006) in their critical appraisal of the implications of the WFD for applied fluvial geomorphology. It follows that proposals to artificially manage or remove sediment at the reach scale are likely to be permitted only if it can be demonstrated that they do not significantly affect longstream sediment fluxes and connectivity – requiring that sediment management actions take place within the context of a catchment-wide sediment management plan.

At present, approaches to hydromorphological classification and the setting of environmental standards vary somewhat between England, Northern Ireland, Scotland and Wales. For example, in Scotland, Controlled Activities Regulations (CAR) reflect the Scottish Environmental Protection Agency's policy on ensuring that engineering in Scottish rivers not only causes no incremental, artificial impairment to their hydromorphology but rather assists them in reaching good ecological status. Further details can be found at: http://www.sepa.org.uk/water/regulations/regimes.aspx.

The need to conserve or restore sediment connectivity in the fluvial system is also one of the key criteria in the Morphological Impact Assessment System (MImAS) used to assess reach-scale, hydromorphological status. Details may be found at: http://www.sepa.org.uk/water.aspx.

Further information on UK research on hydromorphology may be obtained from SNIFFER (see http://www.sniffer.org.uk/) while the UK Technical Advisory Group (UKtag) website makes available technical reports and summaries of feedback from consultation exercises on hydromorphology and the WFD (see http://www.wfduk.org/).

The case for adopting a new paradigm in sediment management that brings together flood defence, land drainage, conservation, recreation and ecological interests, and which is planned at the catchment scale is perhaps most eloquently set out at the *Making Space for Water* homepage (Defra, 2008). This is a consultation process that has quickly moved forward a debate opened by publication of the results of the Foresight Project on Flood and Coastal Defence (Evans *et al.*, 2004a, 2004b; Thorne *et al.*, 2007) concerning the future of flood risk management in the UK and consideration of both broad principles and identification of practical measures capable of merging flood alleviation goals with a range of other multi-functional objectives for rivers. Within the Foresight Project, detailed discussion of issues concerning river processes highlighted particularly how future flood risks could increase markedly unless the way structural measures are implemented to manage flood risk are altered to make them compatible with environmental legislation promoting restoration of natural forms and process in British rivers (Lane and Thorne, 2007).

However, progress towards implementing catchment sediment management in the UK is hampered by the limitations of currently available tools for the analysis of broad-scale sediment dynamics and a shortage of reliable and comprehensive datasets with which to investigate and understand how the driving processes of sediment erosion, transfer and deposition interact with river engineering, management and restoration at the catchment scale.

Recognising the limited utility of existing approaches, a component of the research pursued by the Flood Risk Management Research Consortium (FRMRC) (http://www.floodrisk.org.uk) has been directed at developing new tools to account for river sediment dynamics, concentrating particularly on semi-quantitative and indicative characterisation of the sediment transfer system and its response to the impacts (intentional or unintentional) of interventions in the fluvial system made as part of flood alleviation schemes. A 'toolbox' of analyses and models developed in Phase 1 of the FRMRC is described in a User Focused Measurable Outcome (UFMO) document (Wallerstein, 2006).

The toolbox includes the Stream Power Screening Tool and SIAM approaches described in Section 4.1.6 above. Novel tools in the toolbox, including SIAM (Gibson and Little, 2006) and also the River Energy Audit Scheme (REAS) (Wallerstein *et al.*, 2006) are currently being further evaluated in Phase 2 of the FRMRC (http://www.floodrisk.org.uk/).

4.2.3 Managing sediment sources

4.2.3.1 *Catchment sediment source control*

Sediment-related problems in rivers are often driven by sediment sourced from outside the drainage network. For example, changes in land use involving deforestation, re-forestation, mineral extraction, agricultural intensification or urbanisation have been shown to elevate the catchment sediment yield (Walling, 1999). It follows that controlling sediment input to the river system at source may be a viable solution to a sedimentation problem in that it treats the cause of the problem (accelerated erosion) rather than its symptoms (channel siltation). Control at source may involve changes to land management designed to reduce erosion, prevent the delivery of eroded sediment to water courses, or retain sediment in headwater (that is, non-main river) ditches and tributaries.

The sources of fine-grained, catchment-derived sediment can, like water pollution, be broken down into point sources (such as drain outfalls or tributary confluences) and diffuse sources (such as eroding, overgrazed uplands, arable fields, or afforested areas). Control of point sources is comparatively straightforward once the significant sites have been identified, involving deployment of erosion control technology to reduce or eliminate erosion, or sediment traps to interrupt supply to the main river. The use of horseshoe wetlands at the junction of major drains with stream channels has been found to be efficient in this regard.

In contrast, protection of rivers against the effects of elevated catchment sediment supply from diffuse sources requires cooperation by the relevant authorities, agencies and landowners over a wide area. Measures can only be effective if stakeholders recognise the integrity of the catchment–floodplain–river continuum and realise the importance and benefits that accrue from joined-up stewardship of the land *and* river systems. If the agreement and active support of landowners can be secured, measures that may be employed include changes to land management that conserve soil and reduce erosion through, for example:

- reduced stocking densities
- drilling instead of ploughing
- planting of field and riparian buffering strips.

The use of buffering strips to trap elevated sediment supplies *en route* to the channel system has received much attention (Muscutt *et al.*, 1993). Buffers are known to reduce not only surface runoff and sediment yields in small catchments but also nitrate and phosphate loadings (Owens *et al.*, 2007). However, their positioning is crucial and also they cannot be considered as a stand-alone solution to excessive sediment yields in larger catchments (Verstraeten *et al.*, 2006). The design of strips is to some degree site-specific but common features include:

- buffer width typically 5 to 10 m for small channels ($w < 5$ m)
- plant buffer strip with a mixed assemblage of quick-growing, native riparian species
- fence buffer strip to prevent browsing/poaching by livestock, at least until plants are fully established
- avoid ploughing or harrowing immediately adjacent to channel and ditch margins draining to buffer strip.

4.2.3.2 *Bed controls*

Bed controls are structures installed in the channel to prevent incision, arrest the upstream migration of a knick-point or headcut, or promote aggradation. Weirs are not considered here even though they may act as bed controls because the primary purpose of a weir is usually not erosion control but to pond and then accelerate flow for discharge measurement, aeration, environmental enhancement or fisheries. Bed controls come in a variety of forms including (from lightest to heaviest) sills, grade control structures, and check dams.

A *sill* is the simplest form of bed control. It is installed with its invert at bed level and acts as a non-erodible barrier to eliminate lowering of the bed by scour. Sills may be effective in limiting general scour in a dynamically stable stream but should not be relied upon to withstand incision or knick-point migration associated with reach-scale degradation in unstable channels (Thompson, 2002). Essentially, a sill mimics the effect of a rock outcrop or body of cemented or strongly cohesive alluvium in stabilising the bed by limiting erosion during flood events. The invert of a sill is set flush with the bed, so that there is no afflux or backwater effect upstream and the elevations of a series of sills may be set so that they match the gradient of the bed in the project reach. R&D Note 154 (National Rivers Authority, 1993) presents four different sill designs (Fig. 4.12) and notes that sills may be constructed from timber, rock or concrete. When built of sufficiently strong materials, they have been used successfully in rivers up to 40 m wide, experiencing velocities of 3 m/s and discharges up to 300 m^3/s.

In practice, a single sill will seldom be sufficient to stabilise the bed in a channel that is prone to significant scour and a series of sills is often used to protect a reach. R&D Note 154 (National Rivers Authority, 1993) recommends that sills be spaced along the stream at no more than three times the channel width.

Grade control structures differ from sills in that they are more heavily built and are able to withstand both general scour and reach-scale incision (Fig. 4.13). Usually, the invert of a grade control structure is set above the level of the bed to raise the base level for the reach upstream and so reduce any degradational tendency. Grade control structures should have a stilling basin downstream to dissipate energy and prevent damage to the bed or banks (Little and Murphey, 1982). Grade control structures can prove highly effective at preventing incision in degrading streams that lack natural control (Biedenharn *et al.*, 1990), although it is vital that they are installed in time to catch upstream migrating headcuts and it is necessary to account for the possibility that they may disturb the balance between

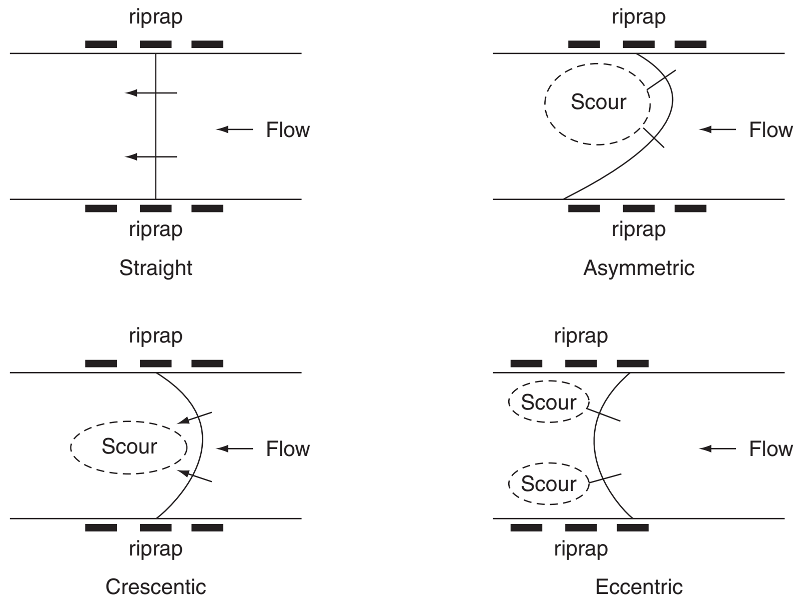

Fig. 4.12 Alternative designs for bed control sill structures. Adapted from the National Rivers Authority, 1993. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

sediment supply and transport capacity in reaches further downstream in the fluvial system (Simon and Darby, 2002). However, there would usually be a presumption against their use in the UK as they constrain the ability of the stream to adjust hydromorphologically and may present a barrier to long stream connectivity in the sediment and ecosystems.

Fig. 4.13 Grade control structure installed to prevent degradation in an incised stream in north Mississippi

Check dams are similar to grade control structures but are structurally even more robust and are usually installed on steep streams with coarse sediment loads and periodic debris torrents. They are designed to trap and retain sediment and debris (to protect the system downstream), as well as arresting knick-points or headcuts migrating upstream and providing a stable base level for the channel upstream. While their use is widespread in eastern Asia and Japan (Nobutomo *et al.*, 2000), the introduction of such heavy, fixed structures inevitably has negative impacts on river morphology and habitats (Brierley and Fryirs, 2008), making it difficult for them to be permitted in the UK.

A number of general construction guidance notes applicable to all bed controls are provided in R&D Note 154 (National Rivers Authority, 1993). These include the following:

- Excavate the area of channel where the bed control is to be located to a depth equivalent to twice the height of the invert above the bed of the channel.
- Construct the structure from logs, rock, masonry or concrete, ensuring that it is well keyed into the banks using slit trenches to prevent flanking by local erosion. Further strengthen the structure using reinforcing rods or sheet piles driven into the bed if there is a risk of channel degradation downstream due to upstream headcut migration.
- Angle the crest of the structure down towards the centre of the channel or curve the profile in order to concentrate flow away from the bank edges.
- Do not set the crest higher than one third of the bankfull depth to prevent the structure reducing the capacity of the channel to convey floods.
- The degree of scour downstream of a bed control may be estimated from:

  $$d_s = 0.4\left(\frac{H_t}{0.3}\right)^{0.225}\left(\frac{q}{0.1}\right)^{0.54} - d_d$$

  where d_s = local scour depth downstream of bed control, H_t = head difference between water surface up and downstream of control, q = discharge per unit width, and d_d = flow depth at a point undisturbed by the bed control structure.
- If scour downstream of the structure is likely to induce bank instability, protect the banks using an appropriate method (see Section 4.2.3.3 below).
- Use riprap to stabilise the banks upstream of the structure to prevent outflanking.

4.2.3.3 *Bank protection*

Environment Agency policy on bank erosion stems from a meeting of the Land Drainage Advisory Committee in April 1974 and a subsequent leaflet (MAFF, 1984). Current policy states that:

- Erosion of river banks is the responsibility of the riparian owner.
- The Environment Agency has no responsibility for erosion of rivers banks.
- Where bank erosion could affect the river regime, threaten flood defences or result in deficient drainage then action can be taken by the Agency but each case must be judged on its merits.
- Where the Agency or its predecessors have carried out works in the channel or on the banks and accepted responsibility for future maintenance then future maintenance can include erosion repairs.

Riparian owners can, through common law, erect erosion protection provided that in doing so they do not alter the flow of the watercourse or cause injury to any other parties. Any such works will usually require land drainage consent from the Agency. Through this mechanism, the Agency can influence the design of bank protection works selected by riparian owners as well as its own engineers to ensure that they meet the requirements of the WFD.

In Scotland, any actions undertaken by local authorities or riparian land owners to provide bank protection fall under the Water Environment (Controlled Activities) (Scotland) Regulations of 2006 (also known as the Controlled Activities Regulations, or CAR). Authorisation must be obtained for all new engineering works and SEPA expects all applications to follow good practice, which they define as: '... the course of action that serves a demonstrated need, while minimising ecological harm, at a cost that is not disproportionately high'.

According to SEPA's duties under CAR to ensure licences represent efficient and sustainable use of the water environment, all applications to protect banks are assessed to ensure that they follow good practice. SEPA has defined five tests to assess whether good practice has been followed and that the proposed works do not jeopardise the capacity of the water environment to support future sustainable development. These are:

1. Has the applicant demonstrated a need for the proposed activity?
2. Has the applicant considered appropriate alternative approaches?
3. Does the proposal represent the best environmental option?
4. Is the activity designed appropriately?
5. Have all necessary steps been taken to minimise the risk of pollution and damage to habitat, plants and animals during construction?

If SEPA finds that a proposed activity fails to follow good practice, the application will be subject to a more thorough and detailed licence assessment and the applicant will be required to provide additional information to justify their plan.

It follows that consideration of the impacts of proposed measures to deal with bank erosion must consider the possible impacts related to sediment dynamics, hydromorphology and habitats, for the activities to have any chance of being permitted in any part of the UK. Detailed guidance on good practice in the selection of a suitable solution and, where justified, the design of engineering works for bank protection is available both from the Environment Agency (Environment Agency, 1997) for England and Wales and the Scottish Environmental Protection Agency for Scotland (SEPA, 2008).

In essence, selection of appropriate solutions to a bank erosion problem should be based on two fundamental analyses. First, the results of a detailed geomorphic assessment should be used to identify the underlying cause of bank retreat and accurately characterise the fluvial and sub-aerial processes responsible for bank erosion and the failure mechanisms responsible for any bank instability. Second, a risk assessment should be performed. This must evaluate the rate of bank retreat, the consequences of allowing erosion to continue, and the risks associated with failure of each of the various options that could be used to solve the problem.

Although there are multiple types of bank erosion problem and literally dozens of potential solutions that might be appropriate to any particular problem and location, the guiding principles underpinning selection of an optimum solution are practically ubiquitous (Table 4.8).

Two case examples serve to illustrate the utility of taking a geomorphic approach and applying the guiding principles of bank protection listed in Table 4.8.

During the 1970s riparian landowners voiced concern about the loss of farmland associated with erosion at the outer banks of actively migrating banks of the River

Table 4.8 Guiding principles for selection of appropriate solutions to bank erosion problems

Guiding principle	Description
1. Identify the problem	If retreat is purely due to natural erosion as part of the fluvial and sediment systems then, if possible, allow it to continue. Avoid disrupting the system unless continued retreat is absolutely unacceptable
2. Gauge whether retreat can be allowed	Where retreat cannot be allowed, and especially if the cause is human activity, seek a solution through active bank management (control the cause) and only intervene with structural protection when this alternative approach is unacceptable
3. Match the solution to the problem	When active management or structural protection is justified, match the scope, strength and length of bank covered by the solution to the cause, severity and extent of the problem. Use of limited schemes and soft protection is commendable, but they are not appropriate for locations of intensive bank instability
4. Balance conflicting bank management goals	When reacting to a bank erosion problem and selecting a course of action, bear in mind the responsibility to balance conflicting management goals to achieve the optimum solution in terms of: efficacy, economy, engineering and environment

Severn between Llanidloes and Newtown, Powys. Detailed investigation of the fluvial system, undertaken as part of the Craig Goch Scheme, revealed that this erosion was occurring naturally, and was in fact an important component of the sediment transfer and exchange system. As described in Section 3.2.4.1, meander migration was associated with the exchange of coarse sediment input from the upland source areas in the Plynlimon catchments with floodplain sediments in the upper Severn valley.

Consideration of the role of bank erosion in reach-scale sediment dynamics led to the conclusion that protecting some bends would lead to a reduction in the capacity of the river to exchange sediment and disturb reach-scale sediment continuity, triggering a morphological response. It was concluded that process–response would probably occur through an acceleration of bank erosion in the remaining, unprotected bends, as the river sought to recover the lost sediment exchange capacity and balance its sediment input and output. This response would, in turn, generate calls for further bank protection works, which, if heeded, would lead inevitably to stabilisation of much of the reach, with considerable capital and maintenance costs, as well as serious impacts on the regional sediment balance and the river environment.

This example shows how application of a geomorphological assessment of the underlying causes of bank erosion led to the conclusion that intervention would be expensive, unproductive and ultimately unsustainable. Consequently, a policy of allowed natural adjustment of the banklines and planform of the river was adopted and remains in place today.

The second example comes from the River Sence in Leicestershire (referred to earlier in Section 3.3.4.2 of Chapter 3). R&D Project Record C5/384/2 (National Rivers Authority, 1994a) reported that capital works were performed on the River Sence between 1973 and 1985. Work involved regrading and resectioning that produced high and steep banks surcharged by spoil taken from the channel (Fig. 3.14). Extensive bank instability began in the engineered reaches immediately following construction and continued for the next 20 years. During the same period, sediment deposition caused further channel instability in the fluvial system downstream.

A Fluvial Audit of the River Sence identified the causal link between problems of bank instability in the engineered reaches upstream and siltation downstream. On the basis of the audit it was concluded that the causes of siltation were:

- increased sediment supply as a result of bank failure following regrading
- livestock poaching of collapsed banks
- locally reduced sediment transport capacity as a result of channel widening
- maintenance working upstream that enhances siltation
- massive weed growth exacerbated by siltation and increased nitrate loadings.

In suggesting options to mitigate siltation, it was recognised that control of sediment sources was a preferable solution to attempting to artificially increase the capacity of the river to transport the excessive supply of sediment and transfer it further downstream.

In the Sence, sediment control centred on management of the banks, despite the fact that the policy at the time was to ignore bank erosion on the grounds that it was a natural process. Further detailed investigation and analysis of the causes of bank retreat, a form of a Geomorphological Dynamics Assessment, revealed the role of mass instability due to increased bank heights and angles following regrading and resectioning. A bank stability diagram was produced using field observations of bank height, angle and stability condition (Fig. 4.14). The diagram revealed the effects of the 1973 works in increasing bank heights to levels greater than the critical height for mass failure. While subsequent slumping, poaching and basal accumulation of debris had decreased bank angles and, to a lesser extent, heights, by 1989 many banks remained at risk of retreat by mass failure. Bank inspection also established that regrading had, in some places, exposed a weak sand layer in the floodplain at the bank toe, further reducing bank stability.

Identification of the causes, driving processes and factors affecting bank instability led to recommendations for mitigation that included elements of active bank management and structural protection:

1. Reprofiling of banks to reduce bank heights and angles sufficiently to prevent mass failure.

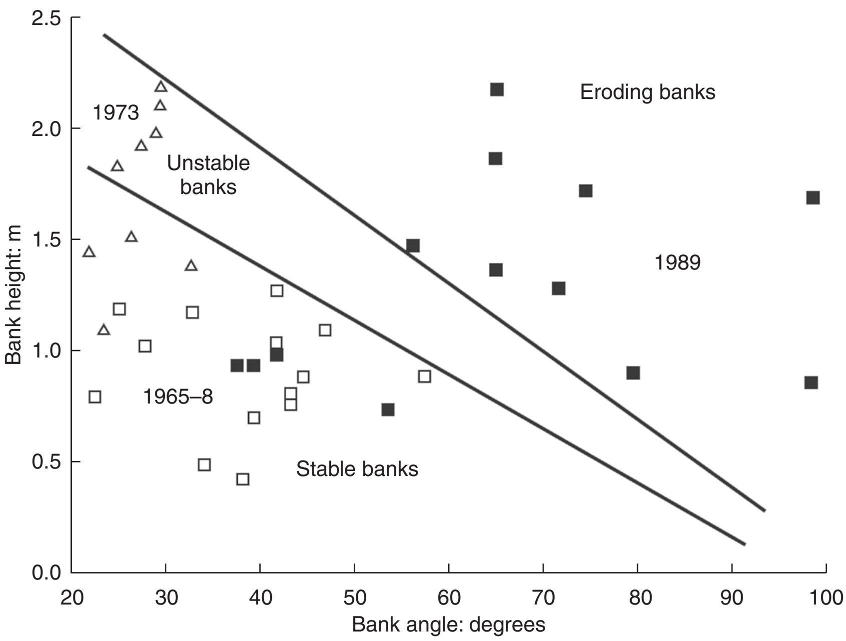

Fig. 4.14 Bank stability graph for the River Sence, Leicestershire. Modified, with permission, from Sear et al., 1995. © 1995 John Wiley & Sons Limited

2. Encouraging farmers to fence off vulnerable banks and prevent livestock access at least until riparian vegetation had recolonised eroding bank faces and slip surfaces.
3. Use of biotechnical protection (willow spiling) where the weak sand layer was exposed at the bank toe in addition to reducing bank heights and angles.
4. Monitoring of bank conditions to assess change in bank condition and appraise the effectiveness of these measures.

4.2.4 Managing sediment transfer

4.2.4.1 Sediment traps

A sediment trap can be installed to ameliorate or prevent completely the transfer of excessive amounts of sediment that would otherwise have to be removed from the channel further downstream in the river system by dredging or desilting operations. Traps are operated in many parts of the UK, and have a particularly long history in Cumbria, where some traps have been in use for over half a century.

The design of sediment traps is demanding and data intensive. To support a suitable design and installation requires detailed knowledge of reach-scale hydraulics as well as data on the quantity, calibre and transport mechanism of the sediment load. Experience from long-term monitoring of traps in Cumbria demonstrates that coarse sediment yield is highly variable through time, depending on sediment availability and the occurrence of transporting events – findings that have been replicated in research studies in the Howgill Fells and other parts of the UK (Harvey, 2007; Reid *et al.*, 2008). This makes it almost meaningless to attempt to derive a single, representative annual sediment yield for design purposes. Clearly, the benefits of the trap only accrue during high runoff events associated with major storms and/or wetter periods and this must be borne in mind when assessing the success of a trapping scheme. Other design considerations include:

1. Whenever possible, traps should be sited at sites of natural deposition such as the upstream side of a riffle. Experience indicates that the effective trapping efficiency of traps located away from natural deposition sites is only about two-thirds that for traps sited at locations of natural deposition.
2. Convenience of access for emptying the trap is vital for its sustainable operation, and ease of entry is, therefore, a major design parameter.
3. The risk of 'over-trapping' to reduce the downstream sediment supply below the local transport capacity. If the trap is too efficient it may starve the channel downstream of sediment resulting in: bed scour, armouring, bar erosion and compaction. Consequently, the implications of the trap for downstream habitats and spawning areas must be considered and this is likely to involve sediment transport modelling studies.
4. As traps can, in some cases, promote downstream bed scour and may enhance any tendency for degradation, they should not be located immediately upstream of scour-sensitive structures (bridges, flood walls) unless these are well protected against the destabilising effects of bed lowering.
5. Traps must be sufficiently well protected to prevent destabilisation by incision downstream and/or sediment accumulation or scour upstream.
6. The stability status of the host reach must be established prior to trap installation. Traps should not be installed in unstable reaches or reaches where stability is sensitive to disturbance as they may exacerbate or trigger local instability.

In summary, as the general purpose of a trap is to limit the delivery of sediment to the reaches downstream, the designer must understand the relationship between sediment transport in the trap reach, sediment transfer to the problem reach and likely patterns of morphological response in the fluvial system between the two. This can be achieved through applying the relevant monitoring and modelling techniques in a SIAM study, perhaps backed up by a GDA. For example, the use of a gravel trap in a headwater stream will only be successful in reducing the desilting requirement in a flood control channel downstream provided that:

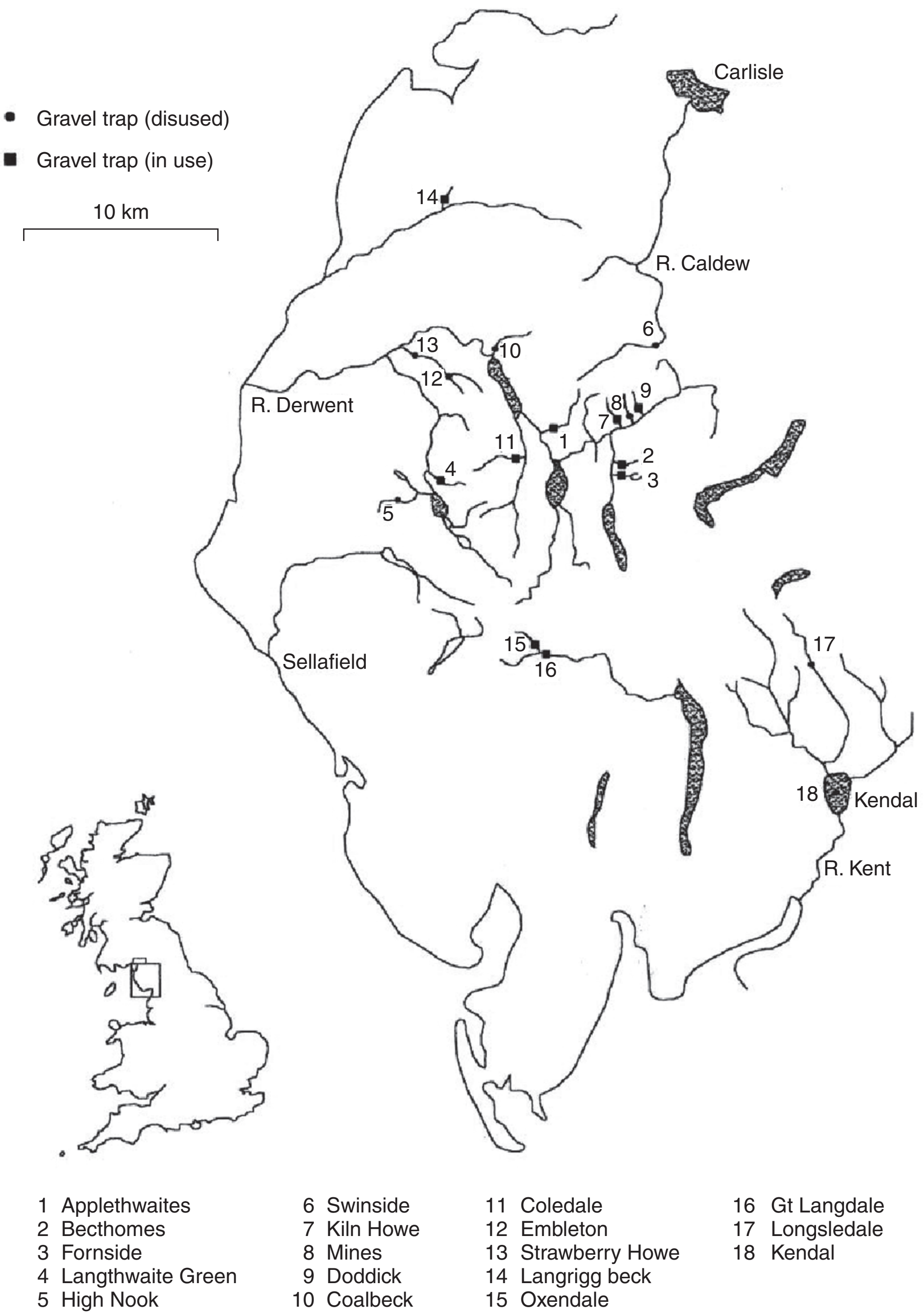

Fig. 4.15 Location of gravel traps installed in the English Lake District. Reproduced from the National Rivers Authority, 1994b. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

1. the trap interrupts what was a significant transfer of sediment between the sediment source and sink reaches
2. the river does not substitute a new source of sediment (derived from morphological adjustment in intermediate reaches) for that trapped, so maintaining the rate of transfer to the downstream reach.

In the English Lake District, gravel trapping has been a relatively common method of controlling the yield of coarse sediment from upland catchments (NRA, 1994b) since the 1930s (Fig. 4.15). Traps consist either of simple boulder weirs reinforced by iron piles or more complicated concrete and pitched stone structures with drains to facilitate emptying. Table 4.9 lists their characteristics.

Long-term records and re-surveys of streams in the Lake District illustrate the downstream impacts of gravel trapping in general and demonstrate the danger of 'over-trapping' in particular. When traps are installed and emptied regularly, the channel downstream may become starved of coarse load, with the bed being scoured to make up the deficit. Records for several traps reveal that bed erosion protection has had to be installed downstream following trap construction. Therefore, it is desirable that trap efficiency be sufficiently below 100% in order that some gravel is allowed to pass through the trap and so mitigate for bed scour downstream.

In addition to promoting downstream bed scour, monitoring of Lake District traps has revealed other sedimentary responses that are potentially important to channel morphology and ecology. Figure 4.16 charts the sedimentary structure and grain size distribution of the bed of Coledale Beck, Cumbria, up- and downstream of a long-established gravel trap. Notable downstream impacts of the trap include changes in bed material composition and changes to the bed structure. Specifically, the bed upstream of the trap has a bimodal grain size distribution with considerable quantities of shingle whereas the bed downstream lacks this material and is dominated by cobble-sized material. The bed upstream also includes a high percentage of particles that are loose and easily entrained whereas most particles in the bed downstream are structurally stable due to interlocking, making the bed compacted and difficult to move. These apparently subtle changes to the character of the bed have serious implications for bedload movement, channel adjustments, and the environmental value of the bed in providing spawning gravels and a wide

Table 4.9 Gravel traps installed in the English Lake District from the National Rivers Authority, 1994b. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

Site	NGR	Date built	Vol.: m^3	Catchment area: km^2	Drainage density	Geology	Reason for construction
Applethwaites	NY263253	1943	67	1.31	2.02	SKS/S	LD
Beckthornes*	NY320290	1937	49	0.51	3.00	An/R/T	LD
Fornside	NY321208	1937	68	0.43	8.00	An/R/T	LD
Langthwaite*	NY160211	1937	667	4.50	1.40	SKS/A	LD/Mine
High Nook	NY130207	1941	88	2.21	1.75	SKS/S	LD
Swineside	NY343324	–	180	23.90	1.62	SKS/S/A	LD
Kiln Howe*	NY321255	1941	95	0.84	2.31	SKS/S	FC
Mines	NY325262	1941	119	0.94	2.28	SKS/S	LD/Mine
Doddick	NY332262	1941	105	0.91	1.88	SKS/S	LD
Coalbeck	NY200321	1941	56	5.83	2.60	SKS/S/A	LD
Coledale*	NY228236	1941	126	6.00	1.40	SKS/S/A	FC/Mine
Embleton	NY162296	1941	60	4.64	2.50	SKS/S/A	LD

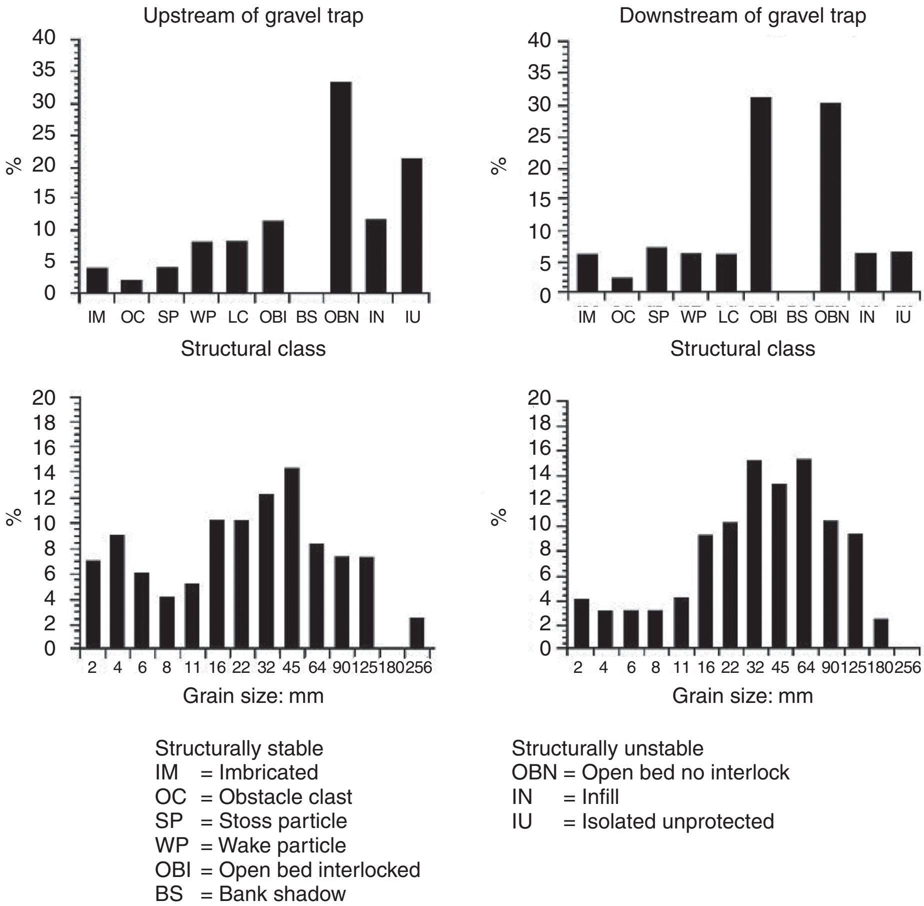

Fig. 4.16 Sedimentary structure and grain size of the bed of Coledale Beck, Cumbria, UK, upstream and downstream of a long-established gravel trap. From the National Rivers Authority, 1994b. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

range of other benthic habitats. Consequently, downstream impacts must be fully investigated even if 'over-trapping' is not an issue when considering the use of a sediment trap to manage sediment transfer in a stream.

4.2.5 Managing sediment deposition

4.2.5.1 Background

The management of deposited sediment in the UK has historically been undertaken as a part of general river maintenance. Examination of maintenance records reveals that, in the past, actions included routine removal of riffles and shoals as well dredging, vegetation clearance and bank reprofiling to remove deposited sediment, with these actions customarily repeated according to a set schedule or a perceived need on the part of flood defence and land drainage interests. However, during the last 20 years there has been a fundamental shift away from routine management of sediment deposition. This is partly a response to the recognition that such actions have adverse impacts on the geomorphology, habitats, aesthetics, ecology and biodiversity of managed rivers. It also results from realisation that routine maintenance as practised in the past was not always cost effective and sometimes even unnecessary (Environment Agency, 2004b; HR Wallingford, 2008). Recently, the focus has shifted towards approaches centred on performance-based management of flood defence assets, including the management of sediment deposition (Dawson *et al.*, 2004; Simm *et al.*, 2006).

The Environment Agency for England and Wales, Scottish Environment Protection Agency (SEPA) and Rivers Agency for Northern Ireland all now have policies which actively discourage sediment removal. For example, the Environment Agency's policy document on gravel removal from rivers states that it 'is generally against the removal of gravel from rivers, other than where specifically allowed for navigation or proven to be essential in specific locations for flood risk management or water supply purposes' (Environment Agency, 2004a). Gravel is defined in this document as being 'bed materials that contain 50% or greater by volume of natural coarse sediments (gravels, cobbles and boulders, being particles of 2 mm or greater intermediate axis)', meaning that a wide range of rivers are covered by the policy.

However, the Environment Agency retains its permissive powers to remove sediment deposits within a channel where necessary under Section 165 of the Water Resources Act 1991 and Section 14 of the Land Drainage Act 1976. In doing so, the Environment Agency still has an obligation under Section 614 of the Land Drainage Act 1991, to 'exercise their power so as to further conservation and enhancement of natural beauty and the conservation of flora, fauna and geological and physiological features of special interest'. Local authorities can serve notice to remove 'siltations' under Section 259 of the Public Health Act 1936, but only in circumstances where these deposits 'pose a statutory nuisance'. In any case, any large-scale sediment management works require an Environmental Impact Assessment and Statutory Instrument 1217 applies. Clearly, while sediment removal is still possible in England and Wales, there are environmental and conservation issues concerning the management of deposition that must be taken into account.

In 2005, SEPA published a position statement on sediment management in light of legislation passed to address the requirements of the Water Framework Directive. In Scotland the relevant legislation is known as the Water Environment (Controlled Activities) (Scotland) Regulations. Several key points are raised in SEPA's position statement. Notably:

1. SEPA promotes the preservation of natural sediment budgets and resulting morphological features within surface waters. Any intervention with, or manipulation of, such sediment must be carefully considered, fully justified and sensitively managed within a catchment perspective.
2. Sediment management in inland surface waters and wetlands is a controlled activity, and as such requires authorisation.
3. SEPA will presume against sediment removal unless it is proven necessary for navigation, flood risk management, water supply purposes, infrastructure protection (e.g. intake/outfall protection) or other sustainable activities. In all circumstances, SEPA will expect proposals to follow good practice and, where necessary, be informed by studies/monitoring to ensure that the activity is both sustainable and environmentally acceptable.
4. SEPA will presume against repeated sediment management operations that involve regular intervention where other long-term and sustainable options are available.

In summary, there is in the UK an increasing emphasis on any management of sediment deposition being fully justified, environmentally aligned and sustainable. The onus is now on the proponent of a sediment management scheme or action to demonstrate to the statutory authority that the risks associated with the 'do nothing' option are unacceptable and, where sediment removal is proposed, that there is no more sustainable, alternative method of managing the sediment-related problem, prior to any intervention in the fluvial system being permitted.

4.2.5.2 Options for managing sediment deposition

When intervention proves necessary to manage a problem related to sediment deposition, one or more of a range of optional approaches may be adopted. These fall into two major categories. First, steps may be taken to accommodate continued sediment deposition in the problem reach in ways that solve the sediment-related problem. Second, if it is not possible to solve the problem by accommodating sediment deposition, its accumulation may be suppressed through desilting performed as part of operational (routine) maintenance, or dredging performed as part of responsive (emergency) maintenance or capital works (regrading or resectioning). However, before sediment removal is proposed, full consideration should be given to either controlling the source of the sediment (where this can be reliably identified) as outlined in Section 4.2.2 or the transfer pathway delivering it to the problem reach (as addressed in Section 4.2.3). Also, the effects of removing sediment on the balance between sediment supply and transport capacity in the reaches downstream must be considered to avoid triggering further problems related to discontinuity in the sediment transfer system.

Accommodating sediment deposition requires a deep understanding of the geomorphology of the problem reach and the likely trajectory of morphological responses to sediment management. Common approaches include instream measures using artificial deflectors and restoring connectivity between the river and its floodplain.

Instream deflectors, or groynes, are installed to encourage spatially organised deposition of sediment in situations where the granular channel bed is being smothered by fines deposition or shoals are forming incoherently to impede flow or navigation. They may be used in rivers that have the capacity to store excess sediment as a legacy of past capital works or maintenance practices that have left the channel over-wide relative to the prevailing flow and sediment regimes. Deflectors operate by deflecting the filament of maximum velocity around the tip of the groyne to produce an asymmetrical flow field with local acceleration in the channel opposite the deflector and slowing of the flow in the channel up- and downstream of the deflector. They promote local scour and deposition to produce a two-stage cross-section that features a well-defined thalweg channel with a clean, granular bed in the channel opposite the structure and induces deposition to form attached bars up- and, particularly, downstream of the root of the structure. Through time, initially over-wide, trapezoidal channels narrow and develop cross-sectional asymmetry and, where deflectors are installed on alternating sides of the channel, the thalweg develops a sinuous planform. If the deflectors occupy more than about 25% of the width, they may promote erosion of the bank opposite and slightly downstream of the groyne tip and, where bank retreat and the development of a more sinuous planform cannot be allowed, it will be necessary to reinforce the bank in these areas. By increasing morphological diversity and uncovering alluvial bed materials, deflectors improve the value and range of instream habitats and so add to the conservation value of the river as well as storing deposited sediment in an orderly fashion.

Deflectors may be constructed from willow spiling, timber (living or dead), rock or gabions, depending on the intensity of the flow to which they will be exposed and the suitability of the construction material to the environmental attributes of the river in question. A wide variety of deflector designs are available including triangular, wing and spur configurations. Detailed design guidance is available in reports by Hey and Heritage (1993), Hey (1994) and, more recently, the River Restoration Centre (1999).

Reconnecting the channel to its floodplain is an attractive option to manage sediment deposition because it can massively increase the capability of the problem reach to store excess sediment supplied from upstream in a manner that is environmentally beneficial and sustainable in the long term. Reinstatement of hydraulic connectivity between the river and floodplain is a powerful action because it will certainly have significant effects on fluvial processes both in the channel and overbank. In general, increasing the frequency and duration with which the floodplain is inundated will increase the proportion of sediment deposition that occurs on the floodplain rather than in the channel. The effect is most marked for the finer fraction of the sediment load which is transported in suspension, although it is not unusual for relatively coarse sediment to be deposited overbank in the form of natural levees and crevasse splay deposits.

In addition to reconnecting the channel to its floodplain, many restoration projects also feature the reinstatement of the pool–riffle sequence where this is appropriate to the fluvial and environmental setting. Although usually intended to improve the habitat and aesthetics of the watercourse, reinstatement of the pool–riffle sequence will also reduce problems related to sediment storage because it provides for a more efficient transport–storage–transfer system that allows the river to store both coarse and fine sediment between transport events in a spatially organised fashion. This is the case because on the falling limb of a transport event, relatively fine sediment is deposited in pools to be temporarily stored there, before being re-entrained on the rising limb of the next transporting flood. Conversely, coarse sediment is scoured from the pools during peak flows to be stored on the riffles, where it resides between transport events. Hence, reinstatement of pools and riffles not only enhances the conservation and recreation value of the project reach but can also improve its capacity to store and then release sediment deposited within the channel between transport events.

However, achieving this functionality in a reinstated pool–riffle sequence depends critically on the calibre and sorting of material used for riffle construction (National Rivers Authority, 1994a). Ideally, alluvial sediment from the substrate in the project reach should be used, with the flow allowed to winnow away the finer fraction. Fluvial sorting and selective transport of coarser material by size and shape will then create the armouring, sorting and packing pattern characteristic of a natural riffle (Clifford, 1993; Sear, 1996). The result is a bed feature that broadly maintains its form and location in the channel through 'particle queuing', albeit with adjustments to the height and position of the riffle crest, even though the sediment forming it is mobilised and exchanged with incoming bed load at near-bankfull discharges. It follows that use of over-large or anchored material in riffle construction, while ensuring stability, produces sediment behaviour in the restored reach that cannot replicate the capability of a channel with natural riffles to store and exchange coarse sediment (see Chapter 2).

Reinstatement of pools and riffles has proven challenging in practice and a substantial body of experience has been built up within the river restoration community. This is summarised later, in Section 4.2.6, which deals with river restoration design.

In situations where it is not feasible to enhance the sediment storage capacity of a problem reach, it may be necessary to remove sediment from the fluvial system mechanically. In practice, there are three main approaches that can be used to solve a sediment deposition-related problem in this manner: operational maintenance, responsive maintenance and capital dredging.

Operational maintenance is performed on main rivers with land drainage, flood defence and/or navigation functions to ensure that the channel meets the relevant standards of service. Dredging of sediment is no longer performed as part of operational maintenance, but desilting is allowed. Desilting refers to the removal of sediment that has accumulated recently, customarily within the last few years, and which is perceived to be causing a problem with respect to one or more river function. Desilting is usually performed in conjunction with the clearance obstructions (such as woody debris jams) and excessive in-channel and/or riparian vegetation. Experience during the serious floods of summer 2007 reinforced public perceptions that operation maintenance is essential in channels that provide flood defence to urban conurbations and rural settlements (Pitt, 2008). This is also the prevailing view of the majority of professionals involved in operations delivery for the Environment Agency. However, examination of expenditure on routine maintenance shows that until recently most of the effort has been expended in protecting agricultural land rather than communities, key infrastructure or industrial areas. The priorities for operational maintenance are, therefore being revisited (EA, 2008).

Further, the results of scientific research commissioned by Defra and supervised by the Environment Agency into the effectiveness of routine desilting and vegetation clearance have demonstrated that it is possible to greatly reduce the adverse impacts of these actions on habitats and the river environment through fairly minor changes to practice (HR Wallingford, 2008). For example, in some channels sediment accumulation is morphologically self-limiting and desilting is actually unnecessary while, where it is essential, the adverse impacts of desilting can be greatly reduced if it is undertaken either from a single bank or from alternate banks in a pattern aligned with the natural sinuosity of the channel, so that morphology and habitats are, to the greatest extent possible, conserved. Thus, while desilting and vegetation clearance will remain options for managing sediment deposition for the foreseeable future (SEPA, 2005; EA, 2008), the extent, frequency and nature of the associated actions look certain to change as the action agencies strive to make operational maintenance more efficient in terms of flood risk management, more effective in terms of cost and less damaging with respect to environment and habitats.

Responsive maintenance covers various forms of emergency work performed to deal with specific, sediment-related issues that emerge unexpectedly and which are perceived to pose unacceptable risks to one or more river functions. For example, responsive maintenance may be performed following a major flood event to remove extensive deposits of sediment or debris blocking the channel. Under these circumstances, the removal of sediment features such as shoals, bars or riffles would be allowed where this is deemed necessary to maintain the required flood defence standard of service or navigability of the channel. In practice, pre-emptive removal of deposited sediment may also be performed wherever it is perceived to pose an unacceptable risk and the work may be undertaken prior to performing an Environmental Impact Assessment if the risk is assessed to be high and the threat of disaster imminent (EA, 2008). However, even in the case of these emergency actions, it will later still be necessary to prove that the responsive maintenance was justified and that the way in which it was planned and implemented minimised any adverse impacts on habitats and ecosystems. When evaluating the case for managing sediment deposition using responsive maintenance, it is important to note that statutory authorities in the UK have a duty in some instances to maintain historic rights of navigation and this may leave the staff responsible for operations delivery little choice but to selectively remove deposited sediment from locations where this poses a risk to navigation.

Where sediment deposition causes sediment-related risks that are chronic and unacceptable, *dredging* to regrade the long-profile and/or resection the cross-section may be considered as a management option. However, the removal of sediment to materially change the morphology of the channel is now generally resisted on environmental and sustainability grounds and an unanswerable case will have to be made to demonstrate that the works are essential to protect people and property from unacceptable risks related to flooding and/or channel instability, that regrading/resectioning is the only feasible solution, and that the works will be performed in the most environmentally aligned manner.

To be sustainable, regrading should increase the bed slope through the project reach in order to increase flow velocities, conveyance and, hence, sediment transport capacity so that it more closely matches the sediment supply from upstream. However, it must be borne in mind that the outcome of such an intervention is to increase sediment input to the reach downstream, potentially exceeding the transport capacity there and so shifting the location of the deposition-related problem rather than solving it.

Resectioning involves significant changes to the dimensions and geometry of the cross-section and often includes reprofiling of the banks. The intention may be to increase the capacity of the channel to convey water and sediment or simply to provide additional space for in-channel storage. Regrading destroys the bed of the river with potentially catastrophic impacts on benthic habitats and ecosystems. Resectioning has similar impacts on the bed, but may also adversely impact the bank and riparian zones. Consequently, before either action is permitted, regulators will need to be convinced that the works provide a solution to the sediment problem that is sustainable without the need for repeated dredging and ongoing disruption to fluvial processes and morphologies, the habitats they provide and the ecosystems they support.

It follows that for regrading and resectioning to have any chance of being permitted, proposed schemes must take full account of the impacts of the works on hydromorphology, habitats, ecosystems and biodiversity in the project reach. For example, initial proposals for capital works to improve flood conveyance in the River Thames between Datchet and Teddington involved broad-scale dredging to remove deposited sediment. However, objections on environmental grounds led to development of a 'patch work' approach to dredging that left key habitats intact while still providing the increased conveyance necessary to meet legitimate goals for flood risk management (Tomes *et al.*, 2005). This demonstrates how a balance may be struck between the flood defence and ecological functions of the river even where re-sectioning provides the only feasible alternative for managing a serious, sediment deposition-related problem.

4.2.6 River restoration

4.2.6.1 *Restoration and sediment management*

The goals of any restoration project should include re-establishing long-stream and lateral connectivity in the sediment transfer system. This may be achieved by recreating the channel cross-sectional, planform and long profile attributes appropriate to the prevailing catchment conditions, flow regime and incoming sediment load. Restoration also makes possible long-term environmental recovery, as the types and variability of morphological forms, sediment features and fluvial processes found in naturally adjusted river channels provide the range of habitats required to support diverse ecosystems.

In this context, re-establishing a dynamic balance between the sediment supply and available transport capacity in the restored reach is one of the principal objectives of many restoration design approaches and this requires a thorough understanding of fluvial processes and sediment transport/transfer dynamics. That understanding may be acquired using the investigative techniques outlined in Section 4.1, and some form of Fluvial Audit and Geomorphological Dynamics Assessment (GDA) feature in most restoration project plans.

Restoration is a particularly suitable response to a sediment-related problem in reaches where significant instability caused by past anthropogenic disturbance or modification has been identified in a GDA and also appropriate in 'moribund' lowland streams that have previously been modified but which lack the stream power and sediment supply necessary to recreate predisturbance morphologies through natural recovery. Restoration is often partial, however, as many channels must continue to provide flood defence or land drainage functions even after restoration. In these circumstances, restoration design may involve the creation of a channel that is sized to accommodate the natural, channel-forming flow that is located within a much larger channel sized to convey the design flood for a flood alleviation scheme. The inner channel and berms around it improve the capacity of the reach both to store and convey sediment while providing a wider range of geomorphological forms and habitats without compromising the flood defence function of the larger floodway.

4.2.6.2 *Restoration design approaches*

Approaches to 'designing with nature' when reconstructing channels as part of river management or restoration are reviewed by Downs and Gregory (2004), who present three criteria essential for success:

1. establishing the catchment context
2. incorporating natural variability in design dimensions and geometries, within the site constraints
3. allowing for environmental change and adjustment of boundary conditions over longer timescales.

Guidance specific to steep, gravel-bed streams in the UK is provided by Hey and Heritage (1993), while a number of documents have been produced in the USA to support restoration design for dynamically stable, alluvial channels (Shields, 1996; Federal Interagency Stream Restoration Working Group, 1998; Soar and Thorne, 2001; Natural Resources Conservation Service, 2007).

Analytical approaches to stable channel design consider flow continuity, flow resistance and sediment transport supported, where necessary by empirical, regime-type equations, to enable the full parameterisation of channel geometry. In addition, within a good-practice design procedure for restoring meandering rivers (Fig. 4.17), Soar and Thorne (2001) demonstrate the use of confidence bands applied to 'typed' morphological equations as a mechanism through which natural streams can be used as realistic analogues for channel restoration design.

When channel restoration is undertaken as part of a project to manage a sediment-related problem, it is recommended that a check is performed to ensure that the restoration design is consistent with continuity of sediment transfer through

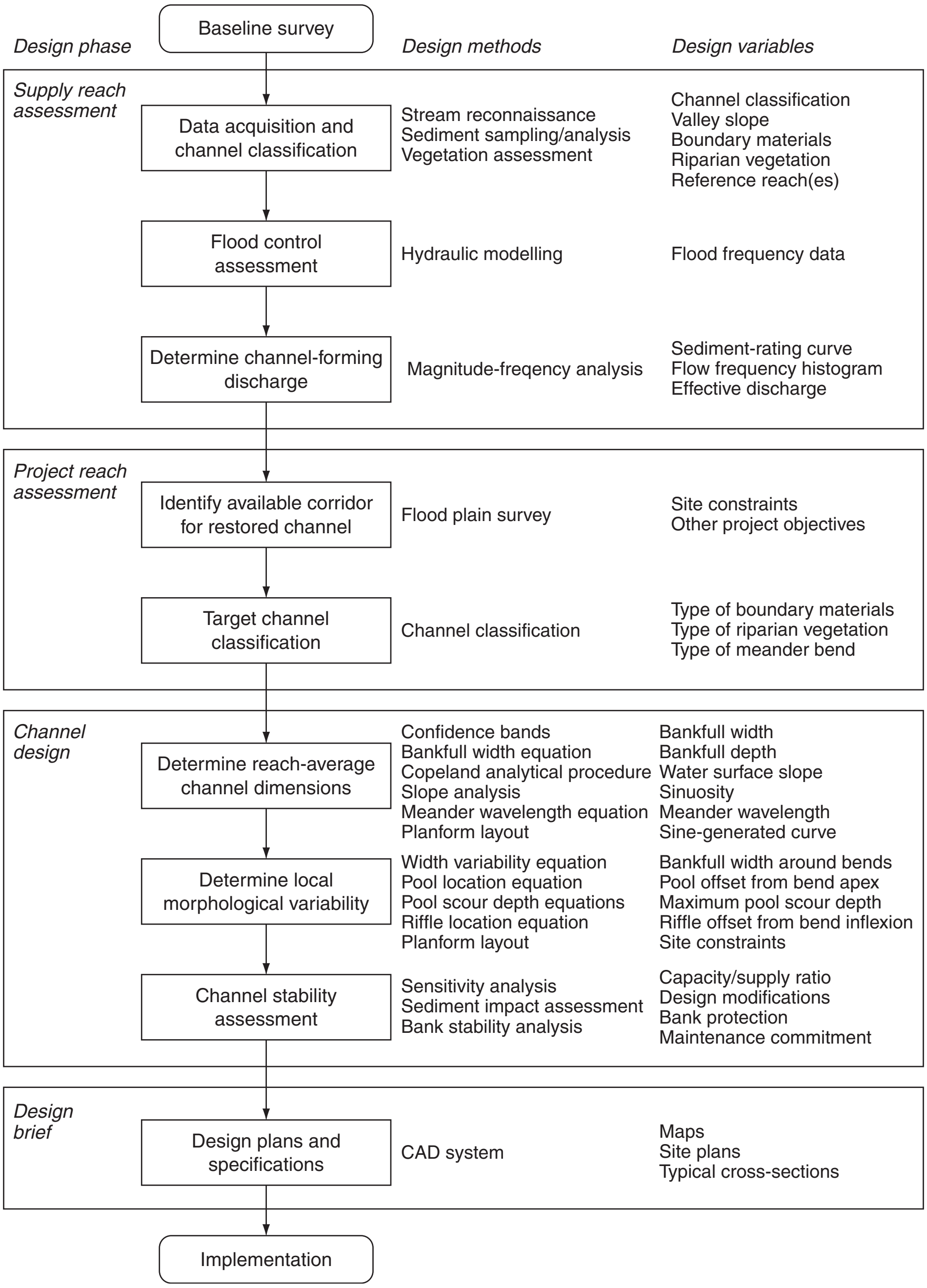

Fig. 4.17 Channel restoration design procedure for meandering rivers (after Soar and Thorne, 2001)

the project reach (Soar and Thorne, 2001). In this check, the performance of the proposed design is tested by modelling flow and sediment transport through the restored reach, with adjustments made as necessary to match its capacity to transport sediment to the supply from upstream and local sources. Balancing the sediment budget should result in channel dimensions and sediment features that are dynamically stable, as the restored morphology is attuned to the flow and sediment regimes imposed by the prevailing hydrological and geomorphological conditions in the catchment. However, short-term morphological adjustments to should still be expected as the channel responds to natural variability in flow and sediment supply and disturbance by flood events. Adjustments of this type occur within the envelope of dynamic stability and are themselves important to ability of the restored reach to 'self-maintain' without the need for further sediment management interventions. That is not to suggest that a restored channel is necessarily 'maintenance free' and this stresses the importance of using Geomorphological Post-Project Appraisal (GPPA) to identify future trends of adjustment that may pose new sediment-related risks that are unacceptable in order that they may be dealt with through adaptive management.

4.2.6.3 *Reinstating pools and riffles*

In a gravel-bed river, reinstatement of the pool–riffle sequence in a channelised reach that is overly uniform provides for a more efficient gravel transport–storage–transfer system that allows the river to store coarse sediment in an organised fashion between transport events and facilitates systematic sorting of grain sizes between scour pools and riffle bars (Clifford, 1993). The pool–riffle sequence is also closely related to the development of the channel planform through its interaction with the flow patterns in sinuous and meandering rivers. Consequently, it is an integral component of the process–form feedback loops that govern river mechanics in alluvial streams. It follows that reinstatement of the pool–riffle sequence must allow for subsequent adjustment of riffle spacing and characteristics, as the channel evolves in response to restoration actions. Reinstatement of pools and riffles not only helps to sustain a properly functioning sediment transfer system but also enhances the conservation and recreation value of the reach. It is not surprising, then, that pools and riffles are often installed as part of river rehabilitation or restoration projects.

When reinstating pools and riffles, care should be taken to mimic the characteristics these features typically display in natural channels (see discussion on the riffle–pool sequence in Chapter 2). The form and spacing may be based on reference pool–riffle features found in neighbouring undisturbed reaches, if suitable reaches can be identified. However, where no relevant reference condition is available, designs should take into account the following characteristics of undisturbed channels:

Pools:

- occupy over 50% of the river length
- are up to 25% narrower than associated riffles
- display low velocities and a tranquil appearance at all but high, in-bank flows
- possess an asymmetrical cross-section, even in straight channels
- have a bed composed of loose, mixed gravel/cobble/boulder material overlain by fines during low flows
- are located at bends (around or downstream of the bend apex) in meandering streams
- are located at anabranch confluences in braided rivers
- tend to fill with sediment deposited on the falling limb of floods and during low flows, but scour during rising limb and high flows
- are ecologically important in providing aquatic habitats and refugia
- add to substantially recreation and aesthetic values of river.

Riffles:

- occupy 30–40% of the river length

- are seldom spaced at a distance less than 3 or more than 10 times the channel width and are often spaced at between 5 and 7 times the width
- project approximately 0.3 to 0.5 m above the mean bed level with the head of water in the pool caused by the downstream riffle acting as an in-channel weir that drives hyporheic flow through the riffle structure, which cleanses it of fines and is very important ecologically
- are up to 25% wider than associated pools
- display locally high velocities even at low flows, with coarse bed grains breaking the surface to give a 'riffled' surface
- possess nearly symmetrical or slightly asymmetrical cross-sections, even in meandering channels
- have a bed composed of a coarse, well-packed surface armour layer underlain by a mixed substrate of gravels and sands
- are located at crossings (around or downstream of the planform inflection point) in meandering streams
- tend to accumulate sediment during bedload transport events, with a tendency to scour on the falling limb of floods and during low flows
- are ecologically important in aerating flow and providing spawning gravels for salmonids, habitats for diverse invertebrate fauna and sites for macrophytes
- add to recreation and aesthetic values of river landscapes.

Pools and riffles will form naturally in channels with mobile gravel-bed materials and an upstream supply of coarse bedload. However, many channelised or dredged rivers no longer possess sufficient stream power or sediment supply to recover these features naturally and in such streams pools and riffles must be reinstated artificially. Although design guidance is limited, recommendations for riffle design have been developed and generally depend on channel materials and gradient (e.g. Newbury and Gaboury, 1993; Hey, 1994). In reinstating pools and riffles in channels that have a flood defence function, it is important to ensure that the additional roughness introduced by the riffles does not raise flood elevations to compromise the statutory standard of service for the channel. This should not discourage the reinstatement of pools and riffles but does require a hydrodynamic analysis that is sufficiently advanced to properly account for energy losses across the riffles rather than simple manipulation of Manning's '*n*' for the channel (Walker *et al.*, 2004).

The design of a riffle–pool sequence is challenging and no 'cook book' design approach is available. However, the following notes provide some guidance based on experience gained from past projects:

- The choice of material for riffle construction is important. Ideally, locally derived, substrate sediment should be used, with the flow winnowing away the finer fraction to create an armoured surface. As the bed is actively involved in reach-scale sediment dynamics, material moves through the reach via temporary storage in the pools (fines) and riffles (coarser fraction). Hence, changes and adjustments of riffle position and morphology should be expected. Based on a statistical analysis of straight and meandering gravel/cobble bed rivers in the UK, Hey and Thorne (1986) found that the median size of sediment particles in a riffle is about 20% larger than the reach-average median size ($r^2 = 0.95$). Where there is no coarse sediment supply from upstream, either reinstated coarse material must remain static under all flow conditions or riffle sediments have to be replaced periodically. However, the use of over-large material, while ensuring stability, will fail to mimic the dynamic behaviour of natural riffles and may fail to provide suitable habitats or spawning conditions.

- Construction of riffles in high-energy environments may require the use of a block stone to avoid washing out of features during high events. Care must be taken to avoid creating a series of block stone weirs under these circumstances, with at least some allowance made for natural morphological adjustment. One alternative is to use a single block stone weir at the downstream end of the project reach to prevent loss of gravels.
- In sinuous channels, pools should be excavated around the outside of meander bends starting upstream of the apex and extending downstream to a point about half way to the next bend. Riffles should be located between bends, around or downstream of the meander inflection point.
- In straight channels, pools should be excavated on alternate sides of the channel, separated by riffles. Riffle crests should be constructed at a slight angle across the river to initiate secondary currents and direct flow towards the outer bank in the pool downstream.
- Riffle spacing should be 3 to 10 times the bankfull channel width, but regular spacing should be avoided to introduce a degree of local variability akin to that found in natural channels. In their analysis of straight and meandering channels, Hey and Thorne (1986) found an average spacing of 6.3 channel widths ($r^2 = 0.88$).
- Riffles should be spaced more closely in steeper reaches and further apart in more gently sloping and/or sinuous reaches.
- Riffles should be designed to be shallower and wider than the average low-flow dimensions of the project reach, with the differences diminishing as the bankfull level is approached. This is based on the finding by Hey and Thorne (1986) that in gravel/cobble bed rivers in the UK, riffle bankfull width is about 5% greater than the average channel width (r^2 of 0.97) and riffle mean depth is about 5% smaller than the average channel depth in the reach (r^2 of 0.97). Empirical equations to support the inclusion of natural cross-sectional variability appropriate for different types of meandering channel are reported in Soar and Thorne (2001).
- Pools should project at least 0.3 m below the mean bed elevation.
- Pools should shallow progressively downstream to the next riffle, with the deepest point within the upstream half of the pool's length. Pool bed sediment should be loose and uncompacted following reinstatement.
- Based on empirical data from the Red River, USA, Thorne (1988, 1992, 1997) demonstrated that the maximum scour depth in pools can be predicted as a function of the radius of curvature to channel width ratio for meander bends, according to the following semi-logarithmic expression:

$$(BD_m/XD_b) = 2.07 - 0.19\log_e[(R_c/w) - 2]) \qquad (7)$$

where BD_m = maximum scour depth in a bend pool (m), XD_b = mean depth at the crossing between bends (m), R_c = bend radius of curvature (m) and w = channel width at crossing (m). This best-fit relationship explained 64% of the variance in a large empirical dataset.

Stemming from this earlier research, a practical design curve for bend scour depth that is on the safe side for bends with R_c/w ratios greater than 2 is defined by Soar and Thorne (2001) as:

$$(BD_m/XD_b) = 1.5 + 4.5(R_c/w)^{-1} \qquad (8)$$

For channels with a radius of curvature to width ratio of less than 1.8, it is recommended that the dimensionless bend scour depth in the safe design curve be capped at 4 times the depth in the approach channel at the crossing upstream. From this upper-bound relationship, the maximum scour depth could be between 3 and 4 times the crossing depth for radius of curvature to width ratios between 1.8 and 3. As these equations were derived from limited datasets, caution must be exercised when they are used as general design tools or outside the south-eastern USA.
- Pools and riffles cannot usually be installed successfully in ephemeral streams, in channels with steep gradients, where there are very high sediment transport rates, or where the banks are highly unstable.

References

Agency, Guidance Note 18, prepared by Thorne, C.R., Downs, P.W., Newson, M.D., Sear, D.A. and Clarke, M.J., National Centre for Risk Analysis and Options Appraisal, London, 56 pp.

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment (1998a) River width adjustment. I: Processes and mechanisms. *Journal of Hydraulic Engineering, American Society of Civil Engineers*, **114**(9), 881–902.

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment (1998b) River width adjustment. II: Modeling. *Journal of Hydraulic Engineering, American Society of Civil Engineers*, **114**(9), 970–1073.

Andrews, E.D. (1980) Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology*, **46**(3–4), 311–330.

Bagnold, R.A. (1966) An approach to the sediment transport problem from general physics. *US Geological Survey*. A Professional Paper 422 – I.

Bagnold, R.A. (1980) An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society*, **372A**(1751), 453–473.

Bathurst, J.C. (1997) Environmental river flow hydraulics. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, 69–94.

Biedenharn, D.S, Copeland, R.R., Thorne, C.R., Soar, P.J., Hey, R.D. and Watson, C.C. (2000) *Effective discharge calculation: a practical guide*. *ERDC/CHL Technical Report TR-00-15*, United States Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi, ERDC/CHL Technical Report TR-00-15 (see http://libweb.erdc.usace.army.mil/Archimages/9084.pdf).

Biedenharn, D.S., Gibson, S.A., Little, C.D. Jr, Mooney, D.M., Thorne, C.R., Wallerstein, N.P. and Watson, C.C. (2006) Sediment Impact Assessment Model (SIAM). In *Accounting for sediment in rivers: a tool box of sediment transport and transfer analysis methods and models to support hydromorphologically-sustainable flood risk management in the UK*. Flood Risk Management Research Consortium, Report UR9, 25-32 (downloadable from: http://www.floodrisk.org.uk/index.php?option=com_content&view=article&id=7&catid=0&Itemid=50 or http://www.engr. colostate.edu/~cwatson/ce_old/CE_613_F06/FRMRC. pdf).

Biedenharn, D.S., Little, C.D. and Thorne, C.R. (1990) Effects of low drop grade control structure on bed and bank stability. In Chang, H.H. and Hill, J.C. (eds) *Hydraulic engineering*. Proceedings of the National Conference on Hydraulic Engineering, ASCE, San Diego, August 1990, 826–831.

Biedenharn, D.S., Thorne, C.R., Soar, P.J., Hey, R.D. and Watson, C.C. (2001) Effective discharge calculation guide. *International Journal of Sediment Research*, **16**(4), 445–459.

Brierley, G. and Fryirs, K. (2008) *River futures: an integrative scientific approach to river repair*. Island Press, Washington, DC, 328 pp.

Brookes, A. (1983) *River channelization in England and Wales: downstream consequences for the channel morphology and aquatic vegetation*. Unpublished PhD thesis, University of Southampton, UK.

Brookes, A. (1987a) The distribution and management of channelized streams in Denmark. *Regulated Rivers*, **1**(1), 3–16.

Brookes, A. (1987b) River channel adjustments downstream from channelization works in England and Wales. *Earth Surface Processes and Landforms*, **12**(4), 337–351.

Brookes, A. (1988) *River channelization: perspectives for environmental management*. Wiley, Chichester.

Brookes A. (2007) *A guide to the use of the stream power tool in river management: Preliminary User Guide* (draft), Jacobs UK Ltd., Reading.

Brookes, A. and Sear, D.A. (1996) *Geomorphological principals for restoring channels. In River Channel Restoration: Guiding principles for sustainable projects*, (eds) Brookes, A. and Shields, F.D., Wiley, Chichester, 75–101.

Brookes, A. and Shields, F.D. (eds) (1996) *River channel restoration: guiding principles for sustainable projects*. Wiley, Chichester.

Brookes, A. and Wishart, D. (In preparation) *Application of a stream power screening tool to UK rivers*.

Bunte, K. and Abt, S.R. (2001) Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. *General Technical Report RMRS-GTR-74*. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado; 428 pp. (download from http://www.fs.fed.us/rm/pubs/rmrs_gtr74.html).

Bunte, K., Abt, S.R., Potyondy, J.P. and Ryan, S.E. (2004) Measurement of coarse gravel and cobble transport using portable bedload traps. *Journal of Hydraulic Engineering*, **130**(9), 879–893.

CEN (2004) *European Standard EN14614*. European Committee for Standardization: Brussels, (available at http://www.cen.eu/).

Clifford, N.J. (1993) Differential bed sedimentology and the maintenance of a riffle–pool sequence, *Catena*, **20**, 447–468.

Clifford, N.J., Harmar, O.P., Harvey, G. and Petts, G.E. (2006) Physical habitat, eco-hydraulics and river design: a review and re-evaluation of some popular concepts and methods. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **16**, 389–408.

Commission of European Community (CEC) (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for the community action in the field of water policy. *Official Journal of the European Union*, **L237**(1-72), 22 December.

Courltard, T.J. and Van de Wiel, M.J. (2006) A cellular model of river meandering. *Earth Surface Processes and Landforms*, **31**, 123–132.

Darby S.E. and Thorne C.R. (1996) Development and testing of riverbank-stability analysis. *Journal of Hydraulic Engineering*, **112**(8), 443–454.

Darby, S.E. and Van de Wiel, M.J. (2003) Models in fluvial geomorphology. In Kondolf, M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 503–539.

Dawson, R., Hall, J. and Davis, J. (2004) Performance-based management of flood defence systems. *Water Management*, **157**(1), 35–44.

Department for Environment, Food and Rural Affairs (Defra) (2008) Making space for water homepage: http://www.defra.gov.uk/environ/fcd/policy/strategy.htm.

Downs, P.W. and Gregory, K.J. (2004) *River channel management: towards sustinable catchment hydrosystems*. Arnold, London.

Downs, P.W. and Thorne C.R. (1996) The utility and justification of river reconnaissance surveys. *Transactions of the Institute of British Geographers*, **21**, 455–468.

Downward, S.R. (1995) Information from topographic survey. In Gurnell, A.M. and Petts, G.E. (eds) *Changing river channels*. Wiley, Chichester, pp. 303–323.

Einstein, H.A. (1950) *The bed-load function for sediment transport in open channel flows*. US Department of Agriculture, Soil Conservation Service, Technical Bulletin No. 1026.

Environment Agency (1997) *Waterway bank protection: a guide to erosion assessment and management*. Environment Agency, Bristol.

Environment Agency (1998a) *River geomorphology: a practical guide*. Environment.

Environment Agency (1998b) *Geomorphological approaches to river management*. Project Record W5A/i661/1, prepared by Thorne, C., Downs, P.W., Newson, M.D., Clarke, M.J. and Sear, D.A., Environment Agency, Bristol.

Environment Agency (1999) *Waterway bank protection: a guide to erosion and assessment and management*. The Stationery Office, Bristol.

Environment Agency (2004a) *The removal of gravel from rivers*. Policy number: 359_04, 6 pp. (www.intertidalmanagement.co.uk/contents/management_processes/pdfs/risks%20benefits/359_04.pdf).

Environment Agency (2004b) *River sediments and habitats and the impact of maintenance operations and capital works*. R&D Technical Report FD1920/TR, prepared by HR Wallingford.

Environment Agency (2007) *Trial application of high status hydromorphology classification procedure for rivers*. Report Ref. B0528500/002 prepared by Jacobs UK Limited, Sale.

Environment Agency (2008) *Channel maintenance*. Briefing note 1988469, Andryszewski, T. and Robinson, P., Flood Risk Management, Asset Management Team.

European Union (2000) *Directive 2000/60/EC of the European Parliament and of the Council of 23rd October, 2000: establishing a framework for Community action in the field of water policy. Official Journal of the European Communities*, Brussels, **L327**, 1–72, 23 December.

Evans, E., Ramsbottom, D.M., Wicks, J.M., Packman, J.C. and Penning-Rowsell, E.C. (2002) Catchment flood management plans and the modelling and decision support framework. *Proceedings of the Institution of Civil Engineers*, **150**, special issue 1, 43–48.

Evans, E.P., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Foresight. Future flooding. Scientific summary: Volume I – Future risks and their drivers*. DTI/pub 7183/2k/04/04/NP. URN 04/939, Office of Science and Technology, DTI, London, (available for free download from http://www.foresight.gov.uk/Previous_Projects/Flood_and_Coastal_Defence/Reports_and_Publications/Project_Outputs/Outputs.htm).

Evans, E.P., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Foresight. Future flooding. Scientific summary: Volume II – Managing future risks.* DTI/pub 7184/2k/04/04/NP. URN 04/946, Office of Science and Technology, DTI, London. Available for free download from (http://www.foresight.gov.uk/Previous_Projects/Flood_and_Coastal_Defence/Reports_and_Publications/Project_Outputs/Outputs.htm).

Federal Interagency Stream Restoration Working Group (FISRWG) (1998) *Stream corridor restoration: principles, processes and practices*. United States National Engineering Handbook, Part 653 (download from http://www.nrcs.usda.gov/technical/stream_ restoration).

Ferguson, R.I. (1981) Channel form and channel changes. In Lewin, J. (ed.) *British rivers*. Allen and Unwin, London, pp. 90–125.

Ferguson, R.I. (2005) Estimating critical stream power for bedload transport calculations in gravel-bed rivers. *Geomorphology*, **70**(1–2), 33–41.

GeoData Institute (2004) *RHS geomorphology and floodplain module*. Report to Environment Agency (on CD), University of Southampton.

Gibson, S.A. (2006) Sediment transport computations with HECRAS. In *Accounting for sediment in rivers: a tool box of sediment transport and transfer analysis methods and models to support hydromorphologically-sustainable flood risk management in the UK*. Flood Risk Management Research Consortium, Report UR9, pp. 33–43. (downloadable from: http://www.floodrisk.org.uk/index.php?option=com_content&view=article&id=97&catid=0&Itemid= 50 or http://www. engr.colostate.edu/~cwatson/ce_old/CE_613_F06/FRMRC. pdf).

Gibson, S.A. and Little, C.D. Jr (2006) Implementation of the Sediment Impact Assessment Model (SIAM) in HEC-RAS. In *Proceedings of the joint federal interagency conferences 2006 (3rd Federal Interagency Hydrologic Modeling Conference and 8th Federal Interagency Sedimentation Conference)*, Reno, NV, 2–6 April.

Gilvear, D.J. (1999) Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. *Geomorphology*, **31**(1–4), 229–245.

Gilvear, D. and Bryant, R. (2003) Analysis of aerial photography and other remotely sensed data. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 135–170.

Gomez, B. and Church, M. (1989) An assessment of bedload sediment transport formulae for gravel-bed rivers. *Water Resources Research*, **25**(6), 1161–1186.

Griffiths, M. (2002) *The European Water Framework Directive: an approach to integrated river basin management*. European Water Management Online, Official Publication of the European Water Association (EWA) (available at http://www.ewaonline.de/journal/2002_05.pdf).

Gurnell, A.M., Peiry, J.-L. and Petts, G.E. (2003) Using historical data in fluvial geomorphology. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 77–101.

Harrelson, C.C., Rawlins, C.L. and Potyondy, J.P. (1994) *Stream channel reference sites: an illustrated guide to field technique*. United States Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, General Technical Report RM-245, 61 pp. (see http://www.stream.fs.fed.us/publications/pdfs/RM245E.pdf).

Harvey, A.M. (2007) Differential recovery from the effects of a 100-year storm: significance of long-term hillslope-channel coupling; Howgill Fells, northwest England. *Geomorphology*, **84**(3–4), 192–208.

Hassan, M.A. and Ergenzinger, P. (2003) Tracers in fluvial geomorphology. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 397–423.

Hey, R.D. (1975) Design discharge for natural channels. In Hey, R.D. and Davies, T.D. (eds) *Science, technology and environmental management*. Saxon House, Farnborough, pp. 73–88.

Hey, R.D. (1994) Environmentally sensitive river engineering. In Callow, P. and Petts, G.E. (eds) *The rivers handbook: hydrological and ecological principles*. Blackwell Scientific, Oxford, pp. 337–362.

Hey, R.D. (1997) Stable river morphology. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 222–236.

Hey, R.D. and Heritage, G.L. (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. National Rivers Authority, Bristol, NRA R&D Note 154.

Hey, R.D. and Thorne, C.R. (1983) Accuracy of surface samples from gravel bed material. *Journal of Hydraulic Engineering, ASCE*, **109**(6), Paper No. 18047, 842–851 and discussion and closure, **110**(7), 1016–1018.

Hey, R.D. and Thorne, C.R. (1986) Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering, ASCE*, **112**(6), 671–689.

Hicks, D.M. and Gomez, B. (2003) Sediment transport. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 425–461.

Hooke, J.M. (1997) Styles of channel change. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 237–268.

Hooke, J.M. and Kain, R.J.P. (1982) *Historical change in the physical environment: a guide to sources and techniques*. Butterworths, Sevenoaks.

Hooke, J.M. and Redmond, C.E. (1989) Use of cartographic sources for analysing river channel change with examples from Britain. In Petts, G.E. (ed.) *Historical change of large alluvial rivers: Western Europe*. Wiley, Chichester, 79–93.

HR Wallingford (2008) *River sediments and habitats: review of maintenance and capital works. Draft final report*. Environment Agency, Bristol.

Kondolf, G.M., Lisle, T.E. and Wolman, G.M. (2003) Bed sediment measurement. In Kondolf, G.M. and Piégay, H. (eds) *Tools in Fluvial Geomorphology*. Wiley, Chichester, pp. 347–395.

Lane, S.N. and Thorne, C.R. (2007) River processes. In Thorne, C.R., Evans, E.P. and Penning-Rowsell, E. *Future flooding and coastal erosion risks*. Thomas Telford, London, pp. 82–99.

Lawler, D.M. (1992) Design and installation of a novel automatic erosion monitoring system. *Earth Surface Processes and Landforms*, **17**(5), 455–463.

Lawler, D.M. (1993) The measurement of river bank erosion and lateral channel change: a review. *Earth Surface Processes and Landforms*, **18**(9), 777–821.

Lawler, D.M., Thorne, C.R. and Hooke, J.M. (1997) Bank erosion and instability. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 137–172.

Leopold, L.B. and Maddock, T. (1953) *The hydraulic geometry of stream channels and some physiographic implications*. United States Geological Survey, Reston, VA, Professional Paper 252.

Little, W.C. and Murphey, J.B. (1982) Model study of low drop grade control structures. *Journal of the Hydraulics Division, ASCE*, **108**(10), 1132–1146.

Miko, M., Pender, G., Hoey, T., Shvidchenko, A. and Petkovek, G. (2003) Numerical simulation of graded sediment transport. *Proceedings of the Institution of Civil Engineers, Water and Maritime Engineering*, **156**(1), 47–51.

Muscutt, A.D., Harris, G.L., Bailey, S.W. and Davies, D.B. (1993) Buffer zones to improve water quality: a review of their potential use in UK agriculture. *Agriculture, Ecosystems and Environment*, **45**(1–2), 59–77.

Nanson, G.C. and Croke, J.C. (1992) A genetic classification of floodplains. *Geomorphology*, **4**(6), 459–486.
National Rivers Authority (1991) *Sediment and gravel transportation in rivers including the use of gravel traps*. National Rivers Authority, Bristol, NRA Report C5.02, prepared by Sear, D.A. and Newson, M.D., University of Newcastle, UK, Project Report 232/1/T.
National Rivers Authority (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. R&D Note 154, prepared by Hey, R.D. and Heritage, G.L., 98 pp.
National Rivers Authority (1994a) *Sediment and gravel transport in rivers: a procedure for incorporating geomorphology in river maintenance*. National Rivers Authority, Bristol, Project Record 384, prepared by Sear, D.A. and Newson, M.D.
National Rivers Authority (1994b) *Sediment and gravel transportation in rivers, including the use of gravel traps*. R&D Project Record, C5/384/2, prepared by Sear, D.A.
National Rivers Authority (1995) *River channel typology for catchment and river management*. Final report, R&D Project 539/NDB/T, prepared by Clark, M.J., Sear, D.A., Hill, C.T., Branson, J., Newson, M.D., Pawson, R. and Juggins, S.
Natural Resources Conservation Service (2007) *Stream restoration design. National engineering handbook, Part 654*. US Department of Agriculture, Natural Resources Conservation Service: Washington, DC, CD-ROM (download from http://policy.nrcs.usda.gov/viewerFS.aspx?hid=21433).
Newbury, R. and Gadbury, M. (1993) Exploration and rehabilitation of hydraulic habitats in streams using principles of fluvial behaviour. *Freshwater Biology*, **29**(2), 195–210.
Newson, M.D. and Bathurst, J.C. (1997) *Sediment movement in gravel bed rivers*. Seminar paper 59, Department of Geology, Newcastle University.
Newson, M.D. and Large, A.R.G. (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, **31**(13), 1606–1624.
Newson, M.D. and Newson, C.L. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*, **24**(2), 195–217.
Nobutomo, O., Noriyuki, M., Shinji, T., Keiji, O., Shigeo, H. and Nobuo, Y. (2000) A study on the standard for the hillside works and the hillside slope management for erosion and sediment control. Examination through the evaluation of implemented hillside works by Sabo Project. *Journal of the Japan Society of Erosion Control Engineering*, **52**(52), 30–40.
Osman, A.M. and Thorne, C.R. (1988) Riverbank stability analysis. I: Theory. *Proceedings of the American Society of Civil Engineers, Journal of Hydraulic Engineering*, **114**(2), 134–150.
Owens, P.N., Duzant, J.H., Deeks, L.K., Wood, G.A., Morgan, R.P.C. and Collins, A.J. (2007) Evaluation of contrasting buffer features within an agricultural landscape for reducing sediment and sediment associated phosphorus delivery to surface waters. *British Society of Soil Science*, **23**, 165–175.
Parker, C., Simon, A. and Thorne, C.R. (2008) The effects of variability in bank material properties on riverbank stability: Goodwin Creek, Mississippi. *Geomorphology*, **101**(4), 533–543.
Pitt, M. (2008) *Learning lessons from the 2007 floods: final report*. Cabinet Office, London, (http://archive.cabinetoffice.gov.uk/pittreview/_/media/assets/www.cabinetoffice.gov.uk/flooding_review/pitt_review_full%20pdf.pdf).
Pollen, N. and Simon, A. (2005) Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*, **41**.
Randle, T.J., Bountry, J.A., Makar, P.W., Fotherby, L.M., Bauer, T.R. and Murphy, P.J. (2006) River processes and restoration. In *Erosion and sedimentation manual*, US Department of the Interior, Bureau of Reclamation, Denver, Colorado, Vol. 7, pp. 1–64. (http://www.usbr.gov/pmts/sediment/kb/ ErosionAndSedimentation/chapters/Chapter7.pdf).
Raven, P.J., Holmes, N.T.H., Dawson, F.H. and Everard, M. (1998) Quality assessment using River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(4), 477–499.
Reid, I., Bathurst, J.C., Carling, P.A., Walling, D.E. and Webb, B.W. (1997) Sediment erosion, transport and deposition. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley: Chichester, pp. 95–136.

Reid, L.M. and Dunne, T. (2003) Sediment budgets as an organising framework in fluvial geomorphology. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 463–500.

Reid, S.C, Lane, S.N., Berney, J.M. and Holden, J. (2008) The timing and magnitude of coarse sediment transport events within an upland, temperate gravel-bed river. *Geomorphology*, **83**(1–2), 152–182.

River Restoration Centre (1999) *Manual of river restoration techniques*. Arca Press, Bedford.

River Restoration Centre (2008) *Testing of the stream power screening tool using data from the Rivers Kent (Cumbria) and Eden (Kent)*. Report to the Flood Risk Management Research Consortium, River Restoration Centre, Cranfield University, Bedford.

Ryan, S.E. and Troendle, C.A. (1997) Measuring bedload in coarse-grained mountain channels: procedures, problems, and recommendations. In *Water resources education, training and practice: opportunities for the next century*. American Water Resources Association Conference, Keystone, Colorado, USA, 29 June to 3 July, pp. 949–958.

Sadler, B. (1988) The evaluation of assessment: post-EIS research and process development. In Wathern, P. (ed.) *Environmental impact assessment: theory and practice*. Unwin Hyman, London, pp. 129–142.

Schmidt, J., Parnell, R., Grams, P.E., Hazel, J.E., Kaplinski, M., Stevens, K. and Hoffnagle, T. (2001) The 1996 controlled flood in Grand Canyon: flow, sediment transport and geomorphic change. *Ecological Applications*, **11**(3), 657–671.

Schumm, S.A. (1977) *The fluvial system*. Originally published by Wiley, now available in facsimile from The Blackburn Press, P.O. Box 287, Caldwell, New Jersey 07006.

Scottish Environmental Protection Agency (2005) *SEPA position statement to support the implementation of the Water Environment (Controlled Activities) (Scotland) Regulations 2005 – Sediment Management*, 6 pp. (www.sepa.org.uk/pdf/wfd/guidance/engineering/positionstate_sedimentman.pdf).

Scottish Environmental Protection Agency (2008) *Good practice guide – river bank erosion*. WAT-SG-23, Vol. 1, 48 pp. (http://www.sepa.org.uk/water/ regulations/guidance/engineering.aspx).

Sear, D.A. (1996) Sediment transport processes in pool – riffle sequences, *Earth Surface Processes and Landforms*, **21**, 241–262.

Sear, D.A., Darby, S.E. and Thorne, C.R. (1994) Geomorphological approaches to stream stabilisation and restoration. Case Study of Mimmshall Brook, Hertfordshire, UK, *Regulated Rivers*, **9**, 205–223.

Sear, D.A., Hill, C.T., Newson, M.D., Emery, J. and Branson, J. (2009) Applying geomorphology for assessing the physical condition of riverine habitats in support of the Habitats Directive. *Aquatic Conservation* (in press).

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment related river maintenance: the role of fluvial geomorphology. *Earth Surface Processes and Landforms*, **20**, 629–647.

Sear, D.A., Newson, M.G. and Thorne, C.R. (2004) *Guidebook of applied fluvial geomorphology*. Defra Flood Management Division, London, ISBN: 0-85521-053-2, 233 pp (available for free download from http://www.defra.gov.uk/science/project_data/DocumentLibrary/FD1914/FD1914 _1147_TRP.pdf).

Shields, F.D. Jr (1996) Hydraulic and hydrologic stability. In Brookes, A. and Shields, F.D. Jr (eds) *River channel restoration*. Wiley, Chichester, pp. 24–74.

Simm, J.D., Wallis, M.J., Sayers, P.B., Gouldby, B.P., Buijs, F., Flikweert, J.J. and Hamer, B. (2006) Developing a performance-based management system tool for flood and coastal defence assets. *Proceedings of the 41st Defra Flood and Coastal Management Conference*, University of York, 4–6 July.

Simon, A. and Castro, J.M. (2003) Measurement and analysis of alluvial channel form. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 291–322.

Simon, A. and Darby, S.E. (2002) Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi. *Geomorphology*, **42**(3–4), 229–254.

Skinner, K.A. and Bruce-Burgess, L. (2005) Strategic and project level river restoration protocols – key components for meeting the requirements of the water framework Directive. *Journal of the Chartered Institution of Water and Environmental Management*, **19**, 135–142.

Skinner, K.S. (1999) *Geomorphological post-project appraisal of river rehabilitation schemes in England*. Unpublished PhD thesis, University of Nottingham.

Skinner, K.S., Shields, F.D. Jr and Harrison, S. (2008) Measures of success: defining the outcomes. In Sear, D.A. and Darby, S.E. (eds) *River restoration: managing the uncertainty in restoring physical habitat*. Wiley, Chichester, pp. 187–208.

Skinner, K.S. and Thorne, C.R. (2005) *Review of impact assessment tools and post project monitoring guidance.* Nottingham University Consultants.

Soar, P.J. and Thorne, C.R. (2001) *Channel restoration design for meandering rivers*. United States Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, Mississippi, September 2001, ERDC/CHL Report CR-01-1, 429 pp. (including appendices) (http://libweb.erdc.usace.army.mil/Archimages/10934.pdf).

Thompson, D.M. (2002) Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon Rivers, Connecticut, USA. *Journal of Environmental Management*, **29**, 250–265.

Thorne, C.R. (1988) *Bank processes on the Red River between Index, Arkansas and Shreveport, Louisiana*. Final report to United States Army European Research Office, contract DAJA45-88-C-0018, Department of Geography, Queen Mary College, 50 pp.

Thorne, C.R. (1992) Bend scour and bank erosion on the meandering Red River, Louisiana. In Carling, P.A. and Petts, G.E. (eds) *Lowland floodplain rivers: geomorphological perspectives*. Wiley, Chichester, pp. 95–115.

Thorne, C.R. (1997) Channel types and morphological classification. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 175–222.

Thorne, C.R. (1998) *Stream reconnaissance handbook: geomorphological investigation and analysis of river channels*. Wiley, Chichester, 127 pp.

Thorne, C.R. and Osman, A.M. (1988) Riverbank stability analysis. II: Applications. *Proceedings of the American Society of Civil Engineers, Journal of Hydraulic Engineering*, **114**(2), 151–172.

Thorne, C.R., Allen, R.G. and Simon, A. (1996) Geomorphological river reconnaissance for river analysis, engineering and management. *Transactions of the Institute of British Geographers*, **21**, 469–483.

Thorne, C.R., Evans, E.P. and Penning-Rowsell, E. (2007) *Future flooding and coastal erosion risks*. Thomas Telford, London.

Thorne, C.R., Newson, M.D. and Hey, R.D. (1997) *Applied Fluvial Geomorphology for River Engineering and Management*. Wiley, Chichester.

Tomes, I.M., Harmar, O.P. and Thorne, C.R. (2005) Sediment impact analysis for the Lower Thames Flood Strategy Study. *Proceedings of the 8th Federal Interagency Sedimentation Conference, Reno, Nevada*, April 2–6.

Trimble, S.W. (2008) The use of historical data and artefacts in geomorphology. *Progress in Physical Geography*, **32**(1), 3–29.

van den Berg, J.H. (1995) Prediction of alluvial channel pattern of perennial rivers. *Geomorphology*, **12**(4), 259–279.

Verstraeten, G., Poesen, J., Gillijns, K. and Govers, G. (2006) The use of riparian vegetated filter strips to reduce river sediment loads: an overestimated control measure? *Hydrological Processes*, **20**, 4259–4267.

Walker, D.R., Millar, R.G. and Newbury, R.G. (2004) Energy profiles across constructed riffles. *Journal of Hydraulic Engineering*, **130**(3), 199–207.

Wallerestein, N.P., Soar, P.J. and Thorne, C.R. (2006) River energy auditing scheme (REAS) for catchment flood management planning. In Ferreira, R.M.C., Alves, E.C.T.L., Leal, J.G.A.B. and Cardoso, A.H. (eds) *River flow 2006*. Taylor and Francis, London, pp. 1923–1932.

Wallerstein, N. (2006) *Accounting for sediment in rivers – a tool box of sediment transport and transferanalysis methods and models to support hydromorphologically-sustainable flood risk management in the UK*. Flood Risk Management Research Consortium, Research Report UR9, United Kingdom (see http://www.floodrisk.org.uk/index.php?option=content&task=view&id= 38).

Walling, D.E. (1999) Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, **410**, 223–240.

Whiting, P.J. (2003) Flow measurement and characterization. In Kondolf, G.M. and Piégay, H. (eds) *Tools in fluvial geomorphology*. Wiley, Chichester, pp. 323–346.

Wolman, M.G. (1954) A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union*, **35**(6), pp. 951–956.

Worthy, M. (2005) *High resolution total stream power estimates for the Cotter River, Namadgi National Park. Australian Capital Territory*, Regolith 2005 – ten years of the Centre for Resources and Environmental Studies. CRC LEMW, Australia National University, Canberra.

Wren, D.G., Barkoll, B.D., Kuhnle, R.A. and Derrow, R.W. (2000). Field techniques for suspended sediment measurement. *Journal of Hydraulic Engineering*, **126**(2), 97–104.

Yang, C.T. (2006) Noncohesive sediment transport. In *Erosion and sedimentation manual*. US Department of the Interior, Bureau of Reclamation, Denver, Colorado, Ch. 3, pp. 1–111. (http://www.usbr.gov/pmts/sediment/kb/Erosion AndSedimentation/chapters/Chapter3.pdf).

5

Geomorphology and river ecosystems: Concepts, strategies and tools for managing river channels, floodplains and catchments

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5.1 Introduction

In parallel with the research and development (R&D) leading to direct applications of fluvial geomorphology alongside traditional engineering approaches, fluvial geomorphologists have been contributing both strategic and operational advice to a much broader, interdisciplinary element of river management. Public policy continues to evolve rapidly to meet the requirements of the international consensus over sustainable development; a large element of this is the protection of biodiversity in all the planet's habitats through actions that conserve and restore (while permitting sustainable exploitation of resources by humankind). Thus, the three Rs: 'R&D', 'RHS' (River Habitat Surveys) and 'Restoration' may be seen as marking the footprint of applied fluvial geomorphology in the UK during the 1990s (Newson *et al.*, 2001). In the early years of the new millennium there has grown up a much stronger framework in policy and practice for considering the catchment scale in all elements of river management, introducing such new agendas for geomorphology as diffuse pollution and siltation, particularly as they impact on biodiversity and ecosystem 'health'. The European Union's 'Water Framework' and 'Habitats' Directives have literally made river ecosystem concepts 'the rule' for management rather than an exception.

Initially, contributions from geomorphologists to river *ecosystem management* tended to be separate from those made for example to river *engineering*, thanks largely to the functional division between the two activities in river management. However, both formal and informal linkages between managers concerned with habitat protection and flood risk management have been forged or forced. This chapter describes the concepts which configure this integration and the management tools already available, or in the process of refinement, to meet the exciting but uncertain challenges (see also Newson, 2002).

The rapidity of change is illustrated by the fact that the main focus for the R&D reviewed in the Defra edition of the Guidebook (Sear *et al.*, 2003) was the river channel itself. Out-of-bank flows are also highly relevant to understanding channel processes in geomorphology – as well as being of huge socio-economic and ecological significance. To geomorphologists the addition of the riparian zone and floodplain is logical and scientifically justifiable in fulfilment of a much broader environmental remit, extending even further to wetlands too – that of the creation and maintenance of habitat in 'fluvial hydrosystems' (Petts and Amoros, 1996a). Simultaneously with the completion of the early R&D reports on channel geomorphology, the NRA's River Habitat Surveys (RHS) were being

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designed; geomorphologists were invited to help with the survey specification and with analysis of the early data (e.g. Newson *et al.*, 1998a; and see Section 5.4 below). Already, and helped along by the institutional shocks delivered by the Millennium Floods (Marsh, 2001, 2002; Howe and White, 2002), an additional component of RHS – GeoRHS (Branson *et al.*, 2005) – has been developed and piloted to reflect the need for more empirical geomorphological survey data, both intensive (in-channel detail) and extensive (floodplain components). An apparent obsession with empirical data against the potential power of mathematical modelling certainly qualifies UK fluvial geomorphology, but this partly stems from the UK's almost total institutional ignorance about sediment fluxes in its river systems (equivalent to the water and sewage utilities not understanding flow in pipes).

Another development which encouraged the deployment of geomorphological expertise towards ecological ends was the River Restoration Project (RRP) (Kronvang *et al.*, 1998; and see Section 5.5 below). River restoration has a dilemma set by the fact that it is a popular, grassroots strategy now set to become a major technical/regulatory operation in achieving national compliance with European Union (EU) legislation.

5.2 'Fluvial hydrosystems' and 'hydromorphology'

It is a paradox that the traditional engineering works associated with river *system* management are best designed as site-specific interventions to deal with particular problems – 'siltation' is a good example: society respects such technically sound procedures (Newson and Clark, 2008). However, the nature of social responsibility in general environmental management appears to be shifting policy and practice towards the larger space scales and longer timescales, inherent in the concept of sustainable development. A critical problem in current R&D lies with reconciling the two lines of approach, not merely leaving holistic system-wide considerations as a precautionary check on 'business as usual' but making them operational. Such is the case in river management, where research frameworks are broadening in both the disciplinary and spatial senses. Information on the state of rivers and their response to management impacts is now sought in many more dimensions than upstream–downstream. Demands for transparency in both strategy and operations also introduce a considerable socio-political element to standard procedures, now beyond that of the inspirational *leitbild* vision of 1992 developed by Kern (Kern, 1992; McDonald *et al.*, 2004; Newson and Chalk, 2004; Newson and Large, 2004).

Petts and Amoros (1996b) demand that:

> A river ecosystem must no longer be viewed as a simple linear feature delimited by the bed and banks of the main channel, and dominated by downstream transfers. Rivers should be viewed as three-dimensional systems [see Fig. 5.1 below] being dependent on longitudinal, lateral and vertical transfers of energy, material and biota.

These authors distinguish five key features of the fluvial hydrosystem approach:

1. It focuses attention on the river corridor, including floodplains.
2. It stresses the lateral and vertical fluxes of energy and materials between the river and alluvial aquifer.
3. Biota are clearly affected by the resulting environmental gradients, modified by biological processes.

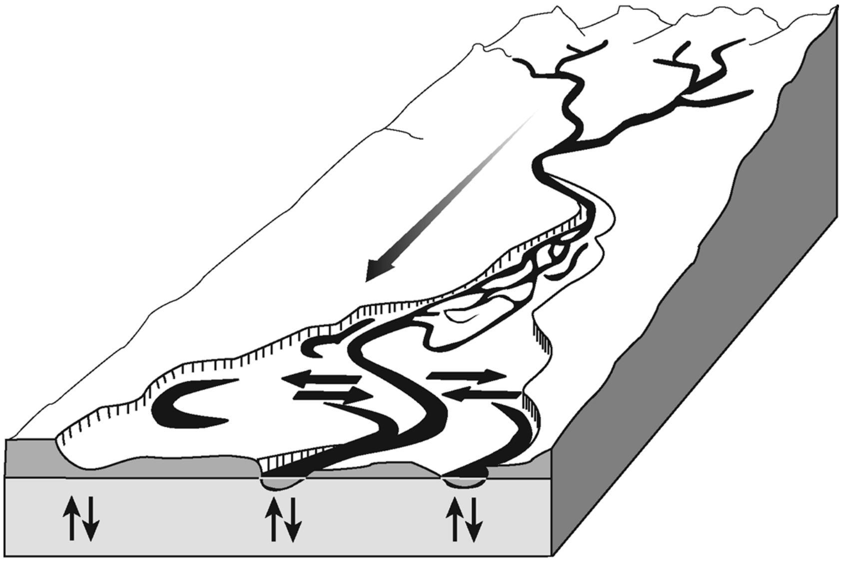

Fig. 5.1 The fluvial hydrosystem in three dimensions (after Petts and Amoros, 1996)

4. Environmental change and anthropogenic impacts become important at the catchment scale.
5. Historical legacies help to explain the contemporary functioning of the system.

A candidate one-word summary of these clauses is 'connectivity', a measurable variable using the increasingly sophisticated spatial modelling tools which have accompanied the widespread introduction of Geographical Information Systems (GIS) to river management.

In England and Wales it is somewhat paradoxical that decades of pressure from freshwater ecologists for balance between the competing interests of humans and non-human biota became absorbed into the reformed 'flood risk management' orientation of engineers. Again a paradox: if we accept 'connectivity' of the fluvial hydrosystem as a principle to guide practice, we also accept applications of knowledge and information which may be incomplete and provisional (Quevauviller *et al.*, 2005; Newson, in press), a commonly observed problem of implementing the European Union Water Framework Directive (European Commission, 2000) and the Habitats Directive (European Commission, 1992). Both Directives are inspired by ecosystem protection and the conservation of biodiversity. Progress is likely to be step by step: the most logical extension of the scope of river R&D for England and Wales is clearly to the floodplain and fortunately this move from the channel is already yielding a little less uncertainty, for example the Environment Agency's publicly available definitive floodplain maps. Considering river flow and sediment systems as occurring at the valley scale inevitably stretches the technology available to carry out research and provide tools for management. Nevertheless, recent compilations on the geomorphology, hydraulics and ecology of floodplains show that the research community has engaged with the challenge (e.g. Carling and Petts 1992; Anderson *et al.*, 1996; Bailey *et al.*, 1998).

In terms of 'tools', each participating discipline must accept the need to 'start again' within the constraints of their colleagues in the interdisciplinary field of river management (Vaughan *et al.*, 2008) but with the added socio-political dimension made vital by the uncertainties (Darby and Sear, 2008). The temporal dimension of climate change requires interdisciplinarity to focus on those areas of

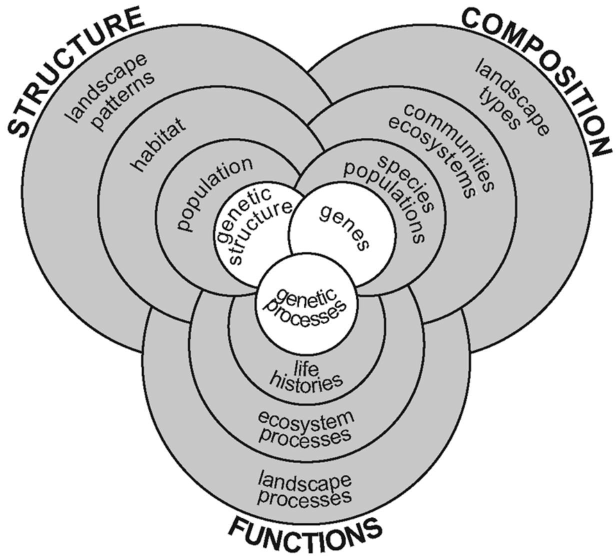

Fig. 5.2 The vital interaction of component sciences in the definition of river attributes susceptible to climate change and achievable through survey (after Large et al.*, 2006)*

overlap driven by the features of the environment of 2050 and beyond. Figure 5.2 was developed by those currently supporting Environment Agency R&D (Large *et al.*, 2006) attempting to cope with:

- catchment scales
- integration of knowledge from disparate fields
- change in the driver variables.

The 'big picture' however needs working up on a thematic split screen with the channel constantly loaded; floodplains, their background and dynamics are a logical starting-point here.

5.3 Channel–floodplain interactions

Of the multi-element 'fluvial hydrosystem', space here does not permit a full treatise on every geomorphological issue relating to biological impacts; there is a growing number of helpful texts and conference proceedings on this theme (e.g. Kondolf and Piegay, 2003; Brierley and Fryirs, 2005; Sear and de Vries, 2008). We give a selective treatment to floodplains because human society and non-human biota directly compete for this space (and with the river's flow in its 'winter channel').

Floodplains are not universal at the margins of British rivers and not the only component beyond the river bank to consider in policy and management. Newson (1992) suggests two other components of relevance to both fluvial processes and to the conservation of habitat for diverse flora and fauna: the river corridor (which may or may not function as a 'buffer zone' – see below) and the valley floor. However, in a significant minority of cases, river channels are confined by elements of the valley side, especially in the uplands and piedmont zone (Newson, 1981). The valley floor (often consisting of relict terraces – the remains of former floodplains into which the river has incised) may totally dominate the modern floodplain. In all cases the behaviour of the flows of water and sediment, once outside the channel itself in large floods, has a highly influential and mutually adjusted impact on channel processes (Bathurst *et al.*, 2002).

From the early 1960s onwards it has generally been considered by geomorphologists that channel-forming processes of erosion and deposition reach an optimum at a river discharge known as *bankfull*, which is said to occur with a frequency of between one and two years. There are two corollaries to this simplistic but useful argument:

1. Empirical equations to predict channel form and dimensions use the value of bankfull discharge if known (or a surrogate) as the independent variable.
2. Any artificial increase in channel conveyance (e.g. by the construction of flood embankments) for flood management purposes will have profound impacts on processes via changes in stream power – see Chapters 2 and 3.

In practice, the bankfull discharge is difficult to identify precisely in field sites (Wharton, 1992, 1995; Navratil *et al*., 2006) and varies in return period according to flow regime, even within the fairly narrow climatic range of the UK (Harvey, 1969, 1975). Channel characteristics controlling conveyance, such as width and depth, can adjust during rarer floods and come to operate as controls on bankfull discharge and its frequency.

One of the most important early findings of the River Habitat Surveys (Raven *et al*., 1998) was that more than 30% of lowland channel sites in England and Wales have been resectioned and that more than 10% have extensive embankments. Brown (1996) has pointed to the emasculation of floodplain sedimentary processes since the beginning of human intervention in lowland river systems. This situation clearly has implications for sediment storage in lowland (and some upland) river basins, with any excess of wash load in rivers passing on down the basin rather than creating aggradation of the floodplain.

5.3.1 Origin of floodplains, their sedimentary record and 'natural' floodplain functions

As a result of the relatively recent glaciation of much of Britain's land surface and of the profound changes of climate during and since deglaciation (around 12 000 years ago), many river channels flow as 'underfit' (Dury, 1970) in their valleys. The valley's dimensions, particularly width, and its veneer of drift materials may owe little to the current river or to fluvial processes. However, the combination of valley-floor alluvium from glacio-fluvial processes and steep perennial rivers whose stream power often exceeds their sediment supply has resulted in considerable reworking of most valley floors in the past 10 000 years. The result of reworking (via channel migration) is a floodplain (or series of them, abandoned as terraces by incision of the channel) whose sedimentary composition matches that of the river, i.e. bed deposits at the base and overbank, finer, deposits on top. This composite bank material is observable in many eroding river banks; equally widespread are banks in just the finer alluvium deposited by floods.

The floodplain is thus a repository for ancient and modern river channel deposits. The sedimentary structures of the floodplain record the bars and backwater deposits of the river (Brown, 1996), leading to rapid variability in floodplain sediment calibre and cohesion – an explanation of highly variable rates of bank erosion in some contemporary systems. Floodplain deposits also form local aquifers, important in water resource planning, both as a valuable resource and in connection with the influence of bank storage on reservoir release volumes and timings.

The floodplain 'archive' of datable sediments has recently permitted fluvial geomorphologists to make a considerable contribution to an understanding of Holocene (last 12 000 years) climate change, particularly the flood regime. Macklin and Lewin (2003) review the climate and land-use signals offered by more than 300 radiocarbon dating analyses of fluvial sediments in a variety of depositional environments. By linking their dating to both global circulation and to historical hydrological proxies (dating techniques) in peat bog development, they develop a model for variability in flood causation: the answer is basically climate – precipitation, with land-use changes a possible catalyst for more widespread impacts within and beyond source areas. Flood-rich periods identified from floodplain sediments alone are at the following dates (before present) in Britain:

- 600 years
- 840 years
- 1110 years
- 2000 years
- 2180 years
- 2570 years
- 2900 years
- 3660–4840 years.

A major lesson of this work is the desirability of 'preservation' of floodplain sediments and the wider floodplain landscape, not just as surface habitat conservation but because there is much more to learn about the variability of UK river systems through environmental change from the floodplain sedimentation 'archive' at depth.

This sort of geomorphological analysis, which could well be overlooked in strategic policy development for flood risk assessment (e.g. Catchment Flood Management Plans – CFMPs), reveals that the flood risk at any site in a catchment, particularly those dominated by a gravel bed material, is a non-stationary variable, slowly changing according to the relative position and capacity of the channel in relation to a floodplain (Macklin *et al.*, 1992). Vertical subtleties introduced by this style of geomorphological adjustment should not (if understood and incorporated) be an insurmountable challenge to design engineers, given the attention to the '*z*' coordinate (elevation) in flood risk assessment.

Floodplains are known in some parts of Europe as the 'winter channel' of the river. While society considers them as both attractive settlement sites/infrastructure routes and hazardous places, viewing them as winter channels may be more sustainable if our aim is to work with a system which appears to both moderate and modulate the fluxes of water and sediment from a catchment. There is an obvious physical principle that systems without storages are both sensitive and prone to rapid irreversible changes in driving flux variables. Floodplains act to store water (and sediments) over a range of timescales and return periods (Archer, 1989). Within this simple physical function they are also able to act to store and exchange genetic material (long-living plant seeds/spores and encysted animals) and to act as sites for the chemical exchange of pollutant material such as nutrients for less harmful materials.

The ecological importance of a 'winter channel' (where appropriate in the system) has many dimensions, perhaps only understood and appreciated by those who observe inundated floodplains as farmers (notably appreciated in the developing world but, increasingly, by those supported by a refocused EU farm policy), birdwatchers, botanists and fisheries experts (not anglers – a subtle difference based on fish vitality versus fish catch). The importance of concepts developed by landscape ecology is only now beginning to be realised and utilised as a tool in supporting biodiversity on floodplains: their role as wetland 'hot-spots' in guises from 'soggy' soils, through temporary wetlands to open water and spring-fed mires and their manifold ecotones – their margins presented by the interaction of the channel flow regime with their highly variable relief and sedimentology.

5.3.2 Geomorphological processes on floodplains

It is realistic, in terms of public policy on flood risk management and conservation, to consider the function of both channels and floodplains as a 'conveyance' for the water and sediment supplied from the catchment. Conveyance is the term best understood by the engineering tradition of managing flood risk (McGahey *et al.*, 2008); we may need to stretch the vocabulary in the interests of biodiversity conservation to 'capacity' and 'quality' and make inventories of all three (see Section 5.4 below).

Conveyance accurately conjures up the processes powered by gravity and obstructed by 'roughness' (hydraulic resistance) for water and sediments, the former element being well studied and modelled by practitioners for centuries, the latter being a newcomer without the benefit of such history. The academic basis of fluvial geomorphology has driven it to small-scale controllable research sites, mainly in the uplands (Newson, 2002) but recent R&D ventures have shifted monitoring of sediment fluxes downstream and into situations where it is vital to include both channel and floodplain, e.g. the LOIS (Land–Ocean Interaction Study) project of the Natural Environment Research Council (Leeks *et al.*, 2001). The LOIS field sites were concentrated in the Yorkshire Ouse and Tweed catchments; the results have been reported in more than 600 published scientific outputs.

LOIS has identified the sedimentary variability of floodplain conveyance on the relatively undeveloped, but flood-protected, floodplains of the main Ouse tributaries – clearly coarser suspended sediments such as sands deposit near the channel and the finer material far from it (Walling *et al.*, 1997). Furthermore, the study attempted to identify the sources of supply for sediments and the proportion of the total flux that becomes stored on the floodplain – 40% according to Walling *et al.* (1999). A further 10% of the flux becomes temporarily stored on channel beds (Walling *et al.*, 1998).

Gross rates of floodplain sedimentation have been derived by dating strata within 'piles' of floodplain sediments; they reveal highly variable and varying rates. It is quite clear that – at any given floodplain site – the relationship with channel conveyance

Table 5.1 Vertical accretion rates on British floodplains (after Macklin et al., 1992)

River floodplain	Catchment area: km^2	Sedimentation rate: cm a^{-1}	Timescale of deposition: years before present
Severn	10 000	0.14	0–10 000
Tyne	2198	2.37	0–97
Avon	1870	0.50	0–3000
Swale	550	0.53	0–130
Swale	550	13.00	1986 flood
Axe	31	0.54	0–312
Ripple Brook	19	0.05	0–2500
Stour	620	10.20	1979 flood
Culm	276	0.05	1983–84

Table 5.2 Floodplain accretion, Low Prudhoe, River Tyne (after Macklin et al., 1992)

Depth below surface: cm	Date of sediments	Sedimentation rate: cm a^{-1}
0	1990	0.3
10	1950	0.8
18	1940	1.2
30	1930	7.0
100	1920	5.0
150	1910	3.0
180	1900	5.0
230	1890	

(and hence the flood hazard) varies through time as the result of relative elevations, even without climate change.

Recent results from the UK Flood Channel Facility have emphasised the complexities of flow patterns and hence sedimentation at the channel–floodplain interface (Bathurst *et al.*, 2002). The Flood Channel Facility is a small channel in its own right, rather than a heavily scaled-down model; coarse sand was used as a bed material load but fine sands added to enter suspension and contribute to floodplain sedimentation. Both straight and meandering channel planforms were experimented with; in the former case deposition occurred as bank-top 'berms', parallel to the channel, but in the latter case the whole 'tongue' of land in the meander necks received deposits of variable depths. This pattern of floodplain construction relates well to both the earlier hydraulic models of Knight (1989) and to the empirical studies of the Yorkshire Ouse system carried out by LOIS (Walling *et al.*, 1997). It also confirms the point made by ecologists that the biotic impact of human flood protection on floodplains centres around interference with the regular supply of water, sediments and energy/nutrition from the channel.

It is very clear that floodplain flow and sedimentary systems will form the next fertile area for conversion of academic geomorphological principles and concepts into practical tools – in the spirit of 'fluvial hydrosystems'. For the remainder of the chapter, however, we need to review the progress already achieved in this transition for channel geomorphology.

5.4 River and riparian habitats – geomorphology and River Habitat Surveys

Thanks to successful 'clean-ups' of water quality in the 1980s and 1990s, physical habitat quality is now the limiting factor to biodiversity and ecosystem health in many, if not most, UK rivers. Thus, attention inevitably switches to the highest remaining regulatory hurdle – that of rehabilitating a damaged physical habitat.

For more than 25 years geomorphologists in the UK have been benefiting from collaboration with the formal conservation movement in its broad desire to reduce the loss of in-channel and corridor habitats during traditional 'hard engineering' river management. For example, in the production of the *Rivers and Wildlife Handbook* (Lewis and Williams, 1984) a chapter was included on 'River processes and form' (Newson, 1984); the successor volume (Ward *et al.*, 1994) raised the sophistication of the geomorphological input with a chapter on 'River morphology and fluvial processes' (Newson and Brookes, 1994). These remain useful introductory texts for practitioners while illustrating 'what can be done', rather than 'what should be done'. They were a stimulation to river management to 'have a go' and form the context to the sophistication now available through empirical data and modelling.

Despite enthusiastic reception for this kind of general geomorphological advice (the Royal Society for the Protection of Birds began organising training courses in fluvial geomorphology for their staff by 1984), there remained no realistic assessment of the true extent of geomorphological features in UK rivers and hence no quantifiable idea of the amount of 'damage' caused by existing river management practice. In anticipation of a future EU Directive concerning ecological quality 'the cupboard was bare', a dangerous policy position and, some would claim, one that persists today. The default situation in the minds of many conservationists was that 'damage' to UK river channels and their floodplains was almost universal from traditional land drainage and flood defence. The inception of the River Corridor Surveys (National Rivers Authority, 1992) had brought about precautionary mapping of remaining features of high habitat quality in the channels of main rivers and in a 10 m river corridor zone – an important token, but partial, recognition of the 'fluvial-hydrosystem' concept.

River Corridor Surveys became noted for a lack of central coordination, standardisation and for their unsuitability for statistical analysis. Nevertheless, they represent an important historical archive and, in many cases (Main River only), they yield the only available empirical evidence of (estimated) river channel dimensions, shape and features (Gurnell *et al.*, 1994). The accompanying sketch maps and photographs can be used to indicate channel change (Newson and Orr, 2004).

5.4.1 *River Habitat Surveys (RHS) – an inventory and benchmark*

Anticipating the need under European legislation for a national approach to collecting inventory data about physical habitat in river ecosystems, the National Rivers Authority established the River Habitat Surveys methodology (Raven *et al.*, 1998), running the first surveys in England and Wales between 1994 and 1997; geomorphologists were appointed to the steering group for the surveys.

As part of the River Habitat Survey methodology, a need was felt to incorporate fluvial geomorphology in two ways:

1. To inventory the simplest set of features and dimensions of the channel and corridor necessary to assess the physical habitat of sites in the context of national strategy.
2. To utilise observations of hydraulic patterns ('flow types') to assess the diversity or otherwise of the 500 m length of stream surveyed.

The following broad categories of geomorphological information were incorporated in RHS:

- topographic information from maps, e.g. altitude, slope and planform
- photographic information about the site (pre-digitial camera and very general)
- basic form, e.g. valley shape, and detailed form, e.g. bank profile types
- dimensions – bankfull width and height (not spatially referenced)
- bank and bed materials (on the Wentworth scale, based on impression)
- bank features, e.g. eroding cliff
- channel features (natural), e.g. riffles, bars (number, not location or size)
- artificial influences on the channel, e.g. embankments, revetment.

By achieving a dense picture of sites representative of whole river networks (Fig. 5.3) RHS becomes a potential foundation for much more than the, hitherto missing,

Fig. 5.3 Distribution of River Habitat Survey sites in Britain, 2006 from the Environment Agency. © Crown copyright is reproduced with permission of Her Majesty's Stationery Office under the terms of the Click-Use licence

national inventory of habitat data (including geomorphology) but, via comparisons with 'benchmark' sites of excellent habitat quality, for semi-quatitative assessments of 'damage' and prescriptions for restoration. Clearly, however, a pre-requisite is both confidence in expert (often abstract) views of physical habitat quality and ecological proof of actual causal links via biotic processes (problems reviewed by Newson and Large, 2006).

Geomorphologists have made significant strides in working with ecologists to define, parametrise and measure the physical element of habitat. Clearly, the full compass of physical habitat involves the interplay of flow and substrate variables: that the EU's choice of 'hydromorphological' to describe the key elements is apt (if not elegant!) in emphasising this dynamic element. RHS incorporates simple, hydraulically validated, description via the nine 'flow types' but there remains pressure on the research community in geomorphology to design effective tools for the survey, assessment and management of 'hydromorphology'. The role of hydromorphological quality in defining river quality such as to retain and restore freshwater ecosystems (a central role of the Directive) is demonstrated in Fig. 5.4 and the technical challenges are returned to below.

5.4.2 *RHS – significance of results to date in relation to river management policies*

To date (2006) more than 40 research papers have made use of the information base provided by RHS. They cover topics ranging from assessments of general river 'health' or integrity, through development of predictive tools for individual species to a major refinement of the basic survey system for the special conditions of urban channels (Davenport *et al*., 2004; Boitsidis *et al*., 2006).

Among the many relevant extensive-scale findings forthcoming from the first three years of RHS data collection in the UK (Raven *et al*., 1998) were the following:

- Coarse woody debris occurs in less than 5% of all UK channels.
- Braided channels are much rarer than at first thought.
- Full-width 'pools' are rarer than anticipated in both upland and lowland channels: shallower, faster 'runs' predominate, together with the 'glides' typical of engineered, uniform sections.
- More than 80% of lowland sites in the UK have at least part of the channel modified by engineering works or structures.

The latter is both the most disappointing outcome of the surveys and the most stimulating to further study on an extensive scale; it also raises questions about the frequent recourse to 'riffle' emplacement during river restoration schemes. Fox (personal communication) estimates that 54% of natural riffles have been 'lost' in managed channels, a total of 174 000 in a managed length of 25 500 km. Possibly, land-use and land management patterns have helped ensure that the sediment delivery system of intensively used catchments does not allow recovery of storage features after intensive channel maintenance. Clearly, Fox's estimate entails many assumptions, not the least of which is that riffles occur universally in 'natural' channels – one element of the current demand to define 'natural', with which geomorphology is still coping.

Riffle location and catchment controls thereon were also the focus of a major utilisation of RHS data by Emery *et al.* (2004). They demonstrate a relatively high explanatory value for locational factors, slope and substrate size but also suggest that the unexplained variance might only be solved following the addition of more information during field surveys – a similar conclusion to that of Newson *et al.* (1998a).

'What is natural; how can we measure 'damage'?' (Large and Newson, 2005; Newson and Large, 2006). Without doubt such a definition, if incorporated in policy, needs to be at least semi-quantitative to permit quality assurance. In

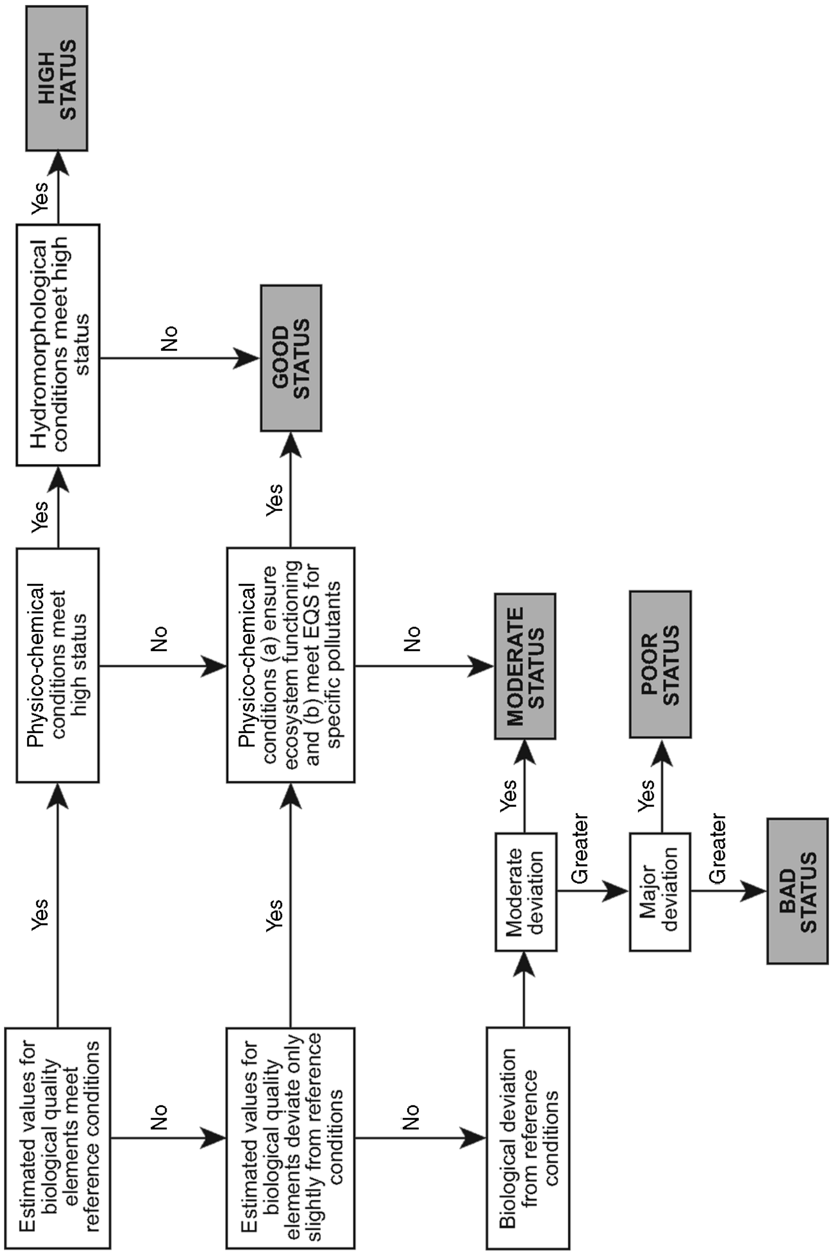

Fig. 5.4 The location, within policy implementation, of the various component measures of good ecological quality within the Water Framework Directive (after Large and Newson, 2005)

contrast to the highly variable, qualitative nature of the data collected during the era of River Corridor Surveys, the RHS database is open to expansion and to quantitative analysis, albeit with statistical caveats concerning the variety of scales – nominal, ordinal, interval – on which habitat variables are measured. Perversely, however, UK rivers appear reluctant to be classified objectively (Newson *et al.*, 1998a) and the routes forward to develop policy tools appear split between retaining an empirical route to quality (or damage) measures, via analysis of RHS data and schemes involving subjective, purely geomorphological, typologies of river behaviour and form.

In the United States, Rosgen's deterministic typology of wilderness channels is being applied by government agencies as a basic strategic guide, despite considerable debate about its validity and the way in which it has been used as a 'recipe book' (Miller and Ritter, 1996; Rosgen, 1996). Geomorphologists are generally concerned that typologies or classifications based upon morphology alone (however discerning the choice of variables) are too static to reflect the vital management concern with dynamic adjustment. Hence, in Australia, the application of a 'River styles' typology (Brierley and Fryirs, 2000) has become successful largely because it stresses *adjustment* 'styles' from the outset (whereas the Rosgen approach infers them from *morphology*).

Using the first set of RHS data for semi-natural sites in England and Wales, Newson *et al.* (1998a) drew disappointing conclusions about the success of objective multivariate classification of channels. The same database was already being used in two other ways to create working typologies:

1. An entirely subjective and qualitative approach based upon the map variables recorded for each site, resulting in convincing maps of river segment types (see NRA, 1996).
2. An approach through an entirely different spatial perspective, also using map variables: principal components analysis (Jeffers, 1998).

The latter is now the preferred classificatory route in RHS, permitting any site of interest for conservation, protection from development or restoration to be compared with statistically similar river channels in the database and with benchmark, high-quality sites. One method of ensuring compliance with the EU Water Framework Directive (WFD) is that involving the quest for Physical Quality Objectives (Walker *et al.*, 2002); these Objectives require an objective assessment of reference conditions for relevant river types and measures of departure from those reference conditions in order to index what aspects of 'hydromorphological quality' require management action to bring ecosystem improvements. However, at the time of writing (early 2009), research and development is creating methods to support the more intensive needs of the WFD in Scotland (see Chapter 6 of this Guide); these may yet define the application of more purely geomorphological tools in support of the Directive throughout the UK.

A return to the dilemma of typologies is signalled by Orr *et al.* (2008) who combine evidence from a review of hydrological, geomorphological and ecological 'drivers' to produce a working, predictive typology for hydromorphology and use it in the River Eden catchment in north-west England. The typology appears successful in delimiting habitat for juvenile salmonid fish.

5.4.3 Geomorphology and 'hydromorphology'

During the 1990s considerable R&D effort went into attempts to add detail to the broad hydraulic description of habitat available since the 1980s via one-dimensional hydraulic models of flow such as PHABSIM (Bovee, 1996). The first generation of hydraulic habitat models are known generically as IFIM (Instream Flow Incremental Methodology) because they seek to assess the quantity of habitat appropriate and available to particular species, mainly fish, in regulated rivers below dams. In the UK, contributions to the assessment of physical habitat need to recognise the context of smaller river systems, requiring more local specificity and with channel form/substrate more often heavily modified by decades of hard engineering than by flow regime (Newson *et al*., 2002).

In moves to incorporate more detail of the spatial patterns inherent in physical habitat, principally contributed by fluvial geomorphological features and dimensions, R&D ventures moved in two directions (Newson and Newson, 2000). Freshwater ecologists moved from the 'top, down' by classifying communities of invertebrate organisms and relating these groups to simple channel characteristics, creating 'functional habitats' or 'meso-habitats' (Harper *et al.* 1992; Pardo and Armitage, 1997). In terms of predictive tools, the large body of data on invertebrates available to the Environment Agency in England and Wales can be merged with physical habitat data (principally flow – geomorphological data remain sparse) to become the basis of the 'LIFE' scoring system (Extence *et al*., 1999).

Geomorphologists moved closer to the growing body of research in 'habitat hydraulics' or 'eco-hydraulic' in a bottom-up approach via the classification of habitat units in the channel, labelled 'physical biotopes'. The contrast is shown in Fig. 5.5 but subsequent R&D based upon the RHS database (that includes both) has shown that the approaches are compatible (Newson *et al*., 1998b; Harper *et al*., 2000).

At an early stage of this research a basic typology of hydraulic flow patterns, observable and mappable from river banks, became incorporated as part of River Habitat Surveys as 'flow types' ('physical' or 'hydraulic' biotopes to, for example, Padmore *et al*., 1998; Wadeson, 1994). This incorporation has expanded the amount of geomorphological and physical habitat information in RHS and provided the basis for national maps of such features as riffles and pools, for assessments of habitat diversity and quality and for monitoring change between surveys. It has now been suggested that statistical analysis of the RHS data on physical biotopes – a working

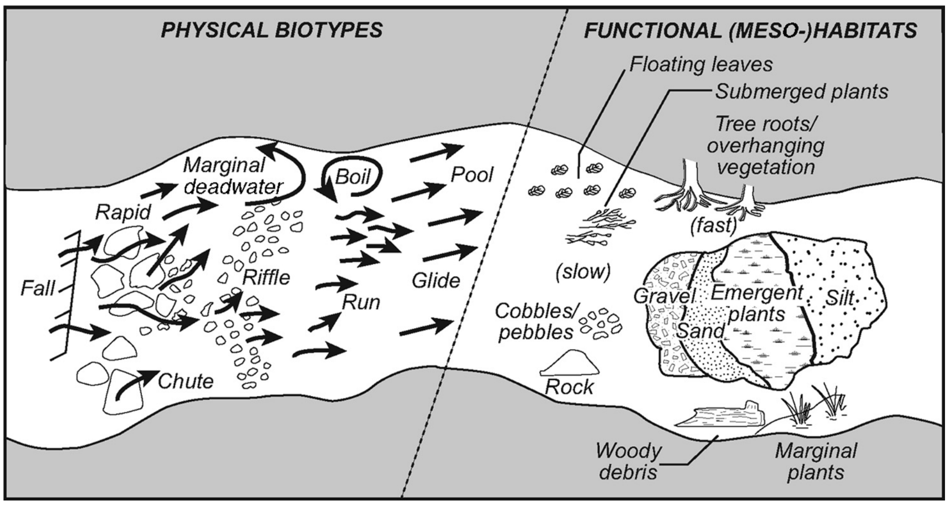

Fig. 5.5 The interaction of 'functional habitats' (mainly lowland derived) and 'physical biotopes' (mainly upland) in the definition of hydromorphological habitat (after Newson and Newson, 2000)

term for meso-habitats defined by flow type – has good ecological relevance (Clifford *et al.*, 2006).

A more basic but far-reaching tool required for WFD and Habitat Regulations compliance in the UK is the use of geomorphological principles to characterise, assess and monitor river channels at each ecological quality level and to use this information to judge the sensitivity of channel and ecosystem response to development, e.g. a proposed construction near or in the channel or a change of flow regime. We return to this theme in Chapter 6 because of the clear need for new reconnaissance and survey techniques – the theme of that chapter. As a preface, considering the urgent need for 'ready-made' tools for regulatory purposes, it is worth listing geomorphologists' concerns that local conditions are made central to any regulatory system. For example, Natural England, the government conservation body in England, has a need to regulate siltation impacts on rivers that are Sites of Special Scientific Interest (SSSIs): how far can the critical levels of fine sediment yield be used as a blanket standard? In this and other regulatory circumstances the following local contexts are vital to consider:

- Fluvial action is less than 10 000 years old: most of the sediments are not fluvial.
- Britain is an island – sea-level has adjusted base-level on many occasions – there is no 'graded profile'; slope is a local driver.
- Rivers are short and steep on a world scale, reducing the number of representative classes in typologies drawn from abroad.
- Rivers have been heavily utilised (if not 'heavily modified') for 2000 years.
- The fluvial system is 'supply-limited' for sediment, making local sources vitally important on the 'jerky conveyor belt' (Ferguson, 1981) of channel sediment transport and morphological response.

It is also important to consider the system and network properties of river channels and floodplains – continuity and Markovian transfer of impacts affect many of the geomorphological effects of development and many of the results of rehabilitation/restoration (see below). Statements of the hierarchical nature of river systems (e.g. Fig. 5.6) are many and frequent but, to date, there have been few analyses capable of yielding the appropriate tools for expanding site or reach assessments to the catchment scale (Newson and Newson, 2000; Poole, 2002).

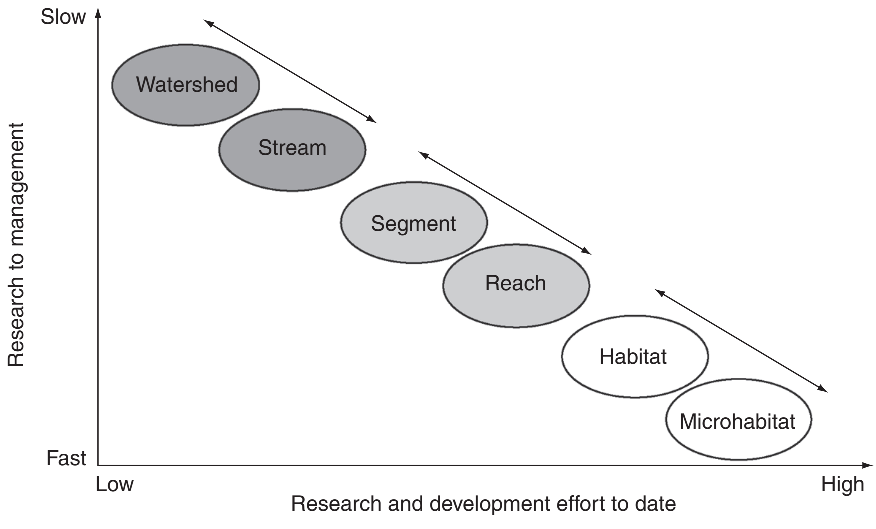

Fig. 5.6 A redefinition of the hierarchical concepts of Frissell et al. *(1986) in terms of available scientific evidence for supporting WFD regulators (after Newson and Large, 2006)*

5.5 Fluvial geomorphology and river restoration

At an international conference on river conservation and management in York in 1990 (Boon *et al.*, 1992) the terms 'rehabilitation' and 'restoration' were already being used to define a new form of management intervention in those channels whose ecosystem functions had been damaged by traditional management or neglect (Brookes, 1992; Kern, 1992). A clear role was created for geomorphological predictions (e.g. dimensions of meander bends, riffle spacing) concerning those features considered part of the restoration/rehabilitation 'recipe' for a site. Geomorphology was not, however, required to create strategies for restoration, nor to offer guidance on intellectually coherent definitions of 'natural'. Predictive tools for the re-establishment of, for example, riffle–pool sequences were already available (Keller, 1978) and many had been tested in the USA for decades. Successes for restoration (generally in low energy systems) were written up for the science literature as generally-applicable principles but failures were generally ignored, despite the 'live experiment' ethos of the time. There is now, of course, a more serious political environment created by the need to achieve 'good ecological quality' under the WFD and restoration projects are under greater scrutiny to assess whether they can achieve the WFD targets, rather than those set by the heady enthusiasm of communities seeking a 'nicer river'.

The River Restoration Project, a UK (eventually EU) outcome of the York meeting, began its work in this atmosphere of opportunistic enthusiasm for applied science.

5.5.1 *The River Restoration Project*

The river restoration movement, working through the River Restoration Project (RRP: Holmes and Nielsen, 1998; Vivash *et al.*, 1998), has rapidly achieved a very influential position in UK river management policies, partly by carrying out two prestige schemes (on the Rivers Cole and Skerne) and partly by providing guidance on such central issues as environmentally acceptable ways of controlling bank erosion (RRC, 1999). The River Restoration Centre (RRC) now acts as a vital hub to efforts by both the scientific and technical community and the stakeholder community; it runs training courses, conferences and communication devices, all within a wider EU context coordinated by the European River Restoration Centre in Denmark.

The RRP achieved a major impact on two lowland channel lengths, both 2 km long, in the catchments of the Skerne (250 km^2) and the Cole (129 km^2) (Kronvang *et al.*, 1998). Both involved the construction of new asymmetrical channels in a meandering planform in place of the straightened, trapezoidal, engineered forms characteristic of the preceding era. Channel features and bank revetment devices were also installed and the experience disseminated to the professional community via a handbook (RRC, 1999). Neither length has a high stream power and it might be claimed that the longer-term 'stability' of restored channel designs has not yet been tested in risky conditions (see Brookes, 1990 and Brookes and Sear, 1996 for discussions of stream power approaches to channel adjustment). However, partly as the result of weak/variable bed and bank materials, adjustments in the restored channel of the River Cole (and downstream impacts) have both been significant (Sear *et al.*, 1998).

The RRP pioneered the use of two forms of geomorphological survey (and has also promoted post-project appraisal; see Kronvang *et al.*, 1998; Sear *et al.*, 1998). These formalised procedures resulted from an R&D programme sponsored by the

National Rivers Authority and subsequently the Environment Agency in England and Wales (Newson and Sear, 2000). Both the Skerne and the Cole were given Catchment Baseline Surveys and Fluvial Audits before works began (Kronvang *et al.*, 1998) but the design framework and operational activities in terms of channel dynamics and structures on both streams remained within the engineering field. This partly reflects societal problems with the uncertainty associated with 'natural channels' and their maintenance (Newson and Clark, 2008; Newson and Large, 2006). Thorough geomorphological survey (catchment, corridor and channel scales) and hydraulic treatment of rehabilitation schemes, such as those on the River Waveney (see below) and on the River Idle (Downs and Thorne, 1998) may now, however, become a norm, especially following recent fatal and damaging flood events in the English lowlands.

Nevertheless, geomorphological researchers have continued to press for the broader and fuller incorporation of their concepts, if not tools. They fear, particularly, for the long-term sustainability of river restoration sites in the wider spatial context of the catchment and its changing environmental conditions (e.g. Sear, 1994; Newson *et al.*, 2002). There have also been strong calls for post-project appraisal of restoration to enable improvements in design and operations – a sure way to reduce the high levels of uncertainty inherent in 'live experiments' (Clarke *et al.*, 2003; Newson and Clark, 2008).

The reality of river restoration in Britain is however that, as a result of their vulnerability to flooding, lowland channels have suffered the main impacts of traditional engineering and have attracted the major efforts in restoring degrees of 'naturalness'. Community or river-user vision often dominates over scientific vision, and rehabilitation (notably of fish habitats) dominates over restoration of the fluvial sediment system (McDonald *et al.*, 2004). As a case study of such a scheme of rehabilitation, the following example (Box 5.1) is taken from Newson *et al.* (1999) – see also Sear and Newson (2004).

Box 5.1 Geomorphological inputs to a lowland rehabilitation scheme: the River Waveney, East Anglia (Newson et al., 1999; Sear and Newson, 2004)

The River Waveney drains a catchment of 889 km^2, 670 km^2 of which is non-tidal. The catchment is of low relief and everywhere is below 100 mAOD. The main channel profile is generally virtually flat with an average non-tidal gradient of 1 : 2250; engineering has reduced this further in many places (e.g. between Billingford and Earsham the gradient drops to 1 : 5500). Many of the tributary channels are, in contrast, significantly steeper, lack control structures and actively transport fine sediment produced on the surrounding catchment (e.g. from roads and intensive farming). Catchment-scale issues are very important in assessing the sustainability of UK schemes of restoration and rehabilitation. Among the terms of reference for the Waveney geomorphological surveys (Catchment Baseline, Fluvial Audit, Dynamic Assessment) were to describe and map:

- the features considered as typical of this type of river in this part of Britain;
- the location of the segments/reaches suitable for works;
- the potential threats posed by current sediment dynamics and channel/catchment management;
- the design specification of the features selected;
- the stability of the features once emplaced;
- the influence of the features on physical habitat (flow types/biotopes).

The Catchment Baseline Study (CBS) identified more than 20 'lengths' based on channel character in the field and heavily influenced by the backwater conditions created by the many mill structures in the channel. The basic channel character of the Waveney is the result of the amount of available gradient (and therefore flow types/morphological features), local sediment sources and riparian tree cover (which in turn controls instream macrophyte growth). The more active tributaries were, however, divided into reaches (in the geomorphological sense) and the Fluvial Audit became an essential basis for a precautionary approach to catchment management after rehabilitation (see below).

Installation of 'riffles' (see also Chapter 2)

After consultation with angling interests, the Fisheries function of EA Anglian Region decided that 'riffles' were appropriate and feasible target features for rehabilitation of the Waveney channel. It was not clear at this stage what physical aspect of in-channel habitat was to be recreated by 'riffles' (substrate, flow field, spawning, aeration), but the target fish species were dace (*Lenurus lenisus*) and chubb (*Lenurus cephalus*). True riffles are major components of an active bed material transport process and their hydraulics reflect this; what was required on the Waveney (under the term rehabilitation, rather than restoration) was a series of mimic features based upon natural riffles.

To assist in the design of riffle *spacing*, the literature was reviewed and a new empirical equation derived from a dataset of 85 separate streams covering the following range in variables: riffle spacing (17.1–1200 m), river bed slope (0.00093–0.0215), bankfull width (5.2–76.6 m). This dataset was used to illustrate how riffle spacing increases as bed slope declines and how spacing increases with bankfull width. As channel gradients increase beyond the values covered in this dataset, spacing reduces still further and riffles become replaced by steps irrespective of channel width. Riffle spacing may initially be predicted as follows:

$$\lambda_r = 7.36w^{0.896}S^{-0.03} \qquad r^2 = 0.67, p > 0.001 \tag{5.1}$$

where λ_r is riffle spacing in metres, w is bankfull width in metres and S is the channel bed slope through the pool–riffle sequence.

Values of riffle *amplitude* are time-dependent as pools tend to fill with sediments and riffles tend to scour during floods, while both may fill when sediment transfer through a reach is increased. The scientific literature suggests that riffle *bed-widths* should be 7–16% wider on average than pools. Given the low gradients and the effect that this might have on conveyance, it was recommended that banks should be reprofiled at the riffle crests to provide a maximum crest width 15% greater than the reach average.

Bankfull stream power assessment provides guidance on the likelihood of erosional or depositional *adjustments* at each reach, based on proximity to an empirically derived threshold of 35 $\text{W}\,\text{m}^{-2}$ (Brookes, 1990; Brookes and Sear, 1996). Above this threshold, sites may be expected to experience erosional adjustment (depending on boundary materials), below 10 $\text{W}\,\text{m}^{-2}$ then depositional adjustment may be expected. Shear stress calculations indicate that gravels of intermediate diameters up to 47 mm may be *transported* under bankfull flow conditions; however, generally material above 5–10 mm would be stable. As such, it was recommended that the gravel be composed principally of material of the order of 10–20 mm with smaller proportions of larger material. However, a compromise was needed between this guidance, the local availability of materials and the needs, for spawning, of chub (*Leniscus cephalus*) and dace (*Leniscus leniscus*), for which there is little specific guidance; the cleanliness of the gravels may be paramount, rather than size. Both fish species breed best in flow velocities of 20–50 cm s^{-1}. Because fines are constantly entering the Waveney main channel at points close to some of the rehabilitation sites (and because large concentrations are available nearby), such a trapping action by the new features is inevitable.

Impact of rehabilitation on flood conveyance

To assess the influence of riffle rehabilitation on overall *water surface elevations* at low flows a further one-dimensional hydraulic modelling exercise was conducted using HECRAS (modification of HEC-2 US Army Corps of Engineers step backwater model) for four potential rehabilitation sites. HECRAS also indicates the effect on velocities and so can indicate the potential change in physical habitat conditions resulting from the rehabilitation proposals. HECRAS is a program formulated to determine longitudinal water surface profiles, based on solution of the one-dimensional energy equation with energy loss due to friction over a fixed bed calculated using the Manning equation:

$$U = R^{2/3} S^{1/2} n^{-1} \tag{5.2}$$

where U is the section averaged velocity; S is the energy slope; and, for sufficiently wide reaches, the hydraulic radius (R) is equal to average depth (d). In the absence of sudden and major changes in channel width, energy losses are accounted for by channel bed and bank roughness defined by Manning's n. The model is known to overpredict water surface elevation at low discharges and therefore water surface elevations are expressed as percentage increases on the modelled water surface elevations for existing conditions. The scale of the relative increase is therefore given for each 'riffle' rehabilitation option. Model runs were conducted for a range of scenarios using the survey and discharge measured in the field.

Conclusions from the HECRAS simulations were that much of the hydraulic adjustment resulting from bed elevation changes is taken up via velocity changes – a desirable outcome for rehabilitation. At low flows, the minor increases in water surface elevation predicted by the model result from the accommodation of discharge by increased bed width, and by increased flow velocities. Given a functional objective of flow aeration generated by rough turbulent flow over the 'riffles', the model results seem encouraging. However, at high flows, aeration is unlikely to be effective once the features are drowned out. A full hydraulic monitoring programme is in progress at one of the sites where the installation of 'riffles' has recently gone ahead.

Conclusions

One of the clearest geomorphological conclusions from the work carried out on this project is that there are relatively few active natural sources of sediment *within the main stem of the Waveney channel*: bank erosion and bed scour are highly localised and transport distances limited by the low stream power developed by the river in flood. At the same time, however, sediment transport (notably of sands and finer materials) is active in a number of tributaries. We also include under catchment management any alterations in routine channel maintenance protocols to maintain or protect the emplaced rehabilitation features. These will include

- desilting at some of the rehabilitation sites to permit a firm footing for the gravels;
- desilting a length of channel upstream of the features to delay the onset of infilling and cementation;
- 'ploughing' (or equivalent) of cemented gravels if this becomes a problem.

5.5.2 *What next for fluvial geomorphology and an improving agenda for catchment-river ecosystems?*

Argument abounds over the philosophy and ethics of ecological restoration, and UK geomorphologists have stressed the need for clear aims and objectives, together with a succinct and meaningful terminology to describe important and expensive public works. Sear (1994) has stressed the vital consideration of catchment geomorphological dynamics as virtually defining what can be achieved by way of sustainable rehabilitation or restoration; Newson *et al.* (2002) note that rehabilitation often utilises 'mimic' fluvial forms, e.g. 'riffles' that are static features of the river bed rather than a dynamic part of the sediment transport system. We find it obvious that such features are, for example, perfect sites for 'siltation', the new demon of diffuse pollution: stable open gravels in a low shear stress environment – what more could suspended fine sediments want?

Notwithstanding the availability of information, geomorphologists begin their assessments of restoration potential from three standpoints (Newson *et al.*, 2002):

- The concept of 'damage' to river channels and floodplains must be assessed against an analysis of the flow regime and sediment source–transfer–sink system of the particular basin, in other words, empirically assessed against a theoretical background but also utilising techniques of environmental reconstruction of past channels and floodplains to help formulate a 'vision' of restoration. Appropriate data are, however, in very short supply and an alternative strategy is that behind the derivation of Physical Quality Objectives for rivers, i.e. objective comparison of channel features and dimensions with those judged to be the reference state for the appropriate type of channel (see Walker, 2002).
- The context of restoration, normally 'at a site' (in the tradition of civil engineering responding to community desires) must be basin scale and must extend laterally from the channel to include the floodplain and valley floor. It must also anticipate future channel dynamics in the light of developments in catchment land-use, water management and in the context of climate change. Both spatial and historical analyses are essential (Sear, 1994; Kondolf and Larson, 1995).
- The restored morphology for a reach (whether achieved by flow or form modifications) must be expected to be dynamic and to respond to both intrinsic and extrinsic changes; fluvial morphology is often transient in nature as it responds to, perhaps, distant and long-term signals of this sort.

In detail, the concept of 'damage', essential to restoration strategies and designs, gains expression in fluvial geomorphology in a variety of ways:

- From flow manipulations which distort the spatial or temporal regime of water level variation in relation to key form elements.
- Flow manipulations which distort the broad spatial or temporal workings of the sediment system, both in-channel and in relation to the floodplain, particularly through lateral and vertical channel change (depending on local dynamics).
- Flow manipulations which impact on the detail of river bedforms such as the sorting of sediment sizes, both laterally and vertically.
- Direct 'river training' to create artificial planforms, sections and dimensions which relate to society's conventional development needs of the river (e.g. flood protection).
- Sediment-related 'maintenance' which tends to distort channel dimensions and reduces the diversity of sediment sizes and forms at all scales.

- The sediment impacts of catchment and river management, particularly of dam construction and sediment trapping.
- A variety of secondary impacts from changes to the vital ecotones between channel and floodplain, notably the riparian vegetation zone.

It is also important to stress that the impact of many forms of geomorphological damage are temporary – recovery may occur over a variety of timescales, particularly in channels with sufficient flow energy and substrate material to reactivate basic geomorphological processes (Brookes and Sear, 1996). It is the authors' view, therefore, that restoration schemes which focus, where appropriate, on 'assisted natural recovery' are likely to be most cost-beneficial and sustainable. For example, the River Deben in Suffolk has suffered from recent drought- and abstraction-related low flows within a channel formerly maintained in an over-wide condition to improve flood conveyance within-banks. Fluvial Audit confirmed the impression of freshwater ecologists that some reaches of the Deben had escaped 'damage' from traditional channel management and retained at least a semi-natural sequence of erosional and depositional features. Further, the Audit identified that the winter floods of 1999 and 2000 had reactivated sediment supply in some parts of the catchment. Logically, therefore, a rehabilitation strategy could focus on extending reaches of high physical habitat quality on the basis of 'assisted natural recovery'. Reduced maintenance and direct installation of channel marginal 'berms' (RRC, 1999) were selected, working downstream from the Cretingham site in the headwaters and learning by experience with the outcomes, i.e. requiring a continuing post-project appraisal.

5.5.3 *Interfacing with society: stakeholders beyond the traditional context of flood 'defence' and land 'drainage'*

River restoration has become widespread, taking on some of the characteristics of a 'movement' while abandoning many of the traditional features of a technocratic, engineering interpretation of normative human values (e.g. safety) which persisted in river management before the ideals of sustainable development emphasised non-human values and a much broader constituency for decision making.

This expansion is highly relevant to the development and use of 'tools', notably to the need for an expansion of the tool 'box' into decision-support and for realism on the part of the scientific community about why, when and how predictive techniques are used. Describing their experience with the rehabilitation of an engineered reach of the River Wharfe (see also Chapter 6), McDonald *et al.* (2004) stress the need to integrate a geomorphological model and data for the system with individual and community goals for the site. The result was selection of an option for channel works which 'appeared unsound when evaluated from a technical perspective alone' (p. 278); the authors conclude, nevertheless, that this is an acceptable outcome as it combines in a 'least regrets' sense a strong traditional element with incremental change in river management practices. McDonald *et al.* label the approach 'Rivers of dreams', the implied social uncertainty of this contrasting nicely with a term coined by Graf (2001) to describe scientific uncertainty in designing 'probabilistic rivers'.

The Upper Wharfedale restoration must also be seen in the context of a more general environmental project, described by Newson and Chalk (2004), in which the restoration of the river channel at several sites was selected as a priority for sustainable land management, using a formal decision-support mechanism (Quality of Life Capital) and a heavy commitment to community debate.

The expansion, diversification and socio-political embedding of river restoration have now been documented by Wheaton *et al.* (2006) as the result of an international web-based survey whose respondents classified themselves as advocates, managers, practitioners, scientists and stakeholders. More than 500 responses were received, though the authors also record startling restoration rates noted from other sources: 1068 projects in Denmark, 750 in the UK and 30 000 in the USA. A working hypothesis of the survey was that a traditional chain of research, development, application and review in fluvial techniques had been broken and dismembered by the restoration 'movement'. Thus, respondents were asked about their defining objectives for projects, the scale of projects (in relation to prevailing scientific principles) and their treatment of uncertainty. The authors are unwilling to use the survey for hard-and-fast conclusions, offering that function to survey users instead. They do, however, note the vital role of context, despite the ethos of reporting being that of general applicability. Their final note is that 'ample opportunities exist in restoration for research from a mix of social, biological and physical sciences' (p. 140). The principle of converting biophysical assessments, such as fluvial audits, into decision support frameworks has recently been put to practical test in East Anglia (Sear *et al.*, 2008). Everard (2004) makes a related point in stressing the role of socially relevant economic benefits accruing from the conservation or rehabilitation of catchment ecosystem services – he assesses these for eight prominent UK catchment initiatives.

5.6 Conclusions

The subject matter of this chapter has been divergent from the book's basis in tradition: that of providing guidance to those whose daily and direct influence in river management is on channel form and process, i.e. those working in the fields of flood defence and water resources. As suggested at the outset, there is no longer room for rivalry between professionals concerned with human and non-human biota in terms of a sustainable river environment; instead a balance based upon ethics and politics (translated into policy by for example the EU WFD) now rules. The publicly imposed duty of river managers to promote conservation led directly to early precautionary schemes such as River Corridor Surveys. These have been quickly replaced by a much bolder, progressive use of geomorphology in the field of conservation, encouraged by newer policy frameworks such as sustainable development, biodiversity and restoration/rehabilitation. The adoption by the EU Water Framework Directive of a river ecosystem framework for water management policy has, almost surreptitiously, confirmed the need for the forms of geomorphological guidance described in this chapter.

In conclusion, therefore, it is the EU's term *hydromorphological*, considered with its accompanying need for reference conditions (effectively, 'What is natural?') that sets the agenda for future geomorphological guidance for those concerned with river ecosystems. Newson (2002) risked an attempt at defining some elements of jargon found within policy from the viewpoint of geomorphology; it was later revised by Large and Newson (2005) (see Table 5.3).

It would be ridiculous if the WFD was not seen as an opportunity to unify both the content and form of geomorphological guidance to river managers, rather than separating the conservation guidance from the engineering guidance, as is inevitable in this Guidebook. Another European Union Directive, that on Habitats, may

Table 5.3 Suggestions for geomorphological interpretation of some components of 'hydromorphological status' in the Water Framework Directive, relevant to UK rivers. Modified, with permission, from Newson, 2002. © 2002 Cambridge University Press

Terminology	Suggested geomorphological description
Reach	Length of river in which channel dimensions and features relate characteristically to identifiable sediment sources and sinks. Reaches may be demarcated by tributary inputs under certain conditions of climate, river regulation or land use
'Stable'	Essential to demarcate between engineering concepts of stability, legal/popular interpretation and natural resilience or 'robust' behaviour. Geomorphological stability incorporates adjustments, short of threshold behaviour, that can be predicted from assessment of channel 'styles'
Reference conditions (or 'natural')	Rivers with planform/sectional geometry and features which represent the full interplay of water and sediment fluxes with local boundary conditions. 'Natural' rivers are free to adjust their form and features (by aggradation/degradation and lateral migration across floodplain/valley floor) to both system-scale drivers and local conditions
Heavily modified rivers	Rivers which, through human modification or repeated actions, are constrained in their direction/rate of adjustment and diversity of features, frequently to the extent that they create a geomorphological hiatus in the flow/sediment system, causing upstream or downstream impacts or both. Depending on system location and conditions they may recover if human action is ceased or modified

encourage a technical dialogue between geomorphologists, ecologists and engineers on those rivers designated as Special Areas of Conservation (SACs) and there are further demands to return SSSIs to 'favourable condition' in terms of morphology, connectivity and siltation. Decision support systems are already being commissioned for these rivers and require the difficult linkages to be made between physical habitat, its modification for human uses of the river and the conservation/restoration of biodiversity. The different interpretation of the WFD requirements in Scottish law may well promote a uniquely geomorphological response to creating 'tools' for such evaluations.

References

Anderson, M.G., Walling, D.E. and Bates, P.D. (1996) (eds) *Floodplain processes.* Wiley, Chichester.

Archer, D.R. (1989) Flood wave attenuation due to channel and floodplain storage and effects on flood frequency. In Beven, K. and Carling, P. (eds) *Floods: hydrological, sedimentological and geomorphological implications.* Wiley, Chichester, pp. 37–46.

Bailey, R.G., Jose, P.V. and Sherwood, B.R. (1998) (eds) *United Kingdom floodplains.* Westbury, Otley.

Bathurst, J.C., Benson, I.A., Valentine, E.M. and Nalluri, C. (2002) Overbank sedimentation patterns for straight and meandering flume channels. *Earth Surface Processes and Landforms*, **27**(4), 659–665.

Boitsidis, A.J., Gurnell, A.M., Scott, M., Petts, G.E. and Armitage, P.D. (2006) A decision support system for identifying the habitat quality and rehabilitation potential of urban rivers. *Water and Environment Journal*, **20**(3), 130–140.

Boon, P.J., Calow, P. and Petts, G.E. (eds) (1992) *River conservation and management.* Wiley, Chichester.

Bovee, K.D. (1996) Perspectives on two-dimensional river habitat models: the PHABSIM experience. In Le Clerc, M., Capra, H., Valentin, S., Boudreault, A. and Cote, Y. (eds) *Ecohydraulique 2000: Proceedings of the 2nd IAHR Symposium on Habitat Hydraulics*, Quebec IAHR, pp. 150–162.

Branson, J., Hill, C., Hornby, D.D., Newson, M. and Sear, D.A. (2005) *A refined geomorphological and floodplain component River Habitat Survey (GeoRHS)*. R&D Technical Report SC020024/TR, Environment Agency/Defra, Bristol.

Brierley, G.J. and Fryirs, K. (2000) River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management*, **25**(6), 661–679.

Brierley, G.J. and Fryirs, K. (2005) *Geomorphology and river management: application of the River Styles framework*. Blackwell, Carlton, Victoria, Australia.

Brierley, G.J. and Fryirs, K. (eds) (2008) *River futures: an integrative scientific approach to river restoration*. Island Press, Washington, DC.

Brookes, A. (1990) Restoration and enhancement of engineered river channels: some European experiences. *Regulated Rivers: Research and Management*, **5**(1), 45–56.

Brookes, A. (1992) Recovery and restoration of some engineered British river channels. In Boon, P.J., Calow, P. and Petts, G.E. (eds) *River conservation and management*. Wiley, Chichester, pp. 337–352.

Brookes, A. and Sear, D.A. (1996) Geomorphological principles for restoring channels. In Brookes, A. and Shields, F.D. (eds) *River channel restoration: guiding principles for sustainable projects*. J. Wiley, Chichester, pp. 75–101.

Brown, A.G. (1996) Floodplain palaeoenvironments. In Anderson, M.G., Walling, D.E. and Bates, P.D. (eds) *Floodplain processes*. Wiley, Chichester, pp. 95–138.

Carling, P.A. and Petts, G.A. (1992) (eds) *Lowland floodplain rivers: geomorphological perspectives*. Wiley, Chichester.

Clarke, S.J., Bruce-Burgess, L. and Wharton, G. (2003) Linking form and function: towards an eco-hydromorphic approach to sustainable river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **13**(5), 439–450.

Clifford, N.J., Harmar, O.P., Harvey, G. and Petts, G.E. (2006) Physical habitat, ecohydraulics and river design: a review and re-evaluation of some popular concepts and methods. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **16**(4), 389–408.

Darby, S.J. and Sear, D.A. (eds) (2008) *Uncertainty in river restoration*. Wiley, Chichester.

Davenport, A.J., Gurnell, A.M. and Armitage, P.D. (2004) Habitat survey and classification of urban rivers. *River Research and Applications*, **20**(5), 687–704.

Defra/Environment Agency (2003) *A refined geomorphological and floodplain component – River Habitat Survey. GeoRHS fieldwork survey form and guidance manual*. GeoData Institute, University of Southampton, Report FD1921, R&D Project 11793.

Downs, P.W. and Thorne, C.R. (1998) Design principles and suitability testing for rehabilitation in a flood defence channel: the River Idle, Nottinghamshire, UK. *Aquatic Conservation: Marine and Freshwater Systems*, **8**(1), 17–38.

Dury, G.H. (1970) General theory of meandering valleys and underfit streams. In Dury, G.H. (ed.) *Rivers and river terraces*. Macmillan, Basingstoke, pp. 264–275.

Emery, J.C., Gurnell, A.M., Clifford, N.J. and Petts, G.E. (2004) Characteristics and controls of gravel-bed riffles: an analysis of data from River Habitat Survey. *Journal, CIWEM*, **18**(4), 210–216.

European Commission (1992) *Council Directive 92/43/EEC on the Conservation of Natural Habitats and Wild Fauna and Flora*. Official Journal of the European Communities, L206, 7–50.

European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council Establishing a Framework for Community Action in the Field of Water Policy. *Official Journal of the European Communities*, Brussels, 22 December, **L327**, 1–72.

Everard, M. (2004) Investing in sustainable catchments. *Science of the Total Environment*.

Extence, C.A., Balbi, D.M. and Chadd, R.P. (1999) River flow indexing using British benthic invertebrates: a framework for setting hydroecological objectives. *Regulated Rivers: Research and Management*, **15**(6), 543–574.

Ferguson, R.I. (1981) Channel form and channel changes. In Lewin, J. (ed.) *British rivers*. Allen and Unwin, London, pp. 90–125.

Graf, W.L. (2001) Damage control: restoring the physical integrity of America's rivers. *Annals of the Association of American Geographers*, **91**(1), 1–27.

Gurnell, A.M., Angold, P. and Gregory, K.J. (1994) Classification of river corridors: issues to be addressed in developing operational methodology. *Aquatic Conservation: Freshwater and Marine Ecosystems*, **4**(3), 219–231.

Harper, D.M., Smith, C.D. and Barham, P.J. (1992) Habitats as the building blocks for river conservation assessment. In Boon, P.J., Calow, P. and Petts, G.E. *River conservation and management*. Wiley, Chichester, pp. 311–319.

Harper, D.M., Kemp, J.L., Vogel, B. and Newson, M.D. (2000) Towards the assessment of 'ecological integrity' in running waters of the United Kingdom. *Hydrobiologia*, **422/423**, 133–142.

Harvey, A.M. (1969) Channel capacity and the adjustment of streams to hydrological regime. *Journal of Hydrology*, **8**(1), 82–98.

Harvey, A.M. (1975) Some aspects of the relations between channel characteristics and riffle spacing in meandering streams. *American Journal of Science*, **275**(4), 470–478.

Holmes, N.T.H. and Nielsen, M.B. (1998) Restoration of the rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(1), 185–196.

Howe, J. and White, I. (2002) The geography of the autumn 2000 floods in England and Wales: causes and solutions. *Geography*, **87**, 116–124.

Jeffers, J.N.R. (1998) Characterisation of river habitats and prediction of habitat features using ordination techniques. *Aquatic Conservation, Marine and Freshwater Science*, **8**(4), 529–540.

Kern, K. (1992) Rehabilitation of streams in south-west Germany. In Boon, P.J., Calow, P. and Petts, G.E. (eds) *River conservation and management*. Wiley, Chichester, pp. 321–335.

Knight, D.W. (1989) Hydraulics of flood channels. In Beven, K. and Carling, P. (eds). Wiley, Chichester, pp. 83–105.

Kondolf, G.M. and Larson, M. (1995) Historic channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **5**(2), 109–126.

Kondolf, G.M. and Piégay, H. (eds) (2003) *Tools in Geomorphology*. Wiley, Chichester.

Kronvang, B., Svendsen, L.M., Brookes, A., Fisher, K., Moller, B., Ottosen, O., Newson, M. and Sear, D. (1998) Restoration of the rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project. 3: Channel morphology, hydrodynamics and transport of sediment and nutrients. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**, 209–222.

Large, A.R.G. and Newson, M.D. (2005) Hydromorphological quality – a policy template for channel design in river restoration. In Anderson, M.J. (ed.) *Encyclopedia of hydrological sciences*. Wiley, Chichester.

Large, A.R.G., Walsh, C., Orr, H.G., Newson, M.D. and Kilsby, C.G. (2006) *Incorporating climate change in river typologies*. Environment Agency, Bristol, Science Project Record SC030301.

Leeks, G.J.L., Huntley, D.A. and Walling, D.E. (eds) (2001) *Land–ocean interaction: measuring and modelling fluxes from river basins to coastal seas*. IWA Publishing, London.

Lewis, G. and Williams, G. (eds) (1984) *The rivers and wildlife handbook*. Royal Society for the Protection of Birds, Sandy.

Macklin, M.G. and Lewin, J. (2003) River sediments, great floods and centennial-scale Holocene climate change. *Journal of Quaternary Science*, **18**(2), 101–105.

Macklin, M.G., Rumsby, B.T. and Newson, M.D. (1992) Historical floods and vertical accretion of fine-grained alluvium in the Lower Tyne Valley, northeast England. In Billi, P., Hey, R.D., Thorne, C.R. and Tacconi, P. *Dynamics of gravel-bed rivers*. Wiley, Chichester, pp. 573–589.

Marsh, T.J. (2001) The 2000/01 floods in the UK – a brief overview. *Weather*, **56**, 343–345.

Marsh, T.J. (2002) The UK floods of 2000–2001: a hydrometeorological appraisal. *J.CIWEM*, **16**(3), 180–188.

McDonald, A., Lane, S., Haycock, N.E. and Chalk, E.A. (2004) 'Rivers of dreams': on the gulf between theoretical and practical aspects of an upland river restoration. *Transactions of the Institute of British Geographers*, NS 29, 257–281.

McGahey, C., Samuels, P.G., Knight, D.W. and O'Hare, M.T. (2008) Estimating river flow capacity in practice. *Journal of Flood Risk Management*, **1**(1), 23–33.

Miller, J.R. and Ritter, J.B. (1996) An examination of the Rosgen classification of natural rivers. *Catena*, **27**(3–4), 293–299.

National Rivers Authority (1992) *River corridor surveys*. Conservation Technical Handbook 1. NRA, Bristol.

National Rivers Authority (1996) *River habitats in England and Wales*. NRA, Bristol.

Navratil, O., Albert, M.-B., Herouin, E. and Gresillon, J.-M. (2006) Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed reaches. *Earth Surface Processes and Landforms*, **31**, 1345–1363.

Newson, M.D. (1981) Mountain streams. In Lewin, J. (ed.) *British rivers*. Allen and Unwin, London, pp. 58–89.

Newson, M.D. (1984) Introduction 2: River processes and form. In Lewis, G. and Williams, G. (eds) *The rivers and wildlife handbook*. Royal Society for the Protection of Birds, Sandy, pp. 3–9.

Newson, M.D. (1992) River conservation and catchment management: a UK perspective. In Boon, P., Petts, G.E. and Calow, P. (eds) *River conservation and management*. Wiley, Chichester, pp. 385–396.

Newson, M.D. (2002) Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**(4), 365–379.

Newson, M.D. (in press) Measures and mechanisms for catchment-scale risks: through connectivity to hot-spots. *Aquatic Conservation: Marine and Freshwater Ecosystems*.

Newson, M.D. and Brookes, A. (1994) River morphology and fluvial processes. In Ward, D., Holmes, N. and Jose, P. (eds) *The new rivers and wildlife handbook*. Royal Society for the Protection of Birds, Sandy, pp. 19–30.

Newson, M.D. and Chalk, L. (2004) Environmental capital: an information core to public participation in strategic and operational decisions – the example of river 'best practice' projects. *Journal of Environmental Planning and Management*, **47**(6), 899–920.

Newson, M.D. and Clark, M.J. (2008) The sustainable management of restored rivers. In Darby, S.J. and Sear, D.A. (eds) *River restoration: managing the uncertainty in restoring physical habitat*. Wiley, Chichester, pp. 287–303.

Newson, M.D. and Large, A.R.G. (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, **31**(31), 1606–1624.

Newson, M.D. and Newson, C.L. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography*, **24**(2), 195–217.

Newson, M.D. and Orr, H.G. (2004) *Tools for applying the EU Habitats Directive to the English River Tweed cSAC. Hydromorphological study of the River Till*. Report to Environment Agency, North-East Region, Newcastle.

Newson, M.D. and Sear, D. (2000) Geomorphological procedures and river restoration: science, survey and sustainability. In Nijland, H.J. and Cals, M.J.R. (eds) *River and restoration in Europe: practical approaches*. Proceedings of the Conference on River Restoration, Wageningen, The Netherlands, 2000, RIZA, Leylstad, The Netherlands, 251–254.

Newson, M.D., Pitlick, J. and Sear, D. (2002) Running water: fluvial geomorphology and river restoration. In Perrow, M.R. and Davy, A.J. (eds) *Handbook of ecological restoration*. Cambridge University Press, Cambridge, pp. 133–152.

Newson, M.D., Sear, D.A. and Heritage, G. (1999) *Rehabilitation of selected sub-reaches of the River Waveney, Anglia Region, Environment Agency*. A Geomorphological Assessment. Report to Environment Agency, Ipswich.

Newson, M., Thorne, C. and Brookes, A. (2001) The management of gravel-bed rivers in England and Wales: from geomorphological research to strategy and operations. In Mosley, M.P. (ed.) *Gravel-bed rivers V*. New Zealand Hydrological Society, Wellington, pp. 581–606.

Newson, M.D., Clark, M.J., Sear, D.A. and Brookes, A. (1998a) The geomorphological basis for classifying rivers. *Aquatic Conservation: Marine and Freshwater* Ecosystems, **8**(4), 415–430.

Newson, M.D., Harper, D.M., Padmore, C.L., Kemp, J.L. and Vogel, B. (1998b) A cost-effective approach for linking habitats, flow types and species requirements. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(4), 431–446.

Orr, H.G., Large, A.R.G., Newson, M.D. and Walsh, C.L. (2008) A predictive typology for characterising hydromorphology. *Geomorphology*, **100**(1–2), 32–40.

Padmore, C.L., Newson, M.D. and Charlton, M.E. (1998) Instream habitat in gravel-bed rivers: identification and characterisation of biotopes. In Klingeman, P.C., Beschta, R.L., Komar, P.D. and Bradley, J.B. (eds) *Gravel-bed rivers in the environment*. Water Resource Publications, Colorado, pp. 345–364.

Pardoe, L. and Armitage, P.D. (1997) Species assemblages as descriptors of mesohabitats. *Hydrobiologia*, **344**(1–3), 111–128.

Petts, G.E. and Amoros, C. (eds) (1996a) *Fluvial hydrosystems.* Chapman and Hall, London.

Petts, G.E. and Amoros, C. (1996b) The fluvial hydrosystem. In Petts, G.E. and Amoros, C. (eds) *Fluvial hydrosystems*. Chapman and Hall, London, pp. 1–12.

Poole, G.C. (2002) Fluvial landscape ecology: addressing uniqueness within the river discontinuum. *Freshwater Biology*, **47**(4), 641–660.

Quevauviller, P., Balabanis, P., Fragakis, C., Weydert, M., Oliver, M., Kaschl, A., Arnold, G., Kroll, A., Galbiati, L., Zaldivar, J.M. and Bidoglio, G. (2005) Science-policy integration needs in support of the implementation of the EU Water Framework Directive. *Environmental Science and Policy*, **8**(3), 203–211.

Raven, P.J., Holmes, N.T.H., Dawson, F.H., Fox, P.J., Everard, M., Fozzard, I. and Rouen, K.J. (1998) *River habitat quality: the physical character of rivers and streams in the UK and Isle of Man.* NRA, Bristol.

River Restoration Centre (1999) *Manual of river restoration techniques.* RRC, Silsoe.

Rosgen, D.L. (1996) *Applied river morphology.* Wildland Hydrology, Pagosa Springs, USA.

Sear, D.A. (1994) River restoration and geomorphology. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **4**(2), 169–177.

Sear, D.A. and de Vries, P. (2008) *Salmonid spawning habitat in rivers. Physical controls, biological responses and approaches to remediation*. American Fisheries Society, Bethesda, MY.

Sear, D.A. and Newson, M.D. (2004) The hydraulic impact and performance of a lowland rehabilitation scheme based on pool–riffle installation: the River Waveney, Scole, Suffolk, UK. *River Research and Applications*, **20**(7), 847–863.

Sear, D.A., Briggs, A. and Brookes, A. (1998) A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(1), 167–183.

Sear, D.A., Hill, C.T. and Downes, R.H.E. (2008) *Geomorphological assessment of riverine SSSIs for the strategic planning of physical restoration*. Natural England, Sheffield, Research Report NERR013.

Sear, D.A., Newson, M.D. and Thorne, C.L. (2003) *Guidebook of applied fluvial geomorphology*. Defra/Environment Agency, London, R&D Technical Report FD1914.

Vaughan, I.P., Diamond, M., Gurnell, A.M., Hall, K.A., Jenkins, A., Milner, N.J., Naylor, L.A., Sear, D.A., Woodward, G. and Ormerod, S.J. (2009) Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**(1), 113–115.

Vivash, R., Ottosen, O., Janes, M. and Sorensen, H.V. (1998) Restoration of the Rivers Brede, Cole and Skerne: a joint Danish and British EU-LIFE demonstration project, II – the river restoration works and other related practical aspects. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(1), 197–208.

Wadeson, L.A. (1994) A geomorphological approach to the identification and classification of instream environments. *South African Journal of Aquatic Sciences*, **37**, 130–137.

Walker, J., Diamond, M. and Naura, M. (2002) The development of physical quality objectives for rivers in England and Wales. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**(4), 381–390.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1997) The characteristics of overbank deposits associated with a major flood event in the catchment of the River Ouse, Yorkshire. *Catena*, **31**(1–2), 53–75.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1998) The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology*, **22**(3–4), 225–242.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. (1999) Rates of contemporary overbank sedimentation and sediment storage on the floodplains of the main channel systems of the Yorkshire Ouse and River Tweed, UK. *Hydrological Processes*, **13**(7), 993–1009.

Ward, D., Holmes, N. and Jose, P. (eds) (1994) *The new rivers and wildlife handbook*. Royal Society for the Protection of Birds, National Rivers Authority, The Wildlife Trusts, Sandy.

Wharton, G. (1992) Flood estimation from channel size: guidelines for using the channel-geometry method. *Applied Geography*, **12**(4), 339–359.

Wharton, G. 1995. The channel-geometry method: guidelines and applications. *Earth Surface Processes and Landforms*, **20**(7), 649–660.

Wheaton, J.M., Darby, S.E., Sear, D.A. and Milne, J.A. (2006) Does scientific conjecture accurately describe restoration practice? Insight from an international river restoration survey. *Area*, **38**(2), 128–142.

6

Case studies and outcomes of the application of geomorphological procedures

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6.1 Introduction – geomorphological information, assessment and 'tools'

We make no excuse for introducing a brief history of the development of geomorphological tools for river management: experience is a key quality in the practitioner community and to incorporate geomorphology in vital responses to a rapidly evolving field of policy merits wider understanding of the subject's corporate curriculum vitae.

Since the first publication of this Guidebook (Sear *et al.*, 2003), two milestone review volumes have pointed up the recent success and continuing problems of applying the science of fluvial geomorphology (Kondolf and Piegay, 2003; Downs and Gregory, 2004).

Despite the appearance of the term 'tools' in the title used by Kondolf and Piegay, they are surprisingly catholic in their definition:

> . . . a concept is defined as a representation of reality, and a theory is an explicit formulation of relationships among concepts. Both are tools because they provide the framework within which problems are approached and techniques and methods deployed. (pp. 3–4)

It is clear that, in both the practitioner and stakeholder communities in the UK this definition puts insufficient distance between academic idealism and pragmatic need. The hectic development and deployment of sustainable policies for river management and the penalties for 'getting it wrong' (until we fully understand the difference between uncertainty and ignorance) mean that every source of information, every technique for assessment and any avenue of work earning the epithet 'tool' must deliver comfort to the user (i.e. a complete 'job', free from risk of future litigation). Geomorphology has problems with these strictures.

Downs and Gregory's book also reveals academic idealism in stressing the particularities of geomorphogical evidence (often forensic in its combination of qualitative and quantitative information – see the case studies below) and, in response, advocating changes in management style to incorporate it in 'river management *with nature*'. The inclusion of qualitative, historical ('forensic') evidence is vital to practitioner and stakeholder understanding of geomorphological 'tools': they are not universal equations for solutions of infinite duration and the engineering tradition needs to appreciate this essence. Nevertheless, geomorphology is not standing aloof, even within academe, and is moving rapidly towards a 'toolbox' which can compromise with this tradition via quantification and decision-support frameworks for implementation. The complete 'job' is now feasible, permitting

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Table 6.1 River channel management with nature. Data taken from Downs and Gregory, 2004

Rudiment	Management component
Understanding the past and the present	• Understanding what is nature • Initiate the collation of scientific geospatial databases • Commitment to scientific funding • Commitment to post-project monitoring and evaluation
Incorporating future conditions	• Learn to manage natural recovery • Develop improved predictive models • Learn to manage created environments
Coping with uncertainties: the culture of management	• Promote the use of adaptive management • Set attainable and measurable target indicators • Educate the river managers • Assessment of the risks involved
Management with stakeholders	• Formulate shared visions of management outcomes • Encourage stakeholder education • Facilitation of land acquisition
Management as a reflection of institutional structure	• Ensuring that institutional organisation and structures are sufficiently flexible

geomorphology far more than a contextual, supporting role through interdisciplinary projects.

Downs and Gregory (2004) lay out a 15-point agenda for the application of fluvial geomorphology to 'river management with nature' (see Table 6.1 below).

6.2 Applied fluvial geomorphology in the UK

Figure 6.1 presents a partial picture of the evolution of formal tools, each with a track record of application. It mainly features the particular case of geomorphological assessment, clearly a tool, in filling what was (outside academe) a national vacuum for information on river sediments. Most generic features of assessment are demonstrated by the brief history of Fluvial Audit. During March 1988, North West Water needed urgently to address the viability of their Dunsop supply scheme in the light of the progressive deterioration of a Victorian system of catchwaters – the result of headwater erosion and the resulting sedimentation at the supply intakes. Geomorphologists from Newcastle University undertook to survey the problem in the field as the basis for empirical predictions of sediment supply, transport and for the choice of mitigating measures (including catchment management). The approach to fieldwork in the Rivers Brennand and Whitendale was termed *fluvial auditing* (Newson and Bathurst, 1988, p. 11); the authors had become convinced that sediment transport is a much broader problem than anticipated in engineering science, involving sediment supply, transport and magnitude/frequency complications. The Dunsop study is not directly reviewed here because of its exploratory nature (but see Newson *et al*., 1997); however, it established prominence for two vital geomorphological factors that hitherto had not been considered as providing any potential guidance to managers coping with fluvial sediment problems:

1. flood history
2. land use and land management.

Sources of sediment opened during a low-frequency flood event in 1968 were still contributing to the excessive deposition in the Dunsop supply scheme but newer

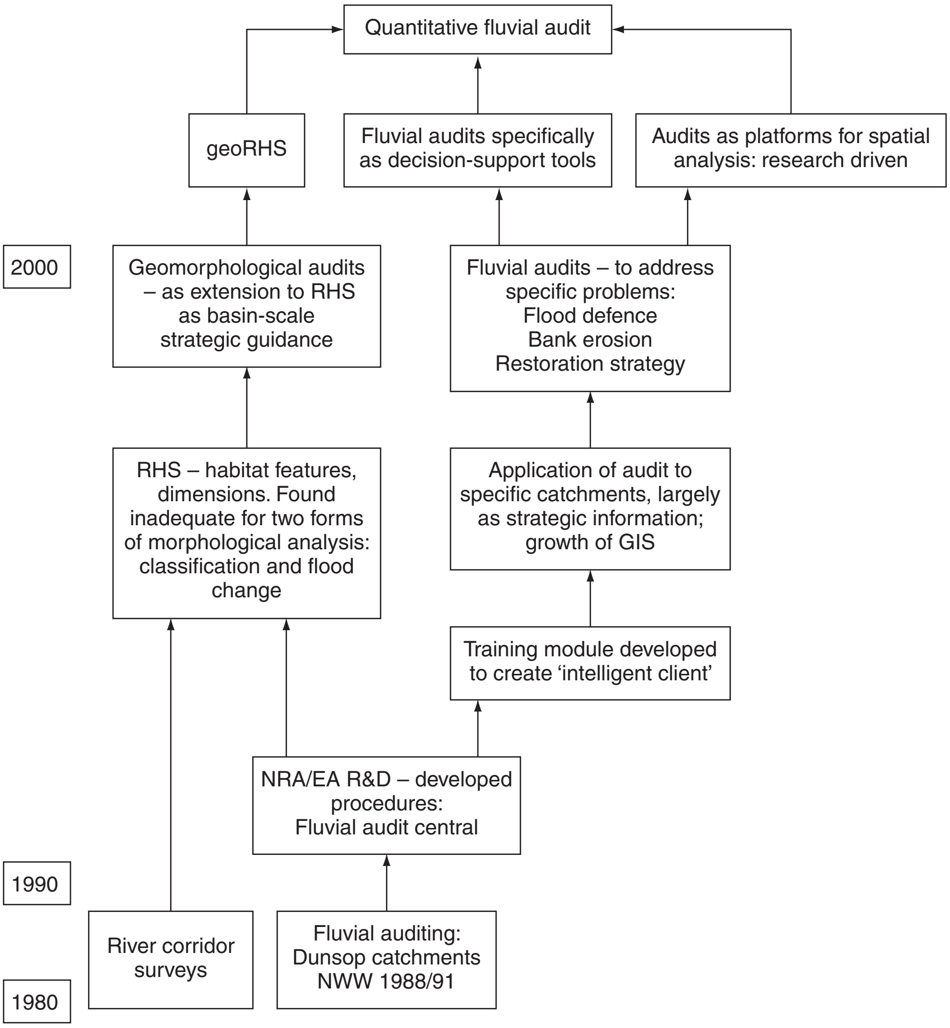

Fig. 6.1 A compressed historical time line showing the evolution of applied fluvial geomorphological assessment, procedures and tools in the UK

sources had been created by, for example, bracken spraying, ATVs (all-terrain vehicles) and rabbit infestation. Thus, catchment management recommendations resulted from fluvial audit and, 20 years later, the water supply authority has used government capital to initiate a widespread Sustainable Catchment Management Programme ('SCaMP': United Utilities, 2006).

In the 1980s it was still very unusual for river managers to commission geomorphological surveys; problems of erosion and sedimentation were normally addressed with engineering solutions such as revetment or traps. While sediment-related problems were widely recognised, Hydraulics Research (1987) pointed out that only a tiny minority of flood defence activity in UK rivers considered the fluvial sediment system. As a consequence, river works often created more geomorphological problems than they solved; channel enlargement to create flood conveyance was notably associated with causing erosion and sedimentation, problems picked up on the maintenance budget in subsequent years. Perhaps the best (or worst) publicised example of neglecting the sediment system was the Brecon flood protection scheme which, unintentionally, widened the channel of the Usk to aid conveyance but instead made it prone to sedimentation. Sedimentation duly ensued, rendering the river 'starved' of sediment downstream and thus promoting bank erosion there: two problems for the price of initial neglect.

While a minority of academic fluvial geomorphologists had become involved in applied work during the 1980s and 1990s, their contribution remained locked up in their confidential consultancy reports. One of the first collations of their approaches and outputs occurred in a comprehensive text produced by an ad hoc 'River Dynamics Group' (Thorne *et al.*, 1997) but, despite the applied slant and title given to that book (initially sponsored by the US Army Corps of Engineers), the momentum that was building in the UK for geomorphological applications, e.g. in the Thames Region of the National Rivers Authority, it was given little shape or structure via this route.

During the 1990s, however, a significant number of R&D contracts were let by National Rivers Authority and the Environment Agency. These established the extent and cost of sediment-related problems (NRA, 1994a), highlighted core processes (NRA, 1994b) and promoted the use of standard procedures to establish geomorphological assessments as routine in river management (EA, 1998a,b).

Simultaneously, NRA/EA were developing the River Habitat Survey (RHS) methodology which incorporated fluvial geomorphology to the degree that channel and riparian forms and dimensions influence the quality of river physical habitat. For a review of how both processes (R&D, RHS), together with the rapidly growing drive towards river restoration, accelerated the incorporation of fluvial geomorphology into river management see Chapter 5 of this Guide and papers by Newson *et al.* (2001) and Newson (2002).

We refer above to the prominence given within the first fluvial audit to flooding and to land use and land management; ironically, these two dimensions also help explain the recent exponential increase in interest. First, the extensive flooding in England during 1998 and 2000 (Environment Agency, 2001) created a traditional public outcry for more 'defences', a mentality at odds with a phalanx of new river management ideals under the banner of sustainability. The clean-up of river pollution achieved by regulation (National Rivers Authority and, from 1996, Environment Agency) left the physical damage to channels by 'defence' as a major ecological impact. Second, traditional attitudes to agriculture and its fiscal support had altered to the point where the hydrological evidence of catchment-wide impacts from land use and its management could become the basis for 'joined-up thinking', a process culminating in the EU Water Framework Directive (European Commission, 2000).

The demand for geomorphological tools was bound to escalate; Fig. 6.1 conceptualises the changes occurring in the toolbox around the millennium. As part of the R&D response to the millennium floods, River Habitat Surveys were repeated at river sections impacted by high flows, revealing shortcomings in RHS's ability to fill both ecological and flood management roles (Defra/EA, 2003a). To fit river surveys for a new clutch of purposes, such as environmental regulation and flood risk management, an R&D programme was launched to develop 'geoRHS' (see Chapter 5 and below), whose principal extension was to the floodplain. Fluvial Audit has become increasingly sophisticated and analytical (see below), restricting its use to high-risk problems; as such, it has never approached a situation of full national coverage. Fluvial Audit has intensified its focus to become a decision-support tool and strengthening its quantitative basis in GIS (geographical information system) to the point where spatial analysis becomes possible (Atkinson *et al.*, 2003). We may, in 2009, be approaching a temporary culmination of this development, one which will inevitably fit better with the engineering tradition, where quantitative fluvial audit becomes the data substrate for a catchment-scale sediment impact assessment model, currently undergoing practical trials (Wallerstein and Thorne, 2005).

6.3 Review of extant case studies in geomorphological assessment

In the Guidebook commissioned by Defra and the Environment Agency it was relatively easy to collate and review three generations of the evolving technique of Fluvial Audit (Fig. 6.1 here and Appendix 6.1 in Sear *et al.*, 2003).

In detail that review sought to provide information on:

- the geomorphological context of the work (what type of river?)
- the river management problem at site or reach scale
- the catchment context of the problem (because fluvial systems are best assessed at the system scale)
- the geomorphological techniques applied
- analytical and archival work also carried out
- the form of reporting and samples
- the use of the information provided as strategic guidance
- the use of the information to guide design or operations
- post-project appraisal where applied.

The sources for the 2003 review essentially fell into six groups of geomorphological projects (Box 6.1). The earliest to be carried out are probably those (including the Dunsop study referred to above) reported by Newson *et al.* (1997) in a textbook (Thorne *et al.*, 1997). Sear and Newson (1994) brought together the first examples of the more formal procedures that are described in *River geomorphology: a practical guide* (EA, 1998a); they used Catchment Baseline Survey and Fluvial Audit on

Box 6.1 Sources for case studies of geomorphological assessment reviewed by Sear et al., 2003

Reported by Newson *et al.*, 1997 (but dating from 1986)
Neath; Blackwater; Mimshall Brook; Upper Severn; Brennand/Whitendale; Wolf/Thrushel; Wensum.

Rivers assessed as part of other R&D (e.g. Hey and Heritage, 1993)
Ecclesborne; Kent.

'First generation' of formal assessments (Sear and Newson, 1994)
Derwent; Ehen; Idle; Mimshall Brook; Sence; Shelf Brook; Tawe; Ure; Wansbeck.

Catchment Baseline Surveys and Fluvial Audits constituting the 'second and third generations' of formal assessments (Universities of Newcastle, Lancaster, Southampton and consultants)
Skerne; Cole; Upper Wharfe; Derwent; Waveney; Kent; Upper Stour; Pant; Deben; Blackwater; Swale; Ure; Wharfe; Caldew; Upper Derwent; Boscastle streams.

Geomorphological Audit (EA extension of RHS system)
Eden; Glaze Brook; Ribble; Mersey; Rock; Pendle Water; Keekle; Calder; Irwell; Trannon; Weaver; Camel; Sankey Brook; Tywi; Mimram; Bollin; Sugar Brook; Byne; Rook; Padgate Brook.

reaches and catchments of ten rivers with a wide geographical distribution in England and Wales.

During the first generation of assessments, pressure was applied by R&D contractors for an opportunity to provide a geomorphological assessment of river management problems involving erosion, sedimentation or both. A wide range of geomorphological research techniques was applied within what was basically the original Fluvial Audit procedure: sediment finger-printing, stream power analysis etc. (Sear *et al.*, 2003). In view of the slightly 'forced' development of tools it is not surprising that attempts to follow the assessments through to implementation of geomorphological guidance (and thus to a post project appraisal) have been frustrated. It would, however, be wrong to conclude that 'nothing has happened' because, in some cases the geomorphological wisdom was 'do nothing!' (i.e. an engineering response was inappropriate) and in others (e.g. the Dunsop scheme) it has taken fully two decades for concerted action to occur (see below)! The lesson is clear – there must be a willingness to incorporate geomorphological advice at the project planning stage and to continue to exploit it in for example post-project appraisal.

It was written, six years ago (Sear *et al.*, published 2003), that:

> Subsequent applications of geomorphological appraisal under the strengthened procedural framework of Guidance Note 18 have yielded more 'action', although the tendency remains one of tentative application of geomorphological advice, except in the field of river restoration/rehabilitation (Newson *et al.*, 2002). It is essential that geomorphological assessment procedures break through into traditional engineering realms, critically Flood Defence, and there are signs that this is about to happen (Guidance Note 18 in EA, 1998a).

Applied science has rites of passage but this prediction has proved that the complexity of these rites is in inverse proportion to pragmatic needs, if key actors are prepared. R&D becomes incorporated only slowly in practice: why? Even the best disseminated material requires familiarisation and a growth in confidence in use for professional purposes. The R&D project completed in Guidance Note 18 involved an additional (unpublished) training element, consisting of a two-day course built around a half-day field trip to discuss data gathering techniques. The course was designed at the University of Newcastle and has been delivered to 18 EA groups in six regions, by staff from Newcastle and from the University of Southampton, with the aim of creating 'an intelligent client' for geomorphological procedures. These courses, together with a gradual rise in appreciation of the appropriateness of geomorphology to answer questions posed by new river management demands (e.g. flood defence combined with habitat protection), have led to opportunities to apply the procedures – mainly Fluvial Audit. These subsequent studies have yielded the 'second and third generations' of assessment and incorporation, guided by a greater awareness in the user community and a greater professionalism in the practitioners in three sectors: universities, the Environment Agency and the consultancy world. During this period it can be claimed that R&D 'procedures' have evolved into 'tools' whose use is clearer throughout a project.

6.3.1 *The current (updated) review*

Among other drivers, the millennium floods and the Water Framework Directive (WFD) changed the river managers' agenda from R&D to commissioning the active deployment of 'tools'. The proliferation of geomorphological assessments

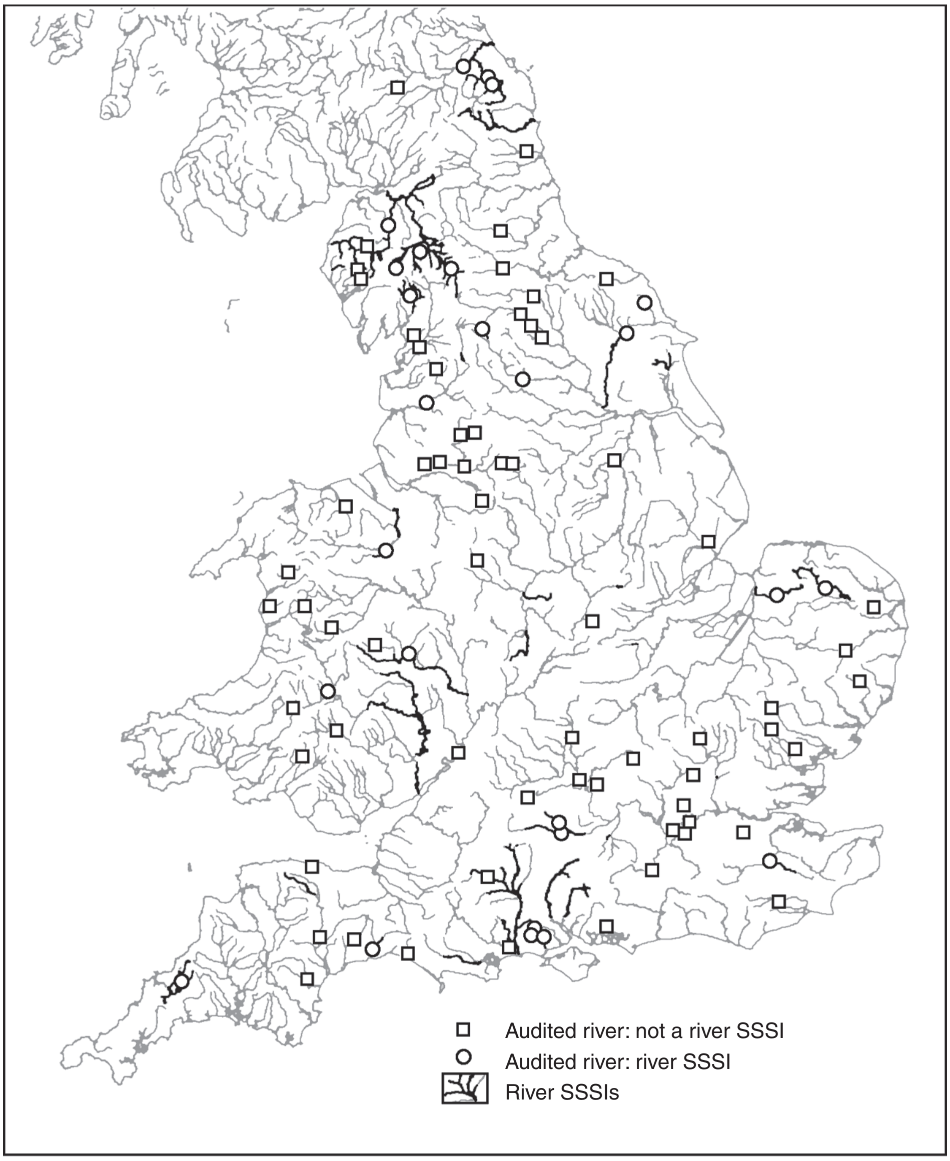

Fig. 6.2 Fluvial audits conducted to date in England and Wales

between 2002 and 2006, explained jointly by an increasing demand for evidence-based policy and an increasing supply of expertise (e.g. from geomorphologists recruited by major engineering consultants) has required a completely new take on the process of review, both spatially (see Fig. 6.1 in Sear *et al*., 2003, as revised here in Fig. 6.2) and thematically. In addition, the translation of a combination of RHS and its more focused derivative geomorphological audit (Walker, 2000) into geoRHS (Defra/EA, 2008) created a free-standing alternative to Fluvial Audit.

Walker *et al*. (2007) make an excellent start to the updated review process from the viewpoint of the major commissioning source for fluvial assessments – the Environment Agency of England and Wales. They tabulate 17 separate tools utilised by the Agency to gain fluvial information and translate it into practicable outcomes. In reconciling among and between the plethora of methodologies they isolate geographical scale (of problem) as a major driver (national, catchment, site etc.) and then determine the role of intensity, objective, cost/complexity and risk as

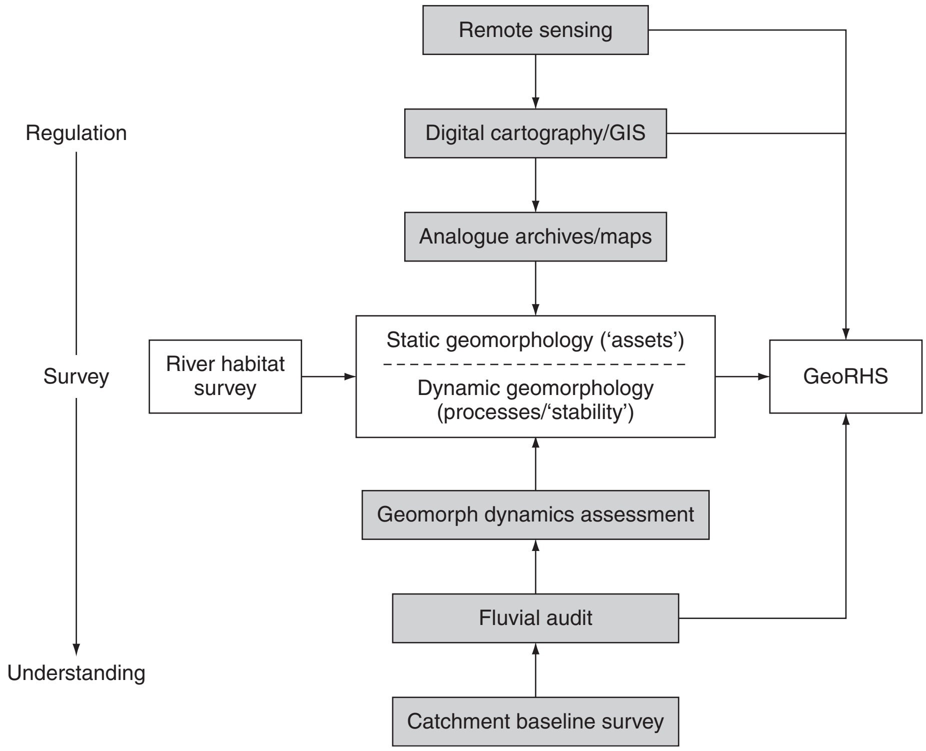

Fig. 6.3 The categorisation of geomorphological assessment procedures and supporting techniques in relation to purpose (after Newson and Large, 2006)

helping with the selection. This is useful guidance in a world of applications that remains project-driven, within a context where there is a national responsibility to create certain standardised, comparable information. The national responsibility has been initially handed to RHS and geoRHS but there are aspirations to achieve a measure of coordination, standardisation and collation of the other assessment methods.

The review by Walker *et al.* is also useful in putting costs to three scales and purposes (description, characterisation and understanding) of surveys within a catchment (Tiers 1 to 3, or Desk Study to Fluvial Audit) as £5–20/km to £250/km at 2005 prices. The examples chosen for the case studies in the paper are from each tier and comprise the characterisation process for compliance with the hydromorphological quality element of the WFD, through strategic development for river rehabilitation in sub-catchments to the same purpose on three large catchments. As a visualisation of the functional fits of the major tools, Fig. 6.3 also differentiates between the 'understanding' required for high-risk projects and the 'information' required for regulatory applications under risk-based scenarios.

We would add here that, in some circumstances, hybrid approaches to geomorphological assessment are inevitable for four reasons:

1. *Catchment size*. Typical catchment size for geomorphological appraisal is increasing to cope with the ecosystem framework for applying for example the European Habitats regulations to rivers.
2. *Source of problem*. The rise to prominence of diffuse pollution under the WFD demands that the wider landscape is considered as a sediment source and 'connectivity' issues need to be addressed.

3. *Size of sediments in focus*. 'Siltation' is now widely perceived as a threat to ecosystems but silt is difficult to observe and record in the field and its routing/budgeting in the catchment requires information about many more locations than is the case for gravel-bed material, especially on floodplains.
4. *Catchment characteristics other than size*. This emcompasses low-gradient, groundwater fed controls such as mills and navigation.

It could well be that the 'pot-pouri' of approaches may be inevitable between catchments but also feasible within catchments via the use of spatial statistics (extrapolation or kriging) or a subjective spatial division of the large problem into smaller ones by setting up a river typology for the problem catchment (e.g. Newson and Orr, 2004).

6.4 Analysis: deployment of geomorphological tools

Experience gained from training river management staff in geomorphological techniques and applications reveals two major shortcomings, highlighted in evaluation questionnaires for such courses: participants are not left empowered to carry out their own geomorphological assessment and there is insufficient time to permit working through an actual management problem. These also present a dilemma for this book. There are also good professional reasons why we cannot create 'instant geomorphologists' (see Sear *et al*., 2003, p. 34), despite the current operation of online training (http://e-learning.geodata.soton.ac/EA/). Engineering consultants have begun to recruit and sustain fluvial geomorphologists and it remains for river management agencies to do the same, rather than relying entirely on 'teach yourself' philosophies to operate an important, if minor, river management function.

To appreciate the recent changes in the capabilities of geomorphological assessments, largely derived through their adoption in follow-on implementation or decision support, it is necessary to reflect briefly on the 2003 Guidebook agenda. In the earlier version of this Guidebook (Sear *et al*., 2003), case studies from the third section of Table 6.2 (i.e. the 'first generation') were given a standard, homogeneous review to establish their features and success. It appeared from this analysis that, despite being carried out by one contractor, there was considerable variation in the data collected, necessitated by the particular brief. Nevertheless, it was possible to make broad comparisons and to draw out the directions in which the professional contribution from geomorphology moved to provide usable information of direct relevance to the river management problem (Table 6.2). Themes receiving emphasis or added during the past five years are shown in bold and italics respectively.

Given the range of local applications, why is a more general adoption of detailed geomorphological assessment apparently slow? Perhaps the best explanation is the recent trend (partly the result of EU Directives) towards rapid application of risk-based regulatory tools; this new policy context diverts effort from primary reconnaissance into larger-scale tools such as river classification. There are also considerable policy/tradition/legal obstructions to the direct incorporation of geomorphological assessment into practical river management; part of the problem relates to the innovative nature of its incorporation, especially as a self-acknowledged 'inexact science' (Newson and Clark, 2008). Thus, fluvial geomorphology itself, through its practitioners, bears a responsibility for fundamentally altering the existing approach to river management problems – it is not merely a technical 'add-on'.

Table 6.2 Geomorphological themes addressed by the case studies

Theme	Sub-theme	Detail
Erosion	**Catchment sources** Bank erosion Bed scour Structures	**Agriculture/forestry** Urban waste/roads STWs Engineering Transferred/regulated flows
Deposition	In-bank Out-of-bank **Interstitial in gravel bed**	Tributaries Zonal Structures
Channel adjustment	Planform change Channel capacity Channel gradient Channel realignment	Progressive Event-related
Channel state	**Reference conditions** **Habitat description** Stable channel or feature Recovery from capital works Reduce maintenance	
Typologies	*Towards type-based reference conditions* *Stratified assessment and decision support*	

River restoration has been vital to the breakthrough for geomorphological tools because it demanded the full range of potential from Catchment Baseline to Dynamic Assessment and Environmental Channel Design (see Chapter 4). Thus, moving to the second and third generations of applications, Catchment Baseline Surveys and Fluvial Audits began to be applied to several, largely headwater, problem rivers during the mid- and late 1990s. Once again, while a sediment-related management problem clearly existed, justifying the deployment of funds for contracts, advice tended to remain strategic or precautionary, with the exception of those cases where specific river modifications were already anticipated (e.g. Rivers Skerne and Cole – River Restoration Project – Upper Wharfe, Waveney and Deben – also restoration projects). In each case Fluvial Audit and/or Catchment Baseline Survey located and gave the context for a Dynamic Assessment. Box 6.2 shows an abbreviated summary of the Catchment Baseline Survey of the Waveney (see also Box 5.1).

The Waveney reconnaissance Fluvial Audit was conducted simultaneously with the Catchment Baseline (a procedure later renamed 'detailed catchment baseline' by the GeoData Institute) but was focused upon separating reaches controlled by extensive milling operations from those where natural flow/sediment interactions remained the driving variables.

In the case of the Waveney Fluvial Audit, two separate Dynamics Assessments were commissioned – at Diss (Heritage, 1999) and at Scole (Newson *et al.*, 1999). They varied slightly in their content but basically they used the same set of scientific principles:

- 'natural' morphology is predictable from historical data or from driving variables
- design of channel features involves decisions about their dynamic nature
- the dimensions of these features can be empirically predicted

Box 6.2 Summary and conclusions of Waveney Catchment Baseline study

Geomorphological considerations

1. Sedimentation
   - Low slope and structures produce ponded flow, allowing siltation.
   - Increasing stream power to 'self-cleansing' levels impracticable.
   - Coordinated sluice operation and bed disruption might aid desilting.
   - Steeper tributaries generate and transport fines to main channel in high flows.

2. Flow regime
   - Recent low flows, abstraction and lack of effective records a problem.
   - Flow augmentation is geomorphologically irrelevant in volume and timing.
   - Hard to predict the effect of each control structure at all flows without a model.

3. Channel maintenance
   - Dredging in the past has removed much of the morphological diversity.
   - Current maintenance levels low, except in some tributaries.
   - Weed growth is part of the siltation problem; may be options for control.

Rehabilitation considerations

1. Siltation
   - Siltation might be ameliorated locally by 'harder' maintenance.
   - Alternatively, in certain sections, reduced weed removal may speed flow.
   - Siltation is a threat to rehabilitation features, especially in gravels but proper design can aid self-cleansing.

2. Flow regime
   - Sediment transport rates will never be high in main channel – active forms, such as 'natural' bars and riffles, may not be an option.
   - Flood frequency may be increased immediately upstream of rehabilitated reaches.

- the impact of features on channel roughness and therefore conveyance can be predicted, either geomorphologically or using industry-standard hydraulic models (Sear and Newson, 2004).

Here, therefore, we see evidence of a transitional 'vehicle' for geomorphological advice because it is delivered in formats that correspond with those of engineering science. The work reported by Sear and Newson (2004) (and see Box 5.2 in Chapter 5 of this Guide) indicates that the Waveney scheme has entered the practical engineering tradition: 'there is a need to apply more rigorous performance criteria to the rehabilitation and design of pool–riffle sequences in order to ensure that the functional attributes of such bedforms are maintained' (p. 861). The sub-text appears to be 'create mimic morphologies but these will only achieve a static equilibrium with more diversity of flow'. An extra detail for this project was that the gravel sizes chosen for the introduced 'riffles' consisted not of those recommended by dynamics assessment, but those available and affordable from a local quarry; the 'riffles' were installed within the competence of a particular machine (accessibility, reach) and its driver!

By the time Newson and Sear (2002) carried out a dynamic assessment on the River Deben (again following Fluvial Audit: Newson, 2000) it was deemed essential to locate the features to be restored, quantity survey the materials involved, and (vitally) to assess their impact upon flood conveyance via survey of cross-sections and roughness calculations. It is important to note that, at this stage, Regional

Flood Defence officers had become 'comfortable' with the changes to river dynamics effected by restoration schemes if geomorphologists were involved in assessment. Once again, however, failure to appreciate 'on the ground' complications of access, cost and health/safety compromised the geomorphological design.

Outside restoration schemes, for the remainder of the second generation of Fluvial Audits, it appears that geomorphological advice is seen by both customer and contractor as simply a strategic procedure for sensitive river systems: information for future action. Quotations from the published Fluvial Audits illustrate this conclusion:

- **Kennet/Lambourn** (Geodata Institute, undated, p. 2): 'the geomorphological issue/issues were never clearly specified, although wider and often multi-functional 'problems' were perceived'.
- **Ure** (Geodata Institute, 2000, p. 1): 'The geomorphological audit of the River Ure from Wooton to Ripon has been undertaken as a response to a number of perceived issues for the sustainable management of the channel and catchment.'
- For the **Caldew** (GeoData Institute, 2001a) the Audit brief included 'catchment wide issues involving poaching, perceived aspects of land-use change and the potential impact of climate change' (p. v).
- **Swale** (GeoData Institute, 2001b, p. iv): 'The Swaledale Regeneration Project Steering Group identified a number of specific management issues, in addition to catchment-wide issues relating to landuse.'
- **Wharfe** (German and Hill, 2002, p. iv) 'Although no specific management issues were identified by the Best Practice Project group as part of this geomorphological audit, identification of local areas of channel instability and catchment wide issues related to landuse are of general concern.'

The Wharfe forms a spectacular example of strategic incrementalism: the German and Hill (2002) Audit followed those by Heritage and Newson (1997) and RKL Arup (1999), each taking successively larger 'bites' out of the catchment and each subtly adapted to the current perceptions of the sponsors. Each also used slight variants of the basic methodology!

Despite this slightly disappointing review, there appears to be no faulting the geomorphological advice; in many cases 'failure' was the result of our 'purist' strategies competing unsuccessfully with another project criterion, be it financial, engineering or from the stakeholder community: work commissioned and completed in isolation on contract is no answer. It quickly became obvious that Fluvial Audits and other geomorphological reports should directly address decision support and operational considerations, i.e. procedures must become tools.

This characterisation became apparent in the cases of the Kent (Cumbria) fluvial audit (Orr *et al.*, 2000) and that for the Ely-Ouse water transfer to rivers in Essex: the Upper Stour (Newson and Block, 2002a), Pant (Newson and Block, 2002b) and Blackwater (Orr *et al.*, 2004). Details are summarised in Boxes 6.3 and 6.4.

As an example of GIS-based Fluvial Audits answering an even more specific river management problem, the recent reports on the Rivers Upper Stour, Pant and Blackwater in Essex were designed to investigate the relationship between water resource management and river erosion/deposition. The Ely Ouse Essex Transfer Scheme has operated to divert water from the Fens into these rivers, via a pipeline, since the 1970s. Recent drought years have led to proposals for an expanded volume of transfers but local opinion has suggested that the receiving channels may be destabilised by their volume and timing. Fluvial Audit was accompanied by the field survey techniques of the EA's *Waterway bank protection* manual (EA, 1999) and

Box 6.3 River Kent – suggestions for managing the sediment system based upon the findings of the geomorphological assessment (Orr et al., 2000)

1. In terms of the 'source–pathway–target' analysis often used for pollution control, the Agency has analogous management opportunities in the sediment system. Only 2% of the Kent catchment comprises 'sediment hotspots', so **management at source** has obvious attractions but two disadvantages. One is that the slugs of sediment which cause channel management problems downstream are already 'on their way'; the other is that complete source control can also evoke channel changes (e.g. incision due to sediment starvation). One might therefore turn to the '**pathway**' – the channel network – in an attempt to reconfigure channel dimensions to produce smoother downstream transfers (bearing in mind that the report identifies mill removal and channelisation as major contributors to 'instability'). A problem here is the lack of certainty with which we can model for, for example tributary contributions and rare events – nevertheless, those reaches and subreaches which are clearly ill-adjusted would benefit from redesign using for example regime equations. Finally, if we regard prominent areas of deposition as the '**target**' under this terminology we simply adopt a Kent trap network, located at strategic points and regularly emptied. This strategy perhaps falls in line with traditional Environment Agency (EA) 'ways of working' but also has problems of sediment starvation, aesthetic problems and disposal problems. An agreed strategic channel maintenance plan should be the aim, with its objective the improvement of the Kent ecosystem towards the notion of 'resilience' in the face of climate change.
2. The second problem impinging on the choice of a narrower, prioritised scheme concerns the degree to which EA wishes to handle the programme alone; if partnership with land owners and users is to be encouraged (it's a popular formula), this dimension needs to be built into a best-practice programme from the start. It has disadvantages of being evolutionary (as land-use impacts reach the river system relatively slowly) and of lacking controls but has all the normal benefits of partnership – shared information, working to common assessments of risk etc. The geomorphological assessment has mapped the Kent and there is now an impressive body of advice on best practice on managing both sediment sources and erosion sites. There is also a reforming mood about alternative directions for agricultural grant-aid which could well improve the uptake of best practices.
3. The critical element of the strategy is information; the assessment forms only a snapshot of a dynamic situation. While the Agency has no formal channels for the collection of geomorphological information (apart from RHS), the provision of training to key staff and advice on simple monitoring techniques can form a secure foundation for an interactive approach – especially if linked to a broader community of interests as suggested above. The training can be extended to, for example, riparian owners and other public authorities. Monitoring can be allocated to the EA function staff with most need to be in the catchment regularly, e.g. hydrometry, pollution control or fisheries, rather than flood defence.

together these techniques formed a strict experimental framework using research hypotheses about the extent and true causes of those cases of severe bank erosion identified.

Box 6.4 lists some of the conclusions.

Following the appearance of the Upper Stour Fluvial Audit, EA commissioned further assessments of the Rivers Pant and Blackwater, secondary receiving channels

Box 6.4 Fluvial Audit leading to geomorphological advice concerning channel stability in a river impacted by transferred flows (Newson and Block, 2002a,b)

We have used a combination of literature and archival searches and primary field survey to address the problem of bank erosion in the Upper Stour.

Perhaps the most important conclusion comes from the field: despite 'missing' 25% of the river's length, the recorded length of eroding banks is small, around 1%; those lengths of river omitted from field survey were heavily controlled and mainly protected by regular backwater conditions, so it is unlikely that the erosion total is an underestimate. The erosion recorded by the River Corridor Survey and not by us has been added to our database in the appropriate RCS length. Upper Stour riparian owners, therefore, have little to complain about and, indeed, certain aspects of riparian management may be implicated in the causes of erosion. It is particularly important to stress to the riparian community that five of the 14 serious erosion sites surveyed are not impacted by augmented flows.

The second important conclusion relates to the 64% association between serious bank erosion and arable land use or where tree lines have been lost. It is tempting to see this as a simple, second-order relationship relating to maximising cultivated area by hedge removal, tree removal and use of heavy machinery – at some sites this may be true. However, if existing land use follows that of the late 1960s it is likely that arable land would have been the most suitable in terms of access for the works described as channel improvement. In the field it regularly appears likely that the 'working bank' for such activity was the open one and that this correlates with arable. Even bank profiles adjacent to arable appear to retain a quasi-trapezoidal outline, with the basal metre or so 'trimmed' by erosion (not recorded under our definition).

It is a pity that, at this point of the analysis, we do not have the design cross-sections. Our study of the long-sections has also been complicated by second-order effects. While there is a potential correlation between degree of works carried out and contemporary erosion, the low-energy backwater reaches created by the scheme structures spoil the clinching argument of 'no improvement, no erosion'. It is, however, perfectly reasonable to assume after 30 years of flows, natural or augmented, that some adjustment by erosion and deposition has occurred in the 'improved' reaches. Apart from at the nine bank erosion survey sites in the impacted length, this adjustment is best described by the term 'trimming' and there is also some 'sapping' in reaches affected by variable backwater.

Our study of the available hydraulic information (gathered for other purposes!) reveals that augmented flows to date may be responsible only for removing weathering products from the base of eroding banks, producing unnatural wetting and drying cycles in bank materials and inhibiting summer colonisation of the lower bank by vegetation. In other words, the augmented flows can be considered as an 'irritant' to the erosion situation but not a prime cause.

Finally, in the whole survey, only one length of river seemed to have an erosion problem classifiable as greater than 'local' – the length upstream of Little Bradley Bridge. While the left-bank land use is not intensive and the banks low, the accumulation of gravels in the channel appears to be creating some vigorous impinging flows against the banks and some secondary flow cells which appear capable of scour. The wooded right bank is also affected. This is the only length where some remedial action may be required and appears to be caused by deposited gravel (perhaps recently produced by sources in arable tributaries) rather than augmented flows.

for transferred flows. The evidence of the morphological impacts of augmented summer flows became vital in a legal case brought by a riparian landowner about the collapse of a farm access bridge, built at the apex of a meander bend. Evidence from the geomorphological assessment, together with a brief follow-up site visit, allowed a convincing defence against an allegation by the farmer that the Environment Agency had mismanaged flow transfer volumes. Meander migration is 'natural' for the Pant and augmented flows do not exacerbate erosive secondary flows at bends (the result of direct observations during a trial transfer). Such legal activity is becoming more routine in geomorphology and the nature of geomorphological evidence has yet to receive rigorous assessment, perhaps because of the context of judgements made on the 'balance of probability', rather than 'beyond reasonable doubt'.

6.5 The most recent developments in the use of geomorphological tools for river management

It is clear from the vocabulary of recent projects that applications are now better judged, expedited and implemented: 'Action Plan', 'Condition Assessment', 'Tools' are terms being used. Even within traditional application routes (e.g. flood defence links to erosion control) there is evidence of more focus. For example, in a Fluvial Audit of the River Otter in Devon, Emery *et al.* (2004) present very detailed bank surveys at 1:2000, showing historical channel location and the style of bank erosion (totalling 23% of the river's length), as well as detailed flood frequency time series and an historical characterisation of channel engineering. While maintaining a traditional geomorphological caution about 'hard' revetment, some sites justify this option under the EA Waterway Bank Protection protocol (EA, 1999), but elsewhere the suggestion is, for consultation with stakeholders, for a Channel Migration Zone to be established and monitored by repeat assessments using aerial survey or remote sensing.

As shown by preceding sections (also Fig. 6.1), the past six years have shown a metamorphosis for Fluvial Audit from contextual, strategic nicety to decision-support tool, as well as a technological advance via GIS. There are clear signs in the more recent clutch of project-scale applications (almost totally restricted to Fluvial Audit procedures) that the EA is expecting a much clearer implementation route for geomorphological advice. This trend is partly promoted by the recent incorporation into UK river management of EU Directives such as the Water Framework and Habitats Directives (European Commission, 2000).

Implementation of habitat regulations offers an obvious explanation for increased focus in geomorphological assessments. For example, the Fluvial Audit for the River Wylye (GeoData Institute, 2002) states that 'the main objective of the project is to develop an understanding of the geomorphology of the River Wylye and its correlation with the condition of the Ranunculus communities in order to identify key reaches for rehabilitation' (p. 4).

The project brief for the River Till in north-east England (Newson and Orr, 2004) gave the following requirement for geomorphological advice:

> The driver for the project is to ensure that decisions taken by the statutory agencies which have the potential to affect the hydrogeomorphological status of the system are well informed by a sound understanding of the system. It is intended that the project will represent best practice for addressing such issues, particularly with regard to SAC rivers and application of the Habitats Regulations 1994.

In particular the project will provide detailed guidance on the future management of:

- works in rivers consented by the Environment Agency
- other riparian works requiring EN consent
- Environment Agency flood defence works
- mechanisms by which the condition of the system can be improved and maintained in future, e.g. linking to agri-environment scheme.

In response, the Till project report contained a qualitative assessment matrix for those proposals deemed to be likely to have significant habitat impact on each attribute and species, together with a risk assessment and confidence levels for the geomorphological evidence. Importantly, a final column in the guidance listed those proposals where the geomorphologists considered it essential for the responsible authority to 'seek advice', i.e. from the professional geomorphological community.

In a more far-reaching appraisal of geomorphological assessments of value to habitat protection, Sear *et al.* (2008b) map (and tabulate) the known Fluvial Audits for England and Wales (see Fig. 6.2, above) and refine the criteria for and interpretation of Audit databases for the specific needs of protected river sites.

In a similar vein, Orr *et al.* (2004) were then involved with an assessment designed to improve land-use practices in the catchment of Bassenthwaite, a prominent Lake District open water body and habitat to the endangered vendace (fish). Here, the additional support of remote sensing and GIS to the traditional field survey proved a major tool in 'covering the ground' (i.e. catchments and channels) and in forming the substrate of data for decision support. The findings of this assessment have since received widespread public exposure in the form of practical guidance to land users and educational exhibits in tourist centres within the catchment.

Another fish species, not rare but economically without rival, the salmon, has been the target of other fluvial audits (e.g. Babtie *et al.*, 2004). The physical quality of salmon habitat can be assessed using the description of bed substrate, morphological diversity, boundary conditions and river continuity. The Babtie surveys hone the audit tool to deliver these as the basis of a characterisation, which in turn becomes the basis of rehabilitation: a 'Geomorphological Action Plan'. Revealingly, the Environment Agency has still required more detailed monitoring in the case of fine sediment fluxes in the Esk catchment (Bracken and Warburton, 2005).

The UK government's emphasis (Public Service Agreement) on bringing sites within its major protective conservation designation (SSSI: Site of Special Scientific Interest) into specified 'favourable condition' has not only turned the screw of focus further for geomorphological assessment but has become typical of an advance into risk-based policy support by geomorphologists (see Section 6.7 below). Early examples of assessments for SSSI and SAC (Special Areas of Conservation) rivers come from two chalk-fed lowland rivers in Norfolk, namely the Wensum and the Nar (Geodata Institute and Newcastle University, 2005a, 2005b). Anticipating the need for a tool focused on diffused pollution, the Wensum and Nar Audits add some dimensions of dynamics assessment (EA, 1998a, 1998b; Sear *et al.*, 2003) by measuring sediment sources during storms, turbidity monitoring in the main channel, fine sediment storage in bed gravels and gravel mobility. Furthermore, in a development currently being refined as a general geomorphological assessment methodology for SAC and SSSI rivers, Sear *et al.* (2008) promote a characterisation of the departures of river reaches from 'favourable condition' and the options for rehabilitation. This then uses multicriteria assessment techniques as a basis for decision support by stakeholders and the responsible authorities. This represents a considerable increase in specificity of information and risk-based policy support than the Physical Quality Objectives route derivable from RHS (Walker *et al*., 2002).

6.6 Regulatory support at a broader scale

In delivering support for new risk-based regulatory frameworks (a partly unwelcome challenge to the inchoate geomorphological database!), fluvial geomorphology has been forced to (temporarily perhaps) drop its obsession with empirical data. The scientific equivalent of 'put up or shut up', this situation is not unique to geomorphology. New, lightly-challenged sciences might be judged by how well they 'stand up in court' when required but when they overtly enter the regulatory environment the legal criterion may edge closer to 'beyond reasonable doubt' (e.g. in judicial review of actions by public agencies).

The regulatory framework within which fluvial geomorphology has been working for the period since the Defra/EA Guidebook (Sear *et al*., 2003), has been dominated by the European Union's Directives on Water and on Habitats. However, there have also been very significant stimuli in the UK policy environment, deriving from the reassessment of 'flood defence' as 'flood risk management' following the millennium floods (Catchment Flood Management Plans, CFMPs) and the new, environmentally precautionary approach to water abstractions (Catchment Abstraction Management or CAMS).

Reviewing the geomorpholgical procedures applied to the implementation of the EU Water Framework Directive (in England and Wales – Scotland is different: SEPA, 2006), Walker *et al*. (2007) point up the ability of a national database (RHS) to assess the current and potential risks of hydromorphological damage. Such general statements of risk are dangerously predicated upon the unstable definition of 'natural' and 'damage', which are only now being addressed by detailed geomorphological appraisal (Newson and Large, in press). This may yet prove a stumbling block to implementation via traditional management philosophies which lack a generic approach to uncertainty (Newson and Clarke, in press).

However, 'needs must' is an appropriate epithet for the situation in Scotland, where structural interference with hydromorphological parameters (by river regulation or channel modification) has now advanced beyond common law issues of nuisance with the comprehensive adoption of the WFD by the devolved Scottish parliament (Water Environment Controlled Activities Scotland Regulations 2005: SEPA, 2006). SEPA's intensive expert scrutiny of the available tools has yielded MImAS – the morphological impact assessment system. The system uses a channel typology to segregate different levels of resilience and sensitivity, coupled with an impact classification (in relation to 'reference conditions' – set as pre-industrial channel conditions by the European Standards Agency – Large and Newson, 2005). The channel types may be a cause for debate among professional geomorphologists, some of whom advised SEPA, but derive eight natural classes plus 'heavily modified', the term inherent in the WFD for channels whose social function for, for example, flood conveyance or navigation outweighs their ecological function. There are then five static attributes and eight process attributes to define the degree of impact (using links to eco-hydrology established by the literature).

Throughout the UK the implementation of the Water Framework Directive requires standards to be set for 'hydromorphology' (Large and Newson, 2005). The broadly based Water Framework Directive Technical Advisory Group was tasked with establishing such standards (UKTAG, 2006) and has been very precautionary in its response, seeking only to assess impacts 'that pose high risk to ecological status' (p. 66), because the UKTAG 'is not yet in a position to develop evidence-based standards for morphology'. The tool adopted is not an engineering design tool, and cannot be used to prescribe river restoration measures; interestingly, 'it does not replace the need for detailed assessments' but there is a hint that UKTAG will suggest protocols for such assessments in future. The 'morphological conditions' contributing to High or Good Ecological Status are defined by the Directive (Annexe 5) and the UKTAG has used expert judgement to set up limits as a percentage of the resilience ('capacity') of each channel and bank/riparian aspect. The amount of capacity used (at present and by a proposed development) is assessed on the basis of the attribute, the channel type, the sensitivity and the pressure occurring, each of which contributes to a score. The system has been trialled by consulting a panel of experts and by field deployment at over 90 sites; two examples are given by the TAG report (UKTAG, 2006).

It seems likely that risk-based regulatory policies will proceed to new levels of detail, creating an urgent requirement for geomorphological tools and data. For example, English Nature has recently sponsored an evaluation of the potential for the slim available database on suspended sediment loads in UK rivers to form the basis for the equivalent of critical ingress of fines and total mean daily loads (TDMLs), as applied in legislation in the USA (Exeter Enterprises, 2005). There remains controversy in the fluvial community as to whether such a 'broad brush' can be credible in enforcement (Newson *et al.*, 2005). The official guidance remains for conservationists to promote Fluvial Audit for sensitive or already damaged catchments (Naden *et al.*, 2003). In a recent desk study of the available options for the 2000 km^2 Derwent catchment in Yorkshire, Newson (2006) suggests that geomorphological assessment faces the challenge that Fluvial Audit is impossibly detailed (hence expensive) at such a scale but that TDMLs are too general to be legally robust. He supports additional use, within a hybrid survey policy, of soil erosion models and GIS-based assessment of 'catchment connectivity'; frequently, only the 'hot spots' of damage can be addressed by either regulatory or 'best-practice' routes.

Finally, in a move combining the traditional routes of geomorphological application in flood defence and the newer habitat responsibilities, Hydraulics Research (2004), supported by a consortium of interests, concerns and efforts, has proposed a network of sites where field trials will be used to deliver standards of service for flood protection and drainage while reducing ecosystem impacts and encouraging rehabilitation by natural processes. Traditionally, say HR, 'little regard has been paid to the impact that removal of vegetation or sediments may have on habitat and the whole sediment dynamics of the river at reach and catchment scales' (p. iii). This operationalises many of the principles of the early (NRA) R&D as reported by Sear *et al.* (1995).

6.7 Recent geomorphological extension of River Habitat Surveys: geoRHS

River Habitat Surveys (RHS: Chapter 5) are necessarily simple, repeatable and rather static expressions of channel and corridor geomorphology. However, the impressive database is of national coverage and of proven catchment-scale relevance (Jeffers, 1998; Walker *et al.*, 2002). A development from RHS, Geomorphological Audit (Walker, 2000) has had a wide deployment in support of EA strategic and operational functions, notably flood defence and river restoration.

Geomorphological Audit, like RHS, is an inventory of features and dimensions whose spatial resolution lies in the accuracy of feature identification, assessment

Table 6.3 Geomorphological management inputs from Geomorphological Audit: erosion statistics for Eden sub-catchments

Catchment	Erosion: $m^2 m^{-1}$	'Natural': %	Accelerated: %	Fine: %	Coarse: %
Belah	0.46	91.5	8.5	63.4	36.6
Lowther/ Eamont	0.30	88.2	11.8	48.6	51.4
Hilton Beck	0.21	87.3	12.7	76.4	23.6
Eden	0.16	82.8	17.2	97.2	2.8
Scandal Beck	0.15	87.9	12.1	74.3	25.7
Mean	0.27	88.9	11.1	65.9	34.1

of scale and the density of the survey reaches. When performed in 500 m 'reaches', 'back to back' and with the results mapped, classified and tabulated it can form the basis of management advice for, for example, conservation of habitats in candidate SAC rivers such as the Eden (Parsons *et al.*, 2001) or schemes promoting river rehabilitation such as the Glaze Brook (EA, 2002).

The aim of the Eden Audit was, for example, 'to determine the state of environment within the Eden and sub-catchments and identify the main pressures on the system in order to derive sound management options' (p. 5). Mapping makes clear those lengths of river with valuable habitat quality, those with poor habitat quality (and the pressures reducing this quality), the 'naturalness' of geomorphological processes and the needs for restoration/rehabilitation. Outputs for the Eden are characterised in Table 6.3.

This is important information and the only reason to regard it as 'static' is that the Geomorphological Audit may never be repeated; the demands of the more fundamental policy requirements made clear above are for longer-term sustainable (albeit uncertain) information about processes. It will be process information which best informs for example rehabilitation and restoration but which also informs our responses in river management to climate change (Wilby *et al.*, 2006).

To this end, the development of GeoRHS (Defra/EA, 2003b; Branson *et al.*, 2005) has been to both expand the (static) representation of floodplains in national archives and to refine the field recording of morphology (features, dimensions) to yield more dynamic, process guidance via derived empirical indices. Geomorphological 'stability' indices, i.e. the trend of channel adjustment, will be a principal output of GeoRHS, which makes use of remote sensing and contemporary/historical map data as well as direct field survey. The R&D project included a piloting network of over 100 sites, selected across scales of stream power and naturalness. GeoRHS is also currently being applied already to a conjunctive flood attenuation and floodplain land management scheme in north Yorkshire (Newson, 2005) and to the problem of siltation in the Yorkshire Derwent (Fig. 6.4). Branson *et al.* (2005) indicate, through tables of indices, how GeoRHS is an effective platform for policy implementation under the Habitats, Water Framework and Flood Risk Management legislation. They develop, for example, a floodplain connectivity index and exemplify its fitness for purpose by case studies.

6.8 Geomorphological assessment: procedures and derived 'tools' – conclusions

In bringing this review to a conclusion, we cannot escape the professional orientation of fluvial geomorphology to direct, field-based, empirical techniques; the boundary

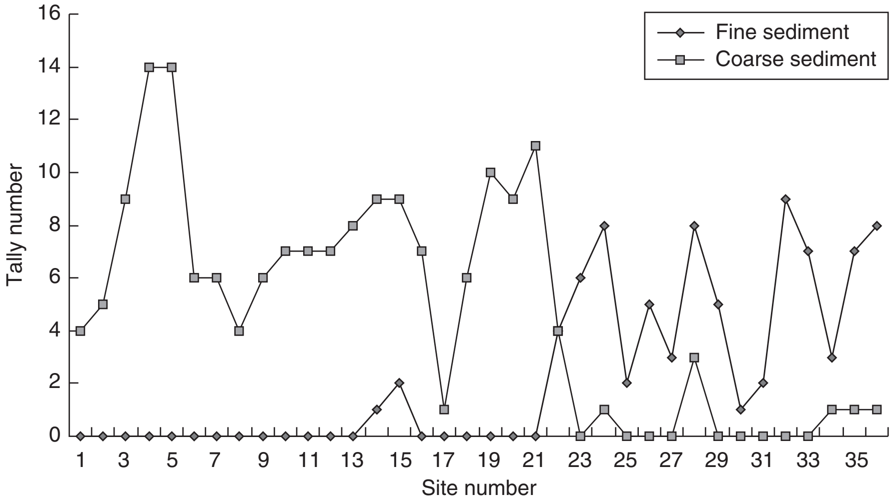

Fig. 6.4 Presentation of GeoRHS survey results (100 m intervals) along the Upper Derwent in Yorkshire to illustrate the technique's ability to highlight the bed siltation problem downstream of the Sea Cut, Scarborough

conditions of river development are seldom subordinated to general theories of physics, making generalised modelling techniques scarce. Nevertheless, there is clearly a professional responsibility to generalise to support public policy, wellbeing and the standing of the discipline.

To venture this publication as a 'Guidebook' shows caution: it is not a 'handbook'; we are witnessing the transformation of a body of academic information into tools and thus prescriptions for action. There are no national networks to gather geomorphological information, either morphological or sedimentological (cf. 3500 river gauging stations in the USA routinely measuring sediment loads). Thus, simultaneously with their incorporation in inter-disciplinary river management efforts and regulatory standards, geomorphologists are still in a reconnaissance phase! Downs and Thorne (1996) lay stress on the value of *reconnaissance* surveys, in other words the identification of first-order features, phenomena and effects. Downs and Thorne define geomorphological reconnaissance as follows (p. 459):

> Stream reconnaissance can be used to gather the descriptive and semi-quantitative data necessary to characterise existing channels, identify flow and sediment processes, and estimate the severity of any flow or sediment related instability processes.

Of these elements the existing River Habitat Surveys can only directly answer the first requirement. Clearly, therefore, the established professional community in fluvial geomorphology has a duty to rationalise and expedite acceptable procedures in the face of an urgent river management need. However, these transitional processes from academic integrity to 'usable knowledge' or 'tools' are not without severe problems of professional identity.

Under the heading 'geomorphological quality control' Downs and Thorne define three issues of particular concern (p. 462):

> The accuracy of field survey and subsequent geomorphological interpretation, whether or not geomorphologists should accept such a technique as a legitimate procedure in their science and whether it is desirable to adopt a standardized approach for surveys, as would be in keeping with recent calls for agreed

> 'professional' standards within geomorphology (Brookes, 1995). They later stress that survey is 'undoubtedly the task of an individual with considerable geomorphological experience even if there may be occasions in which the surveyors do not have a geomorphological background'.

However, they admit that a potential criticism is:

> Many engineers, particularly project managers, accuse geomorphologists of studying rivers self-indulgently, of straying too far from the project's objectives and of failing to supply useful information. (p. 464)

In an associated paper (Thorne *et al.*, 1996) the authors isolate the dimensions of a successful geomorphological approach to a river management problem (exemplified by the River Blackwater (Thames region)). The current review can progress this QA (quality assurance) by isolating geomorphological assessments that have reached, in one way or another, practical implementation or widespread dissemination. The following five case studies (Table 6.4) indicate how, in various ways, geomorphological assessment within a strong project framework, or in support of regulatory action, and if carried out as part of strategic information assembly, leads fairly smoothly to 'best practice', to legal evidence, to engineering modifications at sites and to catchment-scale management of biodiversity assets.

Table 6.4 Geomorphological assessments from the review sample and their outcomes

Catchment/sites	Audit/assessment	Outcomes
Dunsop (North West)	Newson and Bathurst, 1988; Newson *et al.*, 1997	SCaMP programme of United Utilities to promote sustainable agricultural practices on its tenanted farms in the catchments. Currently operating: Post-Project Appraisal not appropriate at this stage
Waveney (Diss and Scole: Anglia)	Newson *et al.*, 1999; Sear and Newson, 2004	Channel engineering works to rehabilitate important coarse fishery, including planform and section modifications, bars and riffles. Works performed within the limit of existing flood risk, hydraulically tested at Scole. Some Post-Project Appraisal
River Pant (Little Sampford: Anglia)	Newson and Block, 2002b	Following collapse of farm bridge at meander bend, a legal case brought by landowner alleging mismanagement of transferred flows (under Ely Ouse – Essex Transfer Scheme). Reference to Audit revealed meander migration a feature of the reach and that extra flow volumes transferred did not exacerbate secondary flows at specific bend. Post-Project Appraisal not appropriate
Bassenthwaite (North West)	Orr *et al.*, 2004	Catchment Sensitive Farming status achieved, with officer in post. Grants for woodland. Individual landowner 'best practice' in reducing grazing and restoring a wetland. Continuous sediment monitoring as in Esk catchment (Bracken and Warburton, 2005). Widespread application of community participation/social learning. 'Bass Restoration Group' promotes publicity, exhibits at tourist centres and coordination of science. Ongoing – Post-Project Appraisal not appropriate at this stage
Wensum and Nar (Anglia)	GeoData Institute and Newcastle University, 2005a, 2005b; Sear *et al.*, 2009	Decision support system constructed from Fluvial Audit results. Feeds directly into CFMP and CAMS long-term planning within the constraints of a return to 'Favourable Condition' as a public service carried out by Natural England. Individual local acts of fisheries rehabilitation (also conducive to wider biodiversity) already constructed following a reconnaissance Audit (Econ, 1998, 1999). Ongoing – Post-Project Appraisal not appropriate at this stage

This review has highlighted the issues that lie at the interface between fluvial geomorphology and river management:

- Geomorphological advice is impossible in most instances in the UK (particularly at the project scale) without a data-gathering exercise; the procedures promoted by R&D and established by applications do not, however, guarantee the incorporation of the advice.
- At a broader scale of setting national standards and protocols for 'hydromorphology' and habitat conditions it has become necessary for geomorphologists to offer 'least worst' statements at the broad-brush scales required by such uniformity and accountability strictures.
- Despite dissemination of R&D outputs and training of practitioners, geomorphological problems in river systems remain poorly perceived, especially outside the ecology and fisheries functions, whose ability to see their value and commission studies is partly explained by their discipline (environmental science, not 'exact' science) and partly by recent legislation; river restoration has been a major driving force.
- Geomorphological expertise remains very thinly spread in the Environment Agency but is becoming more widespread in major consultancy firms; the majority of academic practitioners are driven to a research orientation. While River Habitat Survey data form an important filler in this gap, apparently universal and transparent, it cannot compensate for a profound lack of expertise (as defined above).
- The former dominance of geomorphological procurement by non-engineering river management functions, such as conservation, has tended to emphasise the strategic and indirect incorporation of the advice provided by for example Fluvial Audit. However, recent customisation of Audit Procedures and Principles (e.g. by Natural England and SEPA) to assess Favourable Condition and Good Ecological Quality/Potential have promoted wider practical appreciation.
- However, both a more focused specification by users and a more rigid and technological output from contractors is encouraging more direct incorporation of more extensive inventories of form and dimensions, echoing a switch in geomorphological studies in which 'form is the new process', facilitated by remote sensing, new survey technology and GIS.
- While the first generation of Fluvial Audits attempted to apply a wide range of process-related observations and techniques, such as sediment source fingerprinting and dating techniques, process approaches have tended to become subsumed within finance and scale problems.
- The dynamic assessment procedure resembles more closely the typical river engineering specification (with the addition of sediment dynamics) and has therefore been successful both in aiding restoration designs and in building confidence about river stability and efflux levels.

The convergence and focus for future developments in applied fluvial geomorphology implied by Fig. 6.1 may or may not fix the professional status of the discipline. Applied science 'goes where it can' while pure science 'goes where it must'! However, there are numerous desirable outcomes of the work reported here such that the pure and applied can be reconciled:

- Prestigious catchment-scale hydrological ventures such as LOCAR and CHASM and studies of sediment fluxes such as LOIS must be plundered for guidance.
- Remote sensing, geo-referencing and GIS advances must be deployed as soon as sufficiently robust.

- National inventories of geomorphological data must be assembled and used to derive inductive theories and concepts to strengthen the risk-based approach to regulation. The problem will become acute if, as seems likely, protocols will be developed for assessments to suit the Habitats Regulations as well as (but different from) the Water Framework Directive in addition to the more traditional Fluvial Audit and the national scale (if adopted) GeoRHS.
- Practical modelling platforms, compatible with those available to water managers' will detract from any remaining isolationist image accruing to geomorphology.

Finally, a note on change – the slow evolution of river channel form in relation to environmental change. Undoubtedly, environmental monitoring is now much less fashionable than is reasonable, given that the rapidity of change and river channel change has been neglected by official networks (Sear and Newson, 2003). Perhaps the long-term value of geomorphological assessment will be strategic in that, when and where repeated, comparisons will provide spectacular contributions to the theory of river dynamics. Repeated survey has a particular benefit when carried out as long-term Post-Project Appraisal at sites, e.g. restored channels, where geomorphological contributions have been incorporated. There is no doubt that survey criteria must change again to reflect the need to record climate-sensitive indices (Kilsby *et al.*, 2006; Wilby *et al.*, 2006); this new approach must pre-judge the knock-on linkages between hydrological regime change, geomorphological state change and ecosystem impacts. By constantly refining the criteria for our surveys, the technology available to extend them and the purposeful inclusion of their results in design, our uncertainties can be gradually reduced as we, like engineers before us (Petroski, 2006), 'learn from our mistakes'.

References

Atkinson, P.M., German, S.E., Sear, D.A. and Clark, M.J. (2003) Exploring the relations between riverbank erosion and geomorphological controls using geographically weighted logistic regression. *Geographical Analysis*, **35**(1), 58–82.

Babtie, Brown and Root (2004) *Catchment Geomorphology Action Plan: the River Esk catchment.* Report to Environment Agency, Leeds.

Bracken, L. and Warburton, J. (2005) *Monitoring fine sediment transfer in the River Esk, North York Moors, northern England*. University of Durham, Department of Geography, Report to Environment Agency North-East Region, York.

Branson, J., Hill, C., Hornby, D.D., Newson, M. and Sear, D.A. (2005) *A refined geomorphological and floodplain component: River Habitat Survey (GeoRHS)*. Southampton: Defra/EA R&D Technical Report, SC020024/TR.

Brookes, A. (1995) Challenges and objectives for geomorphology in UK river management. *Earth Surface Processes and Landforms*, **20**(7), 593–610.

Defra/Environment Agency (2003a) *Impact of recent floods on channel morphology and physical habitat using RHS re-survey*. Environment Agency, Bristol, R&D Technical Report W5A-064/TR.

Defra/Environment Agency (2003b) *A refined geomorphological and floodplain component: River Habitat Survey*. GeoData Institute, University of Southampton, Report FD 1921.

Downs, P.W. and Gregory, K.J. (2004) *River channel management. Towards sustainable catchment hydrosystems*. Arnold, London.

Downs, P.W. and Thorne, C.R. (1996) The utility and justification of river reconnaissance surveys. *Transactions of the Institute of British Geographers, New Series*, **21**(3), 455–468.

ECON (1998) *River rehabilitation feasibility study of River Wensum (Norfolk). Phase I*. ECON, University of East Anglia, Report to Environment Agency Anglia Region, Norwich.

ECON (1999) *River rehabilitation feasibility study of River Wensum (Norfolk). Phase II*. ECON, University of East Anglia, Report to Environment Agency Anglia Region, Norwich.

Emery, J.C., Hill, C.T. and Sear, D.A. (2004) *Geomorphological assessment of the River Otter, Devon.* GeoData Institute, University of Southampton, Report UC0672, for Environment Agency, Southwest Region, Exeter.

Environment Agency (1998a) *River geomorphology: a practical guide*. Guidance Note 18, Environment Agency National Centre for Risk Analysis and Options Appraisal, London.

Environment Agency (1998b) *Sediment and gravel transportation in rivers*. A procedure for incorporating geomorphology in river maintenance. Guidance Note 23, Environment Agency National Centre for Risk Analysis and Options Appraisal, London.

Environment Agency (1999) *Waterway bank protection: a guide to erosion assessment and management*. EA, Bristol, R&D Project W5-635.

Environment Agency (2002) *Geomorphological audit of the Glaze Brook*. North West Region Environment Agency, Warrington.

European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council: establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, **L327**, 1–72.

Exeter Enterprises (2005) *Investigations into the use of critical catchment sediment yields for assessing and managing sediment inputs into aquatic ecosystems*. Univeristy of Exeter for English Nature, Contract Report EIT35-05-019.

GeoData Institute. (undated) *River Kennet Fluvial geomorphological assessment: detailed catchment baseline survey*. University of Southampton.

GeoData Institute (2001a) *Caldew Catchment Geomorphological Audit*. University of Southampton, Report UC0475.

GeoData Institute (2001b) *River Swale Geomorphological Audit*. University of Southampton, Report UC0493.

GeoData Institute (2000) *River Ure Geomorphological Audit*. University of Southampton, Report UC446/1.

GeoData Institute (2002) *River Wylye Geomorphological Audit*. University of Southampton, Report UC0526.

GeoData Institute/Newcastle University (2005a) *River Wensum SAC Geomorphological Audit*. English Nature Report UC0762/1.

GeoData Institute/Newcastle University (2005b) *River Nar SSSI Geomorphological Audit*. English Nature Report UC0762/1.

German, S.E. and Hill, C.T. (2002) *River Wharfe Geomorphological Audit*. GeoData Institute, University of Southampton, Report UC0492.

Heritage, G.L. (1999) *Hydraulic evaluation of the proposed rehabilitation of the River Waveney at Diss Golf Course*. Report to Environment Agency, Anglia Region, University of Salford.

Heritage, G.L. and Newson, M.D. (1997) *Geomorphological Audit of the Upper Wharfe*. Newcastle University, Department of Geography, Report to Environment Agency, North-East Region, York.

Heritage, G.L. and Newson, M.D. (1998) *Dynamic assessment of the gravel trap on the River Wharfe upstream of Buckden*. Newcastle University, Department of Geography, Report to Environment Agency, North-East Region, York.

Hey, R.D. and Heritage, G.L. (1993) *Draft guidelines for the design and restoration of flood alleviation schemes*. National Rivers Authority, Bristol, R&D Note 154.

Hydraulics Research (1987) *Morphological effect of river works*. A review of current practice. HR Wallingford, Report SR116.

Hydraulics Research (2004) *River sediments and habitats and the impact of maintenance operations and capital works.* Report on Stage 1. HR Wallingford, R&D Technical Report, FD1920/TR.

Jeffers, J.N.R. (1998) Characterization of river habitats and prediction of habitat features using ordination techniques. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **8**(4), 529–540.

Kilsby, C.G., Large, A.R.G., Newson, M.D., Orr, H.G. and Walsh, C.L. (2006) *Incorporating climate change typologies for the Water Framework Directive.* Environment Agency Science Project Record SC030301, Bristol.

Large, A.R.G. and Newson, M.D. (2005) Hydromorphological quality – a policy template for channel design in river restoration. In Anderson, M.J. (ed.) *Encyclopedia of hydrological sciences*. Wiley, Chichester.

Kondolf, G.M. and Piegay, H. (2003) *Tools in fluvial geomorphology*. Wiley, Chichester.

Nader, P., Smith, B., Jarvie, H., Llewelyn, N., Mathiessen, P., Dawson, H., Scarlett, S. and Hornby, D. (2003) *Siltation on rivers: A review of monitoring techniques*. Conserving Natural 2000 rivers, Conservation Techniques Series, 6 Peterborough: Natural England.

National Rivers Authority (1994a) *Sediment and gravel transportation in rivers, including the use of gravel traps*. NRA, Bristol, R&D Project Record C5/384/2.

National Rivers Authority (1994b) *A procedure for incorporating geomorphology in river maintenance*. NRA, Bristol, Project Record 384.

Newson, M.D. (2000) *Fluvial Audit of the Upper River Deben*. Newcastle University, Department of Geography, Report to Environment Agency, Anglian Region, Ipswich.

Newson, M.D. (2002) Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**, 365–379.

Newson, M.D. (2005) *Ripon FAS: a contribution to the assessment of environmental impacts from fluvial geomorphology*. Newcastle University, School of Geography, Politics and Sociology, Report to Halcrow and Partners, Leeds.

Newson, M.D. (2006) *Desk-based targeting for a Fluvial Audit of the Yorkshire River Derwent*. University of Newcastle upon Tyne, for EA Northeast Region, York.

Newson, M.D. and Bathurst, J.C. (1988) *Sediment movement in gravel-bed rivers*. Seminar Paper 59, Department of Geography, University of Newcastle upon Tyne.

Newson, M.D. and Block, C. (2002a) *Fluvial Audit of the Upper River Stour*. Report to Anglian Region, Environment Agency, University of Newcastle upon Tyne.

Newson, M.D. and Block, C. (2002b) *Fluvial Audit of the River Pant*. Report to Anglian Region, Environment Agency, University of Newcastle upon Tyne.

Newson, M.D. and Clark, M.J. (2008) The sustainable management of restored rivers. In Darby, S.J. and Sear, D.A. (eds) *River restoration: managing the uncertainty in restoring physical habitat*. Wiley, Chichester.

Newson, M.D. and Orr, H.G. (2004) *Tools for applying the EU Habitats Directive for the English River Tweed cSAC: hydromorphological study of the River Till.* Newcastle University for Environment Agency, Northeast Region, Newcastle upon Tyne.

Newson, M.D. and Sear, D.A. (2002) *Rehabilitation of over-widened reaches of the Upper Deben, Suffolk: field survey using the procedures of geomorphological dynamic assessment*. Report to Anglian Region, Environment Agency from University of Newcastle upon Tyne.

Newson, M.D., Pitlick, J. and Sear, D. (2002) Running water: fluvial geomorphology and restoration. In Perrow, M.R. and Davy, A.J. (eds) *Handbook of ecological restoration*, Volume 1. Cambridge University Press, Cambridge, pp. 133–152.

Newson, M.D., Sear, D.A. and Heritage, G.L. (1999) *Rehabilitation of selected sub-reaches of the River Waveney, Anglia Region, Environment Agency: a geomorphological assessment*. Report to Anglia Region, Environment Agency by University of Newcastle upon Tyne.

Newson, M.D., Sear, D.A. and Orr, H.G. (2005) *Sediment inputs to freshwater ecosystems: towards regulatory approaches at the catchment scale; are 'critical yield' philosophies currently practicable?* Newcastle University Report to Exeter Enterprises, Exeter, Devon.

Newson, M.D., Thorne, C.R. and Brookes, A. (2001) The management of gravel-bed rivers in England and Wales: from geomorphological research to strategy and operations. In Mosley, M.P. (ed.) *Gravel-bed rivers V*. New Zealand Hydrological Society, Wellington, pp. 581–606.

Newson, M.D., Hey, R.D., Bathurst, J.C., Brookes, A., Carling, P.A., Petts, G.E. and Sear, D.A. (1997) Case studies in the application of geomorphology to river management. In Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester, pp. 311–363.

Orr, H.G., Block, C. and Newson, M.D. (2000) *Kent catchment geomorphological assessment*. Report to North-west Region, Environment Agency from University of Lancaster.

Orr, H.G., Block, C. and Newson, M.D. (2002) *Fluvial Audit of the River Blackwater*. Report to Environment Agency, Anglian Region, Ipswich.

Orr, H.G., Davies, G., Quinton, J. and Newson, M. (2004) *Bassenthwaite Lake geomorphological assessment, Phase 2.* HYSED, University of Lancaster, Report to EA, Northwest Region, Warrington.

Parsons, H., Walker, J., Scarlet, P. and Hornby, D. (2001) *River Eden RHS and geomorphology evaluation*. North West Region, Environment Agency, Warrington.

Petroski, S. (2006) *Success through failure: the paradox of design*. Princeton University Press, NJ.

RKL-ARUP (1999) *Dynamic assessment of unstable reaches of the Upper Wharfe*. Report to Environment Agency, North-East Region, York.

Scottish Environment Protection Agency (2006) *The Water Environment (Controlled Activities) (Scotland) Regulations 2005*. SEPA, Edinburgh.

Sear, D.A. and Newson, M.D. (1994) *Sediment and gravel transportation in rivers, including the use of gravel traps*. National Rivers Authority, Bristol, R&D Note 315.

Sear, D.A. and Newson, M.D. (2003) Environmental change in river channels: a neglected element. Towards geomorphological typologies, standards and monitoring. *Science of the Total Environment*, **310**(1–3), 17–23.

Sear, D.A. and Newson, M.D. (2004) The hydraulic impact and performance of a lowland rehabilitation scheme based on pool–riffle installation: the River Waveney, Scole, Suffolk, UK. *River Research and Applications*, **20**(7), 847–863.

Sear D.A., Hill, C.T. and Downes, R.H.E. (2008) *Geomorphological assessment of riverine SSSIs for the strategic planning of physical restoration*. Natural England, Sheffield, Research Report NERR013.

Sear, D.A., Newson, M.D. and Brookes, A. (1995) Sediment-related river maintenance: the role of fluvial geomorphology. *Earth Surface Processes and Landforms*, **20**(7), 629–647.

Sear, D.A., Newson, M.D. and Thorne, C.L. (2003) *Guidebook of applied fluvial geomorphology*. Defra/Environment Agency, London, R&D Technical Report FD1914.

Sear, D.A., Hill, C.T., Newson, M.D., Emery, J. and Branson, J. (2009) Applying geomorphology for assessing the physical condition of riverine habitats in support of the Habitats Directive. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **19**(5), 506–519.

Thorne, C.R., Allen, R.G. and Simon, A. (1996) Geomorphological river channel reconnaissance for river analysis, engineering and management. *Transactions of the Institute of British Geographers, New Series*, **21**, 469–483.

Thorne, C.R., Hey, R.D. and Newson, M.D. (eds) (1997) *Applied fluvial geomorphology for river engineering and management*. Wiley, Chichester.

UKTAG (2006) *UK Environmental Standards and Conditions (Phase 1)*. UK Technical Advisory Group on the Water Framework Directive, Final Report SR1-2006.

United Utilities (2006) *Sustainable Catchment Management Project* (website: www.unitedutilities.com/?OBH=3226).

Walker, J.R. (2000) *A Fluvial Audit procedure for use in the Environment Agency's Flood Defence function*. Unpublished MPhil thesis, University of Southampton.

Walker, J., Diamond, M. and Naura, M. (2002) The development of Physical Quality Objectives for rivers in England and Wales. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**(4), 381–390.

Walker, J., Gibson, J. and Brown, D. (2007) Selecting fluvial geomorphological methods for river management including catchment scale restoration within the Environment Agency of England and Wales. *International Journal of River Basin Management*, **5**(2), 131–141.

Wallerstein, N. and Thorne, C. (2005) *Sediment Impact Assessment Method UK (SIAM-UK)*. Flood Risk Management Research Consortium, University of Nottingham (http://www.floodrisk.org.uk).

Wilby, R.L., Orr, H.G., Hedger, M., Forrow, D. and Blackmore, M. (2006) Risks posed by climate change to delivery of Water Framework Directive objectives in the UK. *Environment International*, **32**(8), 1043–1055.

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