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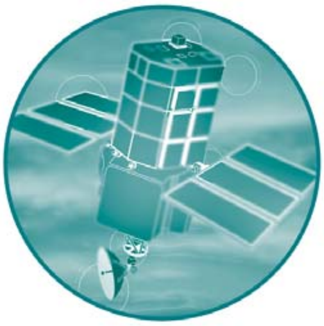

Guidebook of Applied Fluvial Geomorphology

R&D Technical Report FD1914

Department for Environment
Food and Rural Affairs

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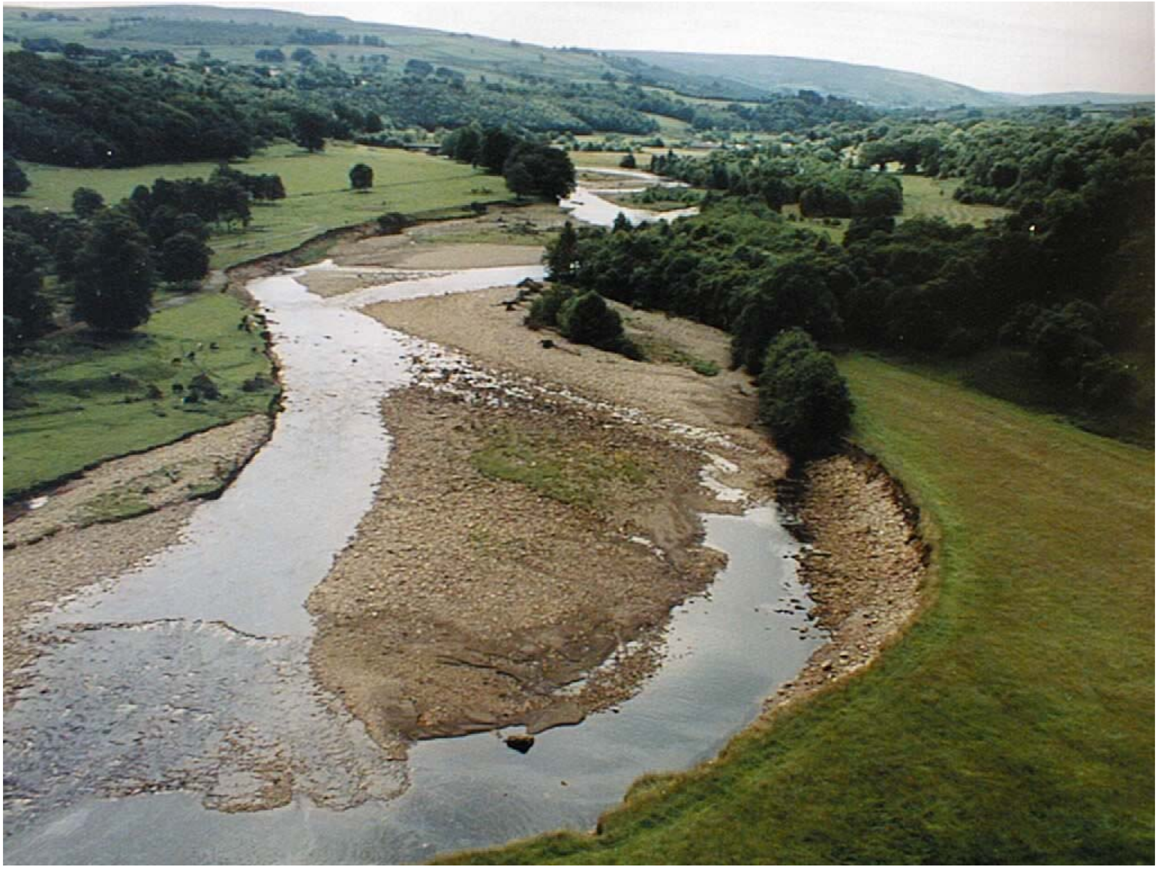

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This document provides guidance to Defra and Environment Agency staff, research contractors and external agencies on the use of fluvial geomorphology in river management within the UK.

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PREFACE

Purpose of the Guidebook

The primary purpose of this guidebook is to collate and summarise the results of geomorphological R&D projects performed for the Environment Agency and its predecessor the NRA during the 1990s. 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 practise now forms a regular part of projects involving flood protection, 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 EU 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 or management. The aims of the guidebook are to:

- Foster a general interest in and understanding of geomorphology in the river environment;

- Develop a realisation of the significance of considering geomorphological processes in river management applications;

- Give an overview of the different methods of incorporating geomorphological science into river engineering and management;

- Provide guidance on when to seek expert geomorphological advice and where to find it.

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 because material of this type cannot be found in the R&D performed during the 1990s that forms the basis for the book. However, recent advances in academic thought and professional practise mean that it would now (June 2003) be possible to produce a handbook of methods and techniques for use by scientists and engineers who have been trained in geomorphology. It is recommended that Defra and the Environment Agency consider commissioning the production of such a Handbook for use alongside this guide.

Basis for the Guidebook

The basis of the guidebook is a series of R&D project records, reports, and unpublished manuscripts produced during the 1990s. The sources used herein are listed in an inventory at the end of the Preface. In selecting material for inclusion in the guidebook, the authors not only sought advice from relevant individuals, but also drew on the results of information gathered as part of training in geomorphology provided by the Environment Agency to its staff and lead by the University of Newcastle. During training, a course evaluation form is administered. The questions on the form are not only comprehensive in appraising training quality, but also seek trainees' opinions concerning their professional needs in Fluvial Geomorphology. Responses to questions such as:

1. What was the most useful new material presented?
2. How can you apply Fluvial Geomorphology in your professional role?
3. What extra training do you need to apply the training more effectively?

have proven particularly relevant and useful in the preparation of this Guidebook. The responses of trainees are illustrated in Figures 1-3.

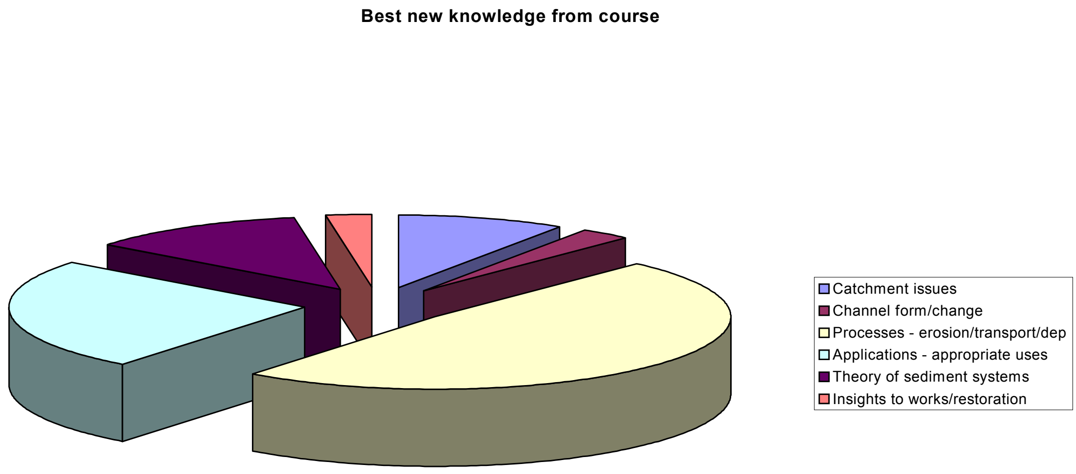

Figure 1 Geomorphological Knowledge

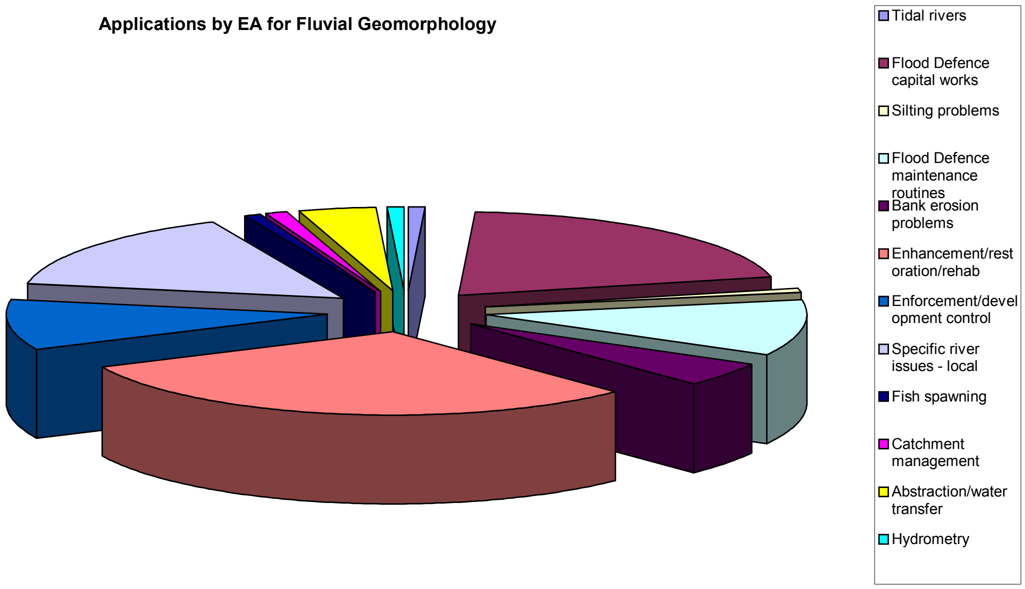

Figure 2 Applications of Geomorphology

Figure 1 shows that the most appealing element of training in Fluvial Geomorphology was the insight it provided into river processes. Almost half (49%) of those responding ranked this as the best new knowledge gained from training. A quarter of all respondents also mentioned the practical (field) aspects of geomorphology - apparently of most benefit as an extension to the normal field orientation of flood defence, conservation and fisheries staff. Others mentioned the importance of theory in providing scientific credibility to geomorphology, together with operation of geomorphology at the catchment scale and over long timescales.

There were more responses to questions concerned with applications, probably because during training specific professional problems are most easily 'mapped' onto the information provided (Figure 2). A class leading 41% of applications concern flood control (combining capital works and channel maintenance), largely thanks to the existence of internal consultation procedures within the Environment Agency that prescribe input from conservation and recreation staff. The recent trend towards sustainable development in river management has, perhaps, led to appearance in this category of applications in river 'enhancement', 'rehabilitation' and 'restoration' (30%). A significant number of respondents (15%) mentioned specific rivers, without citing a generic problem or application. This reflects the fact that real problems have an immediacy seldom matched by generic ones. Other problems referred to directly include erosion, siltation, and abstraction/water transfer and fishery management.

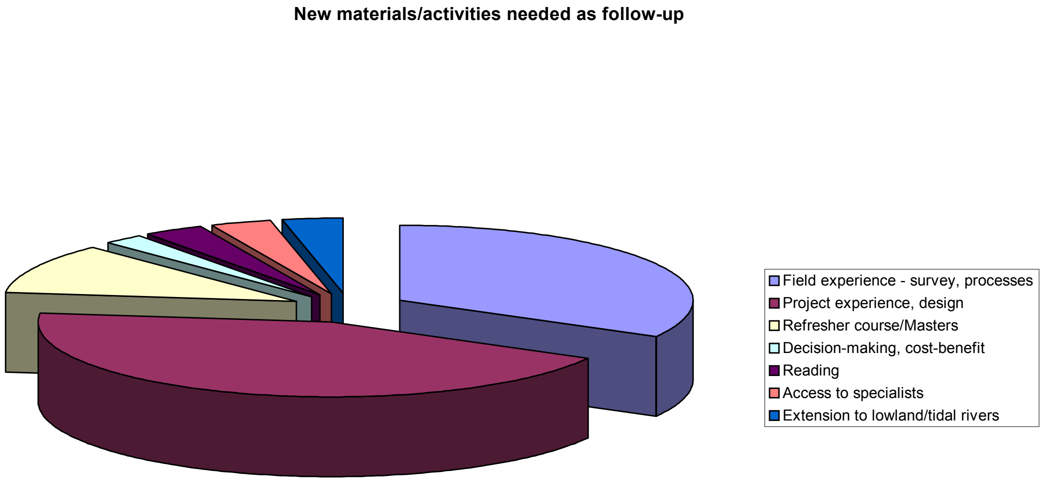

Figure 3 New Materials Required

Perhaps the most significant grouping of answers occurs in the category ‘new materials required’, which was answered with only slightly lower frequency than 'applications' (Figure 3). A massive 77% of respondents refer to the *practical nature* of Fluvial Geomorphology, either demanding further field training in techniques (33%), or project experience in the incorporation of geomorphological principles (44%). This reflects both the inherent nature of the subject and also a tradition of river management in the UK that relies heavily on empiricism and technology transfer based on field case studies. Publication of a handbook could partly address this desire, provided that the emphasis is placed on both processes ('best new knowledge') and case studies ('knowledge needed'). A total of 20% of respondents ask for various means of access to specialist advice - including topics such as confidence limits on predictions, cost-benefit analysis, including fluvial sediments etc. A significant minority requested information specifically relevant to lowland rivers, chalk rivers and tidal rivers – reflecting the regionally-specific nature of many problems in England and Wales.

In drawing together material from R&D Reports produced in the 1990s, the authors have made reference to the opinions of trainees as expressed in the data plotted in Figures 1-3 by:

- Concentrating content on channel form and change, sediment systems, catchment issues and example applications relevant to (and within the context of) the work of the Defra and the Environment Agency;

- Using examples drawn from flood control projects, bank erosion problems, rehabilitation/restoration schemes and a range of site-specific applications of geomorphology;

- Drawing largely on experience gained in the 1990s through project-related fieldwork, analysis and input to the design process.

It is also relevant that trainees were questioned concerning their role within Environment Agency. A total of 142 useable returns have been analysed (18 more did not give a functional identity). Of the questionnaires analysed, 42% were completed by Flood Defence staff (including Development Control Officers), 38% by Fisheries, Conservation, Ecology and Recreation staff and the remaining 20% by staff from Hydrometry, Environmental Assessment, Landscape Architecture and Water Quality.

The proportional division of potential 'end users' has been taken into account in preparing this guidebook, with flood defence and environmental applications of geomorphological knowledge and techniques being stressed. It was also decided to include existing materials used to support training. These materials are outlined in Appendix 6.2 and recorded on a CD-ROM that may be found inside the back cover.

A draft copy of the manuscript for this guidebook was reviewed by a panel of experts selected by the research leader of the Defra/EA Processes Theme. The content benefitted significantly from revisions and additions made in response to the panel's comments. We therefore warmly acknowledge the work of Helen Dangerfield, Karen Hills, Glenn Maas, David Ramsbottom, Mike Thorn, Jim Walker and other anonymous reviewers in reading and commenting on the draft guidebook.

Malcolm Newson
David Sear
Colin Thorne

June 2003

INVENTORY OF SOURCES USED IN PREPARING THE GUIDEBOOK

NRA/Agency R&D Reports, Notes and Related Documents

NRA 1991 *Sediment & gravel transport in rivers including the use of gravel traps*, Project Record, C5.02, prepared by M D Newson & D A Sear, NRA Bristol, 100p.

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1. FLUVIAL GEOMORPHOLOGY: ITS BASIS AND METHODS

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, 1996). 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 & 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, landuse and land management changes, coupled to more efficient drainage networks may have increased system sensitivity to environmental change (Robinson, 1990; Newson & Leeks, 1987). 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 'hydromorphic condition' (the physical outcome of the inter-relationship 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), becoming an important measure both of river management practice and system resilience to external environmental change (Raven *et al* 1998, Newson and Sear 1998). Fluvial geomorphology is a key to understanding long-term river and floodplain processes of change; it is making an increasing contribution to environmental management of river basins and at the coast.

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. 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 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 focussing 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 permit 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. Fluvial geomorphology draws on inputs from hydraulics, ecology and geology. It provides an explanation for the creation and dynamics of the physical habitat concerns of ecology/biology and nature conservation while providing explanations for the channel maintenance and channel instability concerns of flood protection.

The term “morphology” is also used in UK river management. Morphology refers to the description of the features and form of the river channel (and increasingly the floodplain). Morphology has significance to conservation and flood protection 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. For example, an input to channel design that talks about “morphology” refers only to the description of features and river channel shape; it does not mean that the channel will have been designed with regard to sediment transport and channel stability.

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:

1) the extent of modification to the flow regime
2) the extent to which water flow, sediment transport and the migration of biota are impacted by artificial barriers
3) the extent to which the morphology of the river channel has been modified, including constraints to the free movement of a river across it’s floodplain.

Process and form information exists within the broad defining elements and clearly Fluvial Geomorphology will be central both to the definition of hydromorphology, and to the design and implementation of emerging Pan-European monitoring methods (Raven *et al* 2002, Newson 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 to have 1) 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 2) good field experience of interpreting river and floodplain geomorphology. 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 Masters degree in Geography (Physical Geography) or Environmental Science. 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 within the Environment Agency, though tends to be organised at the Area level. 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 & training should fall within normal commercial ranges (e.g. £100 - £800 per diem).

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 (Ph.D) with extensive field experience and track record of working with river management agencies.	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 (Ph.D) with no or limited field experience and no/limited experience of working with river management agencies.	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 / E.S. with Masters training in fluvial geomorphology/river management. No/limited field experience. No/limited experience of working with river management agencies.	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.
Un-trained 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.

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).

Since the early 1990's, applied fluvial geomorphology has risen up the operational and policy agendas of river management authorities (Sear *et al.* 1995, Brookes & Shields 1996). 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 upsurge 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. 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.

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.

Figure 1.1 When to Consider Geomorphology in River Management

At its core, the fundamental philosophy of applied fluvial geomorphology, is to understand, through good 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. Firstly, the localised problem of the flooding itself, the cause of which may be a low point in a flood embankment. Secondly, 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 sustainable. The same approach applies to problems arising from processes of fluvial sediment transport only that here, river managers are only just beginning to appreciate that you need additional specialist input to identify the cause of the problem – Fluvial Geomorphology. 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 in the UK that would benefit from the application of fluvial geomorphology:

1. Problems of excessive levels of fine sediments or pollutant/toxin association with fine sediments (including metaliferous mine waste);
2. Channel instability – river maintenance, habitat change (pool infilling), loss or gain of conveyance, land/infrastructure loss or damage;
3. Design and strategic planning of river rehabilitation, flood channels, and river maintenance and flood protection programmes;
4. 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:

1) Sedimentation of river beds, in particular spawning gravels;
2) Contamination of floodplain soils through overbank sedimentation and floodplain evolution;
3) Influence of channel adjustment on flood conveyance;
4) Bank erosion management;
5) Desilting/shoal removal arising from deposition of sediments that increase flood frequency;
6) Rehabilitation of rivers and floodplains for habitat improvement;
7) Design of environmentally acceptable flood / drainage channels;
8) Strategic assessment of catchment issues including Catchment Flood Management Planning, cSAC monitoring and designation, designation of conservation status;
9) Environmental Impact Assessment.

The forgoing lists, make clear that fluvial geomorphology contributes naturally to issues of flood defence and conservation. 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 how any proposed work / policy may impact the form, function and sediment system of a river channel and surrounding catchment should be among the issues considered.

1.5 Costs and Benefits of using fluvial geomorphology in river management

Previous NRA and EA Research & Development has revealed that problems associated with erosion and deposition in England & Wales are more extensive and expensive than previously thought (EA 1998). Yet little specific cost information is available at a national level. At the same time the number of projects that have used river geomorphology is increasing. A review of over 40 projects in which geomorphology has been used 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 Defence 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 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 river environment and those seeking to manage them.

Before moving further into the detail of geomorphology as a science and source of useful information and assistance to 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, whilst 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!

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 & 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 (eg. 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 & 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 (FD Capital schemes)	Environment Agency responsibilities and works 1997 Flood Prevention & 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 stores 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.

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 using fluvial geomorphology (EA 1998). This can be achieved through efficiently targeting best practice solutions based on identifying the cause(s) of erosion / siltation problems not commonly considered by conventional practice. 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 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 river geomorphology at a project level is not cost prohibitive, whilst the potential benefits though sometimes intangible, are considerable.

1.6 Performance Testing Fluvial Geomorphology

Thirty-eight projects were assessed from seven EA regions, and undertaken by six different, independent consultants. Projects included assessments of bank erosion, channel siltation, river restoration and river instability. All projects had common methodological approaches; 1) assessment of the cause of the problem first, and 2) design of solutions second. Performance testing of these projects revealed the following:

- In 26% of the projects assessed, no intervention was the recommended outcome of the geomorphological investigation;
- Construction costs are not significantly increased and may be decreased in cases where maintenance is reduced, or harder protection methods are dispensed with early on in the project lifetime;
- Design costs may be increased because of the (commonly) more complex designs associated with geomorphological input;
- Although early adjustment is expected, schemes that had experienced bankfull or higher discharges had remained stable or had not significantly varied from the original project concept;

- In all cases, geomorphological advice sought to keep or enhance key channel features so that environmental gains are also included in the benefits;

- For those schemes where information on maintenance was available, no additional maintenance had been required, and the professional opinion of relevant EA Flood Defence staff was that maintenance costs had been saved.

One of the main problems is that of managing the geomorphological advice through to implementation on the ground. This, in part, is the result of the current role of geomorphology that often occurs only at the design or assessment stage of a project. Site conditions, or a gap of in some cases, three or more years between advice and implementation, may result in unsupervised modifications. Without trained staff, the implications of this action are not apparent, and the outcome may not be as beneficial as when first proposed.

The assessment of current geomorphological practice in UK river management reveals that geomorphology provides management information in four key areas:

• **Assessment**	Establishing causes and effects in Flood Defence, Fisheries & Conservation projects.
• **Decision Support**	Strategic decisions when and when not to intervene Operational guidance as to where and what intervention to adopt.
• **Design**	Mainly used on enhancement and restoration projects. Advice on type and dimensions of channel morphology, sedimentology & nature of likely adjustments.
• **Post Project Appraisal**	For a range of Flood Defence, Water Resources and FRCN operations including geomorphological inputs.

At a catchment level, many areas of financial expenditure arise from the action or modification of geomorphological processes. Costs include tangibles such as loss of land or structures through erosion of river banks, or intangibles such as the loss of aquatic habitat. Benefits of including advice from fluvial geomorphology include:

- prediction of impacts
- efficient targeting of solutions
- improved understanding of the problems to be addressed, leading to
- more efficient use of resources and more sustainable solutions.

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 6.0 provides examples of how geomorphology has been applied to real river management issues.

1.7 Geomorphology and sustainability

Whilst there is little agreement on reaching a unified definition of sustainable development the concept stresses an understanding of natural, ecosystem processes and their incorporation in practical management ("working with nature"). The following dimension 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.

1.8 What are Geomorphological timescales?

One of the least understood aspects of fluvial geomorphology practice is the apparent obsession with longer timescales. Why this is so remains unclear, since anyone involved in flood prevention 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. One of the main processes that introduce the need to consider longer timescales in geomorphological studies is 1) the storage of sediment in the catchment and channel network and 2) 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 re-working of the sediments evacuated from these valleys that occurs within the main trunk streams (Macklin & Rumsby 1994).

The movement of sediment across the landscape is often punctuated by periods of storage. For example fine sediments are often stored in floodplain soils, while coarse sediments may be stored in different types of in-channel deposit (Figure 1.2). As a result, the time taken for a release of sediment from the land surface to be detectable within the river network, may vary according to the intervening opportunities for storage. This has the affect of increasing the timescales necessary for the understanding of the sediment system, from single events (a flood, landslip etc.) up to 1000's 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 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.

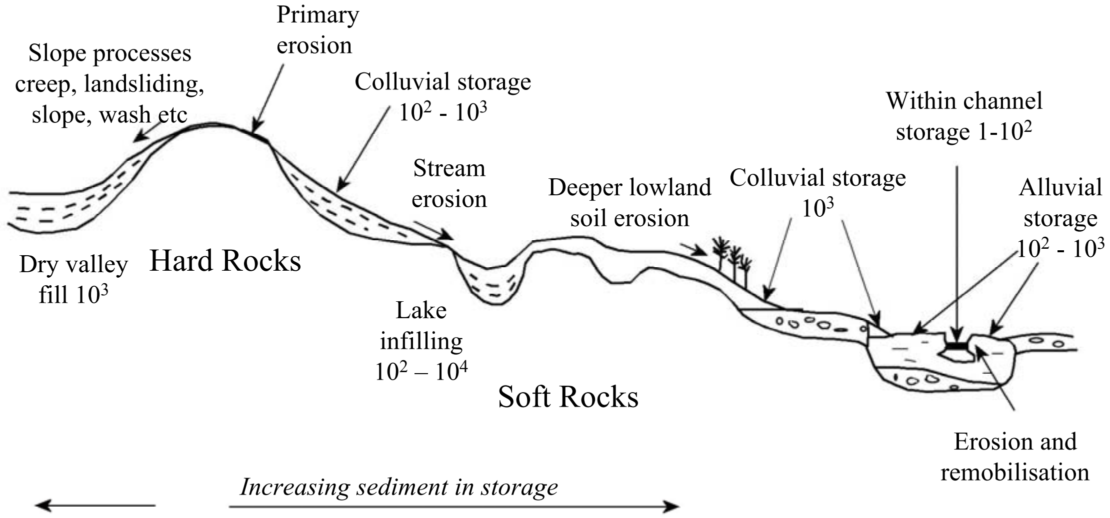


Figure 1.2 Indicative Sediment storage time in the river landscape (after Brown, 1987)

The problem with 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. Significantly, as one begins to view a river system from increasingly longer timescales, there is a shift in emphasis from local events to catchment scale change. Here the significance of a single event reduces as the timescale of investigation extends. Leys (1998) provides a useful example based on the cut-off of a single meander bend (Figure 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. Figure 1.4, links the spatial and temporal scales of river channel evolution with the development of certain river features (bedforms, bars, planform etc.).

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 re-profiling 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	This is part of a general trend, but does it have a

		width over past decade through active bank erosion processes	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 Photo's.	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.

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

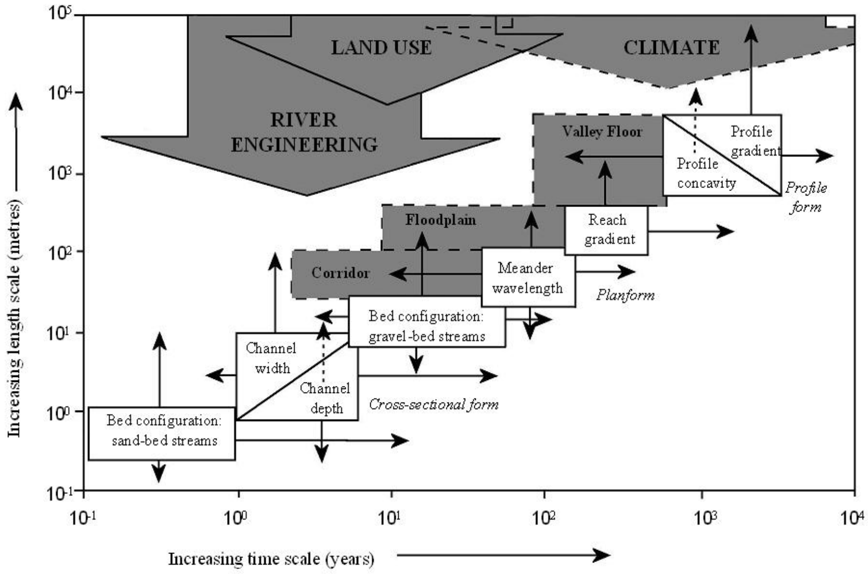


Figure 1.4 Time and spatial scales in the formation of UK River landscapes, (after Newson & Sear 1993).

It also shows how the time and spatial scales of certain catchment management and environmental drivers relate to the development of river morphology. 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 what semi-natural morphology exists today is largely relict, and owes much to the role of woody debris. Restoration of features that were possibly uncommon, or randomly distributed in the system may provide abundant habitat for certain species, but does not restore the full ecological diversity or physical functioning to the river system.

1.8.1 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 (Figure 1.5). 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 features 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 (Figure 1.5).

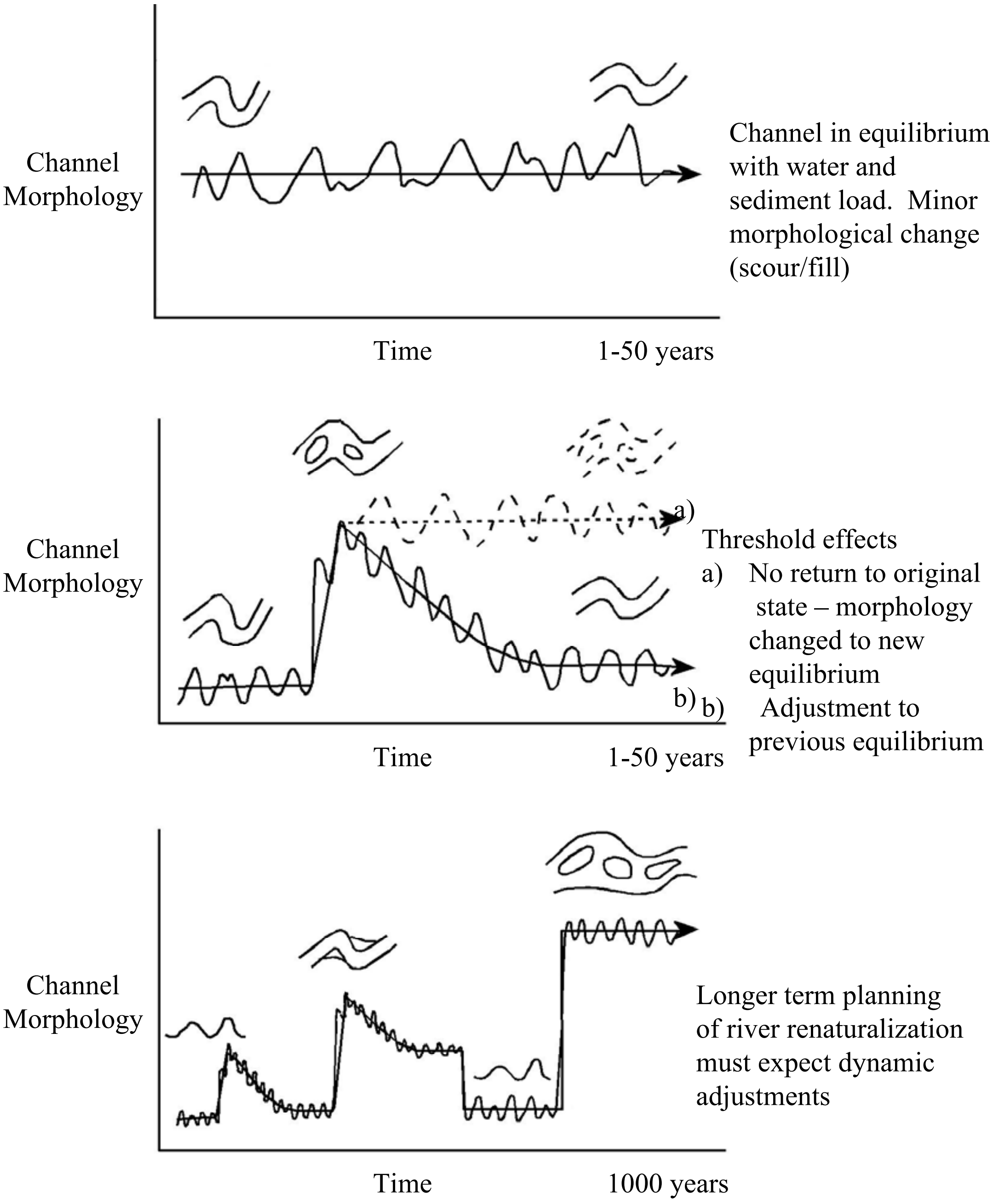


Figure 1.5 The concept of equilibrium in Fluvial Geomorphology (after Sear 1996).

Threshold behaviour in river channels is well documented (Newson 1992) and provides the river manager with potentially difficult scenarios. Rivers close to a threshold state are said to be responsive; they may exhibit quite 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. An example of this may be drawn from the reported response of the Dorback Burn, Scotland (Werrity 1984). A high magnitude flood event arising from intense convective rainfall, generated a change in sediment transport regime in this steep upland watercourse. The resulting morphological response was to switch channel form from single thread meandering channel to a braided channel overnight. However, within 1 year, the channel had returned to a single threaded morphology (Figure 1.6). This landform was responsive in that it changed rapidly, but robust in that it returned back to its former state.

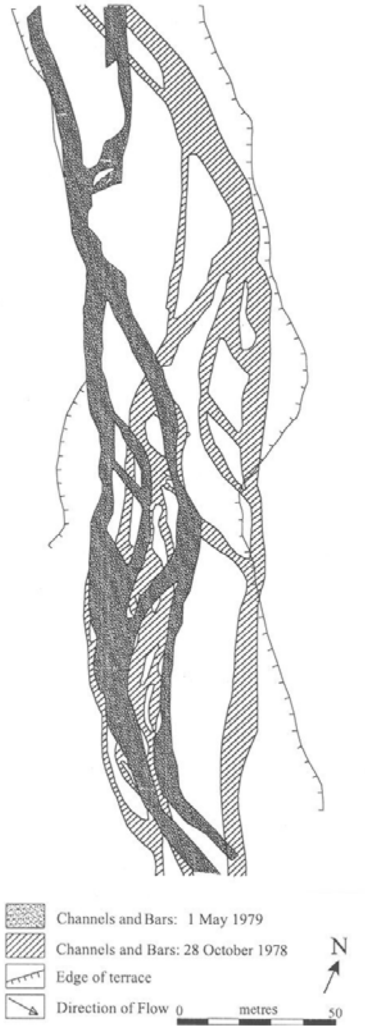


Figure 1.6 Channel planform change following extreme flooding in an upland river; Dorback Burn, Scotland (Werrity, 1984).

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, 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 has a significant impact on the development of ecological communities (Petts & Amoros 1996). 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. 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 impact the ecology.

1.9 What are Geomorphological data?

Many people assume that Geomorphology requires data that is 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 data sets. Where the data needs differ is usually in the demand for information on sediments. Geomorphology differs too in terms of its focus on the arrangement of features/materials etc. within the river network or reach compared with other disciplines. 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 (e.g. RHS, RIVPACS, Flood Defence Asset Surveys, etc.), are concerned with the defining the status of features at fixed locations, not the sequence of movement of those features (dynamics) over time.

Most geomorphological studies require data on three areas of information:

- 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.

- 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.

- The processes associated with the functioning of the fluvial system – these may include slope processes (for example 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 (Figure 1.7). 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 problems 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, 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 qualitative, 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 and easy to monitor, and is essential in order to validate expensive catchment management programmes aimed at reducing fine sediment yields.

Figure 1.7 Types and scales of data used in Fluvial Geomorphological Asssesment (Sear *et al.* 1995)

1.9.1 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. 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.

Much morphological data is derived from existing topographic surveys, aerial photography and increasingly remote sensed data such as LiDaR and Multispectral imagery mounted on aircraft or satellites. 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). In the case of existing topographic maps and air photographs, these provide the opportunity to record changes in channel morphology (for example, planform, channel width, meander dimensions) over periods of time up to 200 years in some cases. Figure 1.8 illustrates how the use of historical map overlay can provide information on the changing 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.

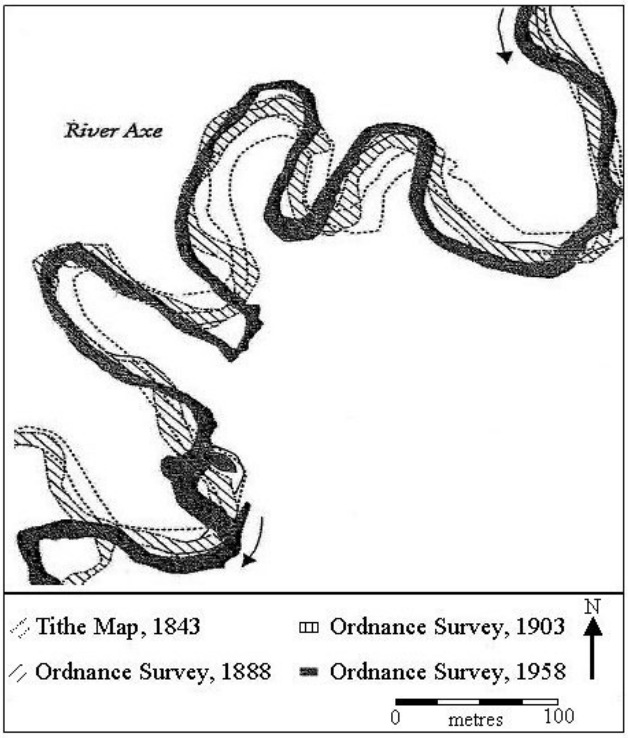


Figure 1.8 Information on historical river planform change derived from overlaying large scale maps (Hooke & Redmond, 1992).

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. Downward *et al.* (1994) and Gurnell (1997) have shown that of those errors that can be quantified, the resulting channel change must be larger than 10m 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 +/- 4m, which for smaller channels may represent a whole channel width.

An increasingly valuable source of information for geomorphology lies in the interpretation of remotely sensed data flown for the Agency 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. The topographic data recorded from LiDar can be used when processed (a non-trivial job) 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).

One of the most important data sources for morphological information is the field survey. Field reconnaissance is a key tool for geomorphology. Recording the spatial arrangement (both downstream, across the valley floor and vertically), provides the geomorphologist with a data set 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 features (Figure 1.9a), and the geomorphological map (Figure 1.9b). The former often simplifies the detail, but covers scales up to the river network, whilst 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.

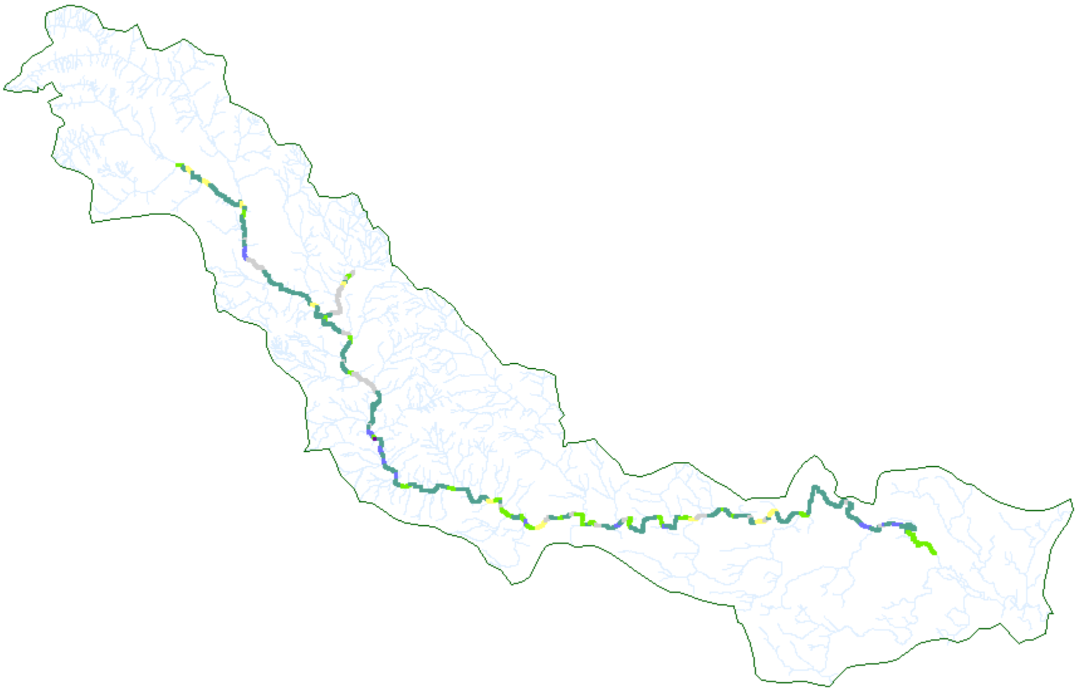


Figure 1.9a Example of fluvial geomorphologial data capture in a catchment scale survey (GeoData, 2000)

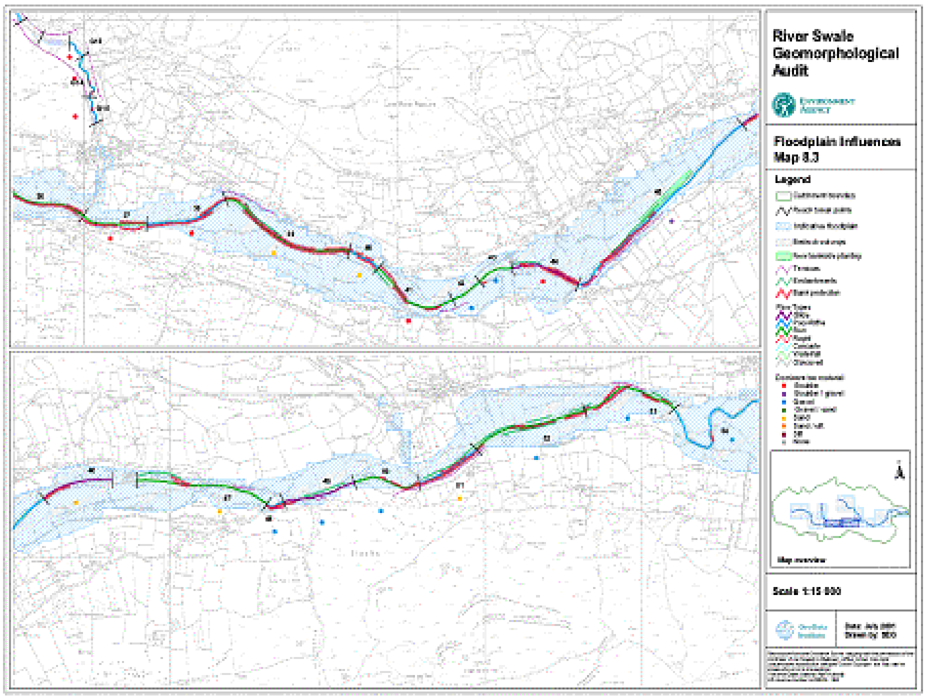


Figure 1.9b Example of fluvial geomorphological data capture at the reach scale (GeoData 2001)

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 takes 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 re-survey 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. The accuracy of this data depends on the ability to re-locate cross-sections, and the degree of change relative to the measurement errors in the survey technique.

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 general, most cross-sections are surveyed at regular intervals 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 water surface slopes are unavailable.

<u>Case Study</u>: 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 data sets used together with the information they provided are given in Table 1.3.

The interpretation of this 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 (Figure 1.10).

Table 1.3 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

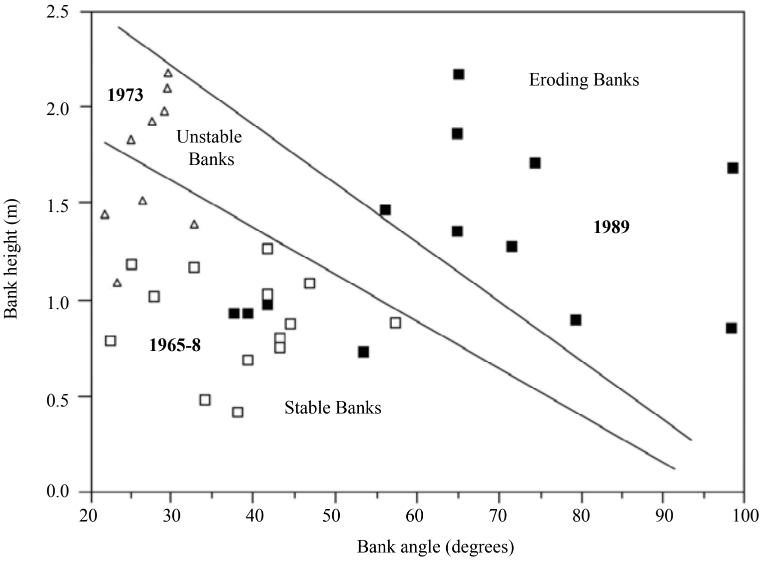


Figure 1.10 Bank stability assessment for a bank erosion problem. Data is based on the analysis of cross-sections supported by ground-truthing through field reconnaissance to identify eroding and stable bank profiles; River Sence, Leicestershire (Sear *et al.* 1995).

1.9.2 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. 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 collected except where this is the primary focus of a project (for example 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 1.4).

Table 1.4 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). Bore Hole 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.

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. 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 (Figure 1.11). Valuable historical 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. These may be relevant where river managers are attempting to recreate past river and floodplain environments.

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.

Figure 1.11 An example of channel incision revealed by exposure of a former river bed level in the bank material. Incision in this instance was a result of a land drainage scheme.

1.9.3 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 inferred from field observation of bed and bank features and through interpretation of historical channel change. Process information draws in the data sets discussed in the preceding sections. Typical geomorphological process interpretation might include the following:

- Identification of the cause of bank erosion i.e. fluvial scour, geotechnical instability or weathering;
- Identification of the role of vertical downcutting (incision) in the instability of a river reach or undermining of a structure;
- Correct interpretation of the process of lateral river movement (type of meander migration);
- Classification of the river network into sediment storage, sediment supply and sediment transfer reaches;
- Interpretation of the historical behaviour of a river and floodplain system over timescales up to 1000's of years;
- Identification of the role of past management vs. natural adjustment processes in the creation of habitat and channel morphology;
- Identifying the role of long-term vs. short-term river processes in the creation of protected river habitat.

Interpretation of geomorphological processes requires a trained field geomorphologist. Further information on the qualifications appropriate to performing different components of a geomorphological investigation may be found in Chapter 4, section 4.6.1a).

1.9.4 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 is 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. This situation is becoming eased by the widespread availability of River Habitat Survey data that can provide a starting point in some sediment management problems. 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 seen in terms of static features – the physical habitat elements, whereas in Flood Defence 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.

1.10 Procedures for the collection and interpretation of geomorphological data

This section introduces the range of survey procedures developed under the R&D programme of the National Rivers Authority, Environment Agency and Scottish National Heritage. Methodological details on each approach can be found in Chapter 4, with examples of the application of the methods in Chapter 6. While practice in applied geomorphology has progressed to the point that 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 somewhat 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. For example, the design of an environmentally aligned channel will require a different level of detail in the recording of channel sediments and the estimation of sediment flux, than a baseline survey in support of strategic catchment management planning, e.g. Catchment Flood Management Planning. Typically, a geomorphological project will include some of the following elements:

- Desk-study to collate historical/ documentary evidence on river channel change, land management and channel management practices, hydrology, water quality and geomorphological datasets (e.g. River Corridor Surveys, River habitat Surveys, Geomophological Surveys, etc.);
- Field Reconnaissance to audit the current river system in terms of materials, forms and processes;

- 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;
- Quantitative measures of morphological change using combinations of 1) & 2);
- Interpretation of the geomorphological functioning of the river/reach;
- Detailed channel design incorporating sediment transport issues;
- Post-project appraisal of existing works in terms of channel stability, appropriateness of channel dimensions and morphology, and sediment conveyance.

Ideally, a geomorphological study should include all of them.

Methodologies appropriate to these elements have been developed through regional and national Research & Development programmes of the Environment Agency (formerly National Rivers Authority) of England and Wales (EA 1998) and, in Scotland, through Scottish Natural Heritage (Leys 1998). In addition, there has been considerable *ad hoc* input from academic and professional geomorphologists working as consultants on river management projects. In addition to these UK-based methodologies, there are also a number of 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), and the River Styles © classification system developed for the New South Wales water management agencies (Brierley & Fryirs 2000). However, though interesting methods in themselves, application of overseas methods outside the strict physiographic environments in which they were developed should be treated with extreme 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 and SNH (Table 1.4). The different methods were synthesised into a single set of procedures (EA 1998) and 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 (EA 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 1.5. 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 report.

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 (DCBS) 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 4.1.2 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 Catchment Baseline Survey 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. This data is integrated with information on historical channel change and channel 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 Geomorphological Assessment (GA) combines DCBS 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 Geomorphological Assessment 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.

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 bolt-on methodology to the standard RHS has further improved the level of geomorphological data available through this approach (Walker 1998). GeoRHS data is suitable, when undertaken “back-to-back”, for Detailed Catchment Baseline Survey. RHS data is standardised and collected within a standard 500m length. 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.

The first reach specific procedure is the Geomorphological Dynamics Assessment (GDA). This procedure is commissioned in order to identify the processes and treatments necessary to manage bank erosion at a reach or site (see Chapter 4, section 4.1.5 for details). It can also be used to gain understanding of the sediment transport implications of existing channel management activity, or to assist in the design of river maintenance programmes where removal of sediment is a problem. GDA is often used in conjunction with hydraulic modelling and sediment transport modelling, and requires professional geomorphological expertise. The GDA process should be conducted in close collaboration with ecological and engineering specialists.

In the GAP framework, if stable channel design or restoration is required, the GDA may then include an Environmental Channel Design (ECD). This will require the same level of input as a GDA but is focused on designing channel dimensions, planform and morphology in support of river rehabilitation or flood protection. It is based on the concept of hydraulic geometry (linking formative discharge to stable channel dimensions), and draws on the results of laboratory and field research output contained within the specialist literature in this field. ECD should consider the inputs of sediment to a project reach (Supply Reach), the routing of sediment through the (Project Reach) and the demands of those reaches downstream of the project (Demand Reach) (Soar 2000, Soar and Thorne 2001). Unless specified otherwise, the basis for ECD is to preserve the continuity of sediment transport through a project reach and, hence, maintain the dynamic stability of the channel design. However, there may be times when a reach is required to export or trap sediment, in which case ECD would focus on the most appropriate design to encompass these requirements. Geomorphologists utilising the ECD approach should work in close collaboration with ecological and engineering specialists.

The final component in the GAP is the Geomorphological Post-Project Appraisal (GPPA). The approach draws on standard Environmental Impact Assessment procedures and is based around a “Compliance Audit” and a “Performance Audit” of the river management scheme (for further details see Chapter 4, section 4.1.6). The compliance audit seeks to establish whether a scheme was installed as designed while the performance audit evaluates the success of the scheme in terms of the features and dimensions of the channel. It does not as currently stands, offer any interpretation of processes. The output of the GPPA is a statement of a scheme Performance and Compliance, together with recommended solutions to mitigate any difference from the original design (Skinner 1999, EA 2000).

The value of GPPA has been shown by Briggs (1999) who undertook an assessment of 20 river restoration schemes within the UK and Europe funded by the Environment Agency. This study concluded that in most cases, some form of geomorphological response had occurred, leading in particular, to downstream impacts on river channel geomorphology. The results of this work also highlighted the inadequacies of existing RHS, CBS and “Rosgen” methods for river evaluation when applied to the post project appraisal of typical UK and NW European river types. The study recommended that a more detailed assessment procedure be used, combining Fluvial Audit and GDA. Furthermore these should be undertaken on an upstream “Control” reach and an “Impact” reach immediately downstream of the project reach.

At present many geomorphological assessments concern Land Drainage Consent applications. No formal tools exist to support this particular use of the GA and GAP approaches. However, the basis of the wider catchment scale surveys is that they should be able to provide information to support the assessment of such consenting. Some training and experience in field geomorphology is required in order to be able to assess a Land Drainage Consent – for example for bank erosion. A recommendation may be made to undertake a more detailed geomorphological assessment. For example, in the Welsh Region of the EA, the high frequency of land drainage consent applications for bank protection on the Afon Dyfi, promoted a detailed investigation of bank erosion processes and the formulation of a management plan for the whole main channel network (German, 2000) before further consents were permitted.

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 professional. 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.

Where further advice on fluvial geomorphology, applications and services is required, interested parties may find the points of contact listed in Appendix 1.1 useful. The list is not comprehensive or inclusive, but may assist interested parties in obtaining advice.

Appendix 1.1 Points of contact for further information on fluvial geomorphology

Organisation	Individual	Office	Email
Environment Agency	Jim Walker	NW Region Richard Fairclough House Warrington	Jim.walker@environment-agency.gov.uk
Environment Agency	Glen Maas	NW Region Richard Fairclough House Warrington	Glenn.maas@environment-agency.gov.uk
SEPA	David Corbelli	Edinburgh	www.sepa.gov.uk
Scottish Natural Heritage	Kath Leys	Edinburgh	Kath.leys@snh.gov.uk
Southampton University	David Sear	Dept. of Geography	d.sear@soton.ac.uk
Newcastle University	Malcolm Newson	School of Social Science	m.d.newson@ncl.ac.uk
Nottingham University	Colin Thorne	School of Geography	Colin.thorne@nottingham.ac.uk
Stirling University	David Gilvear	Environmental Science	DJG1@stir.ac.uk
Lancaster University	Harriet Orr	Dept. of Geography	h.g.orr@lancaster.ac.uk
Kingston University	Stuart Downward	Dept. of Geography	s.downward@kingston.ac.uk
Exeter University	Des.Walling	School of Geography & Archaeology	D.E.Walling@exeter.ac.uk
Portsmouth University	Janet Hooke	Dept of Geography	Janet.hooke@port.ac.uk
Cambridge University	Keith Richards	Dept. of Geography	ksr10@cam.ac.uk
University of East Anglia	Richard Hey	Environmental Sciences	R.Hey@uea.ac.uk
GeoData Institute	Chris Hill	Southampton University	cth@geodata.soton.ac.uk
Giffords	Andrew Brookes	Lyndhurst Office	www.giffords.co.uk
Jeremy Benn and Associates	Tony Green Phil Soar	Atherstone Office	tony.green@jbaconsulting.co.uk philip.soar@jbaconsulting.co.uk
Babties	Helen Dangerfield	London	helen.dangerfield@babtie.com
HR Wallingford	Roger Bettess	Howbery park	roger@hrwallingford.co.uk
Symonds Group	Alan Thompson	Cardiff	alan.thompson@symonds-group.com
Atkins	Karen Hills	London	www.atkins.co.uk

The list above does not represent any recommendation neither is it comprehensive

Table 1.5 GAP Framework for geomorphological investigations (overleaf)

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 in 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 - 300km^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 landuse impacts on sediment system. Historical and contemporary data sets	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' (PDP's) 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.
Destination	Feasibility studies for rehab/restoration, Input to CFMP's, 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	**EA (1998b) Geomorphoogy a Protical Guide**, EA National Centre for Risk analysis and options appraisal, Steel House, London.	**EA 1998a Sediment & gravel transportation in rivers: a geomorphological approach to river maintenance**.EA National Centre for Risk analysis and options appraisal, Steel House, London.	**Leys (1998) Engineering methods for Scottish gravel-bed rivers**, Report no. 47, SNH, Edinburgh. **EA (1999) Waterway bank protection: a guide to erosion assessment and management**, R&D Project W5-635.	**NRA(1993) Draft guidelines for the design and restoration of flood alleviation schemes**, R& D Note 154.EA Bristol. **NRA (1994) Development of Geomorphological Guidance notes for Use by Thames Region Fisheries & Conservation Staff**. Kings Meadow House, Reading.	**EA 1999 Geomorphological Post Project Appraisals of River Rehabilitation Schemes,** Unpublished R&D Report, Bristol – details in K S Skinner's PhD Thesis (1999). **Briggs, A.R. (1999) The geomorphological Performance of river restoration projects**, Ph.D Thesis, University of Southampton.

2 RIVER PROCESSES AND CHANNEL GEOMORPHOLOGY

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 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

Thorne (1997) describes the fluvial system in terms of three sets of variables: (1) driving variables, (2) boundary conditions, and (3) adjusting variables or channel form (Figure 2.1). The driving variables of the fluvial system are the inputs of water and sediment, represented in Figure 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.

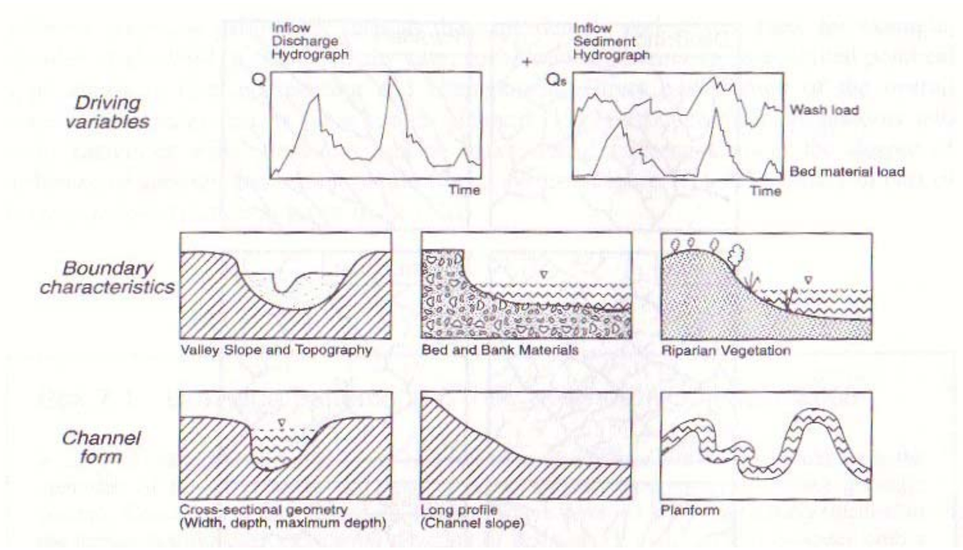


Figure 2.1 Independent and dependent controls on channel form (after Thorne, 1997).

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. 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. Harvey (1986) documents the dynamic nature of river channels occupying this type of valley setting in the uplands, and describes switches in channel morphology from braided to meandering and back, largely driven by high magnitude flood events.

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 between the driving variables and boundary characteristics creates channel and floodplain morphology. These are defined in three dimensions as the channel planform, long profile and cross-section. Alterations in any of these three morphological descriptors, together with sediment size may be defined as adjustment.

The interaction of these variables is further conceptualised in the Figure 2.2 (Ashworth & Ferguson 1986). This figure displays the process-form interactions in a manner that could be represented in numerical or analytical models. The model is 4-dimensional, in that channel form and flow are 3-dimensional in nature, whilst 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, is 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 over-simplification when designing new channels!

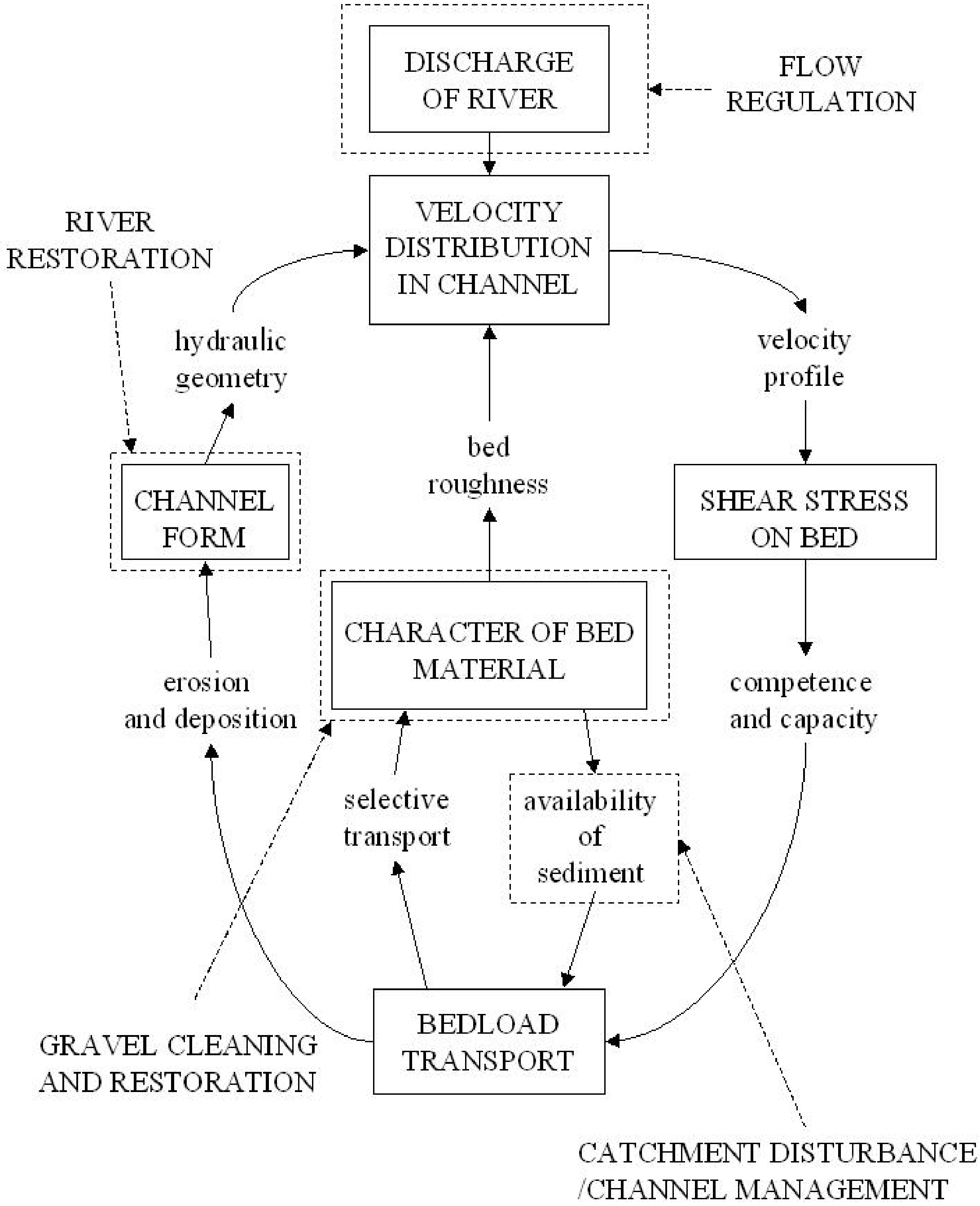


Figure 2.2 A conceptual model of the feedback between channel form, flow, sediment transport and grainsize after Ashworth & Ferguson 1986)

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 (from an orginal by M.D.Newson).

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
Instream vegetation	Little morphological role	Large seasonal impact on sediment transport
Riparian vegetation	Sparse of 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. Modifications to the channel network may render a river channel more or less resilient to climatically induced changes in sediment and discharge regime. Similarly, catchments may be more or less sensitive to changes in climate, (typically expressed as precipitation). 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 a 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 (or scour).

However in order to understand rates of change and types 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 "calibrate" the sediment system of the catchment.

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, whilst particles can be supplied, transported and stored within the river channel over areas of a few square meters. The catchment sediment system can be seen as part of the spontaneous self-regulating functions of a river basin, with important storage and transport components that help to preserve a dynamic equilibrium between production and output of water and sediment (eventually) to the coastal zone.

The supply, transport and storage of water and sediment in a river are controlled by external and internal factors that govern the balance between water and sediment inputs to a reach (Schumm 1977). External factors include catchment geology (including tectonic activity), topography (which may be inherited from past processes that operated in very different environments, e.g. desert, glacial, etc.) soil type, climatic trends, land management practices and base level changes which may include the vertical behaviour of the river catchment into which the channel discharges or the rate of sea level change. Management of the river corridor and channel may also be considered as external controls as these may have impacts on adjacent reaches (Brookes 1988). Intrinsic controls include the grain size and structure of the bed and bank materials, vegetation characteristics of the channel and riparian corridor, valley floor slope, and the channel morphology which determines the distribution of energy within the cross-section and the value of bankfull discharge. Additional internal controls come from sediment storage dominated feed backs that can produce rapid change in morphology such as slope failures or meander cut-off (Schumm 1977).

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.

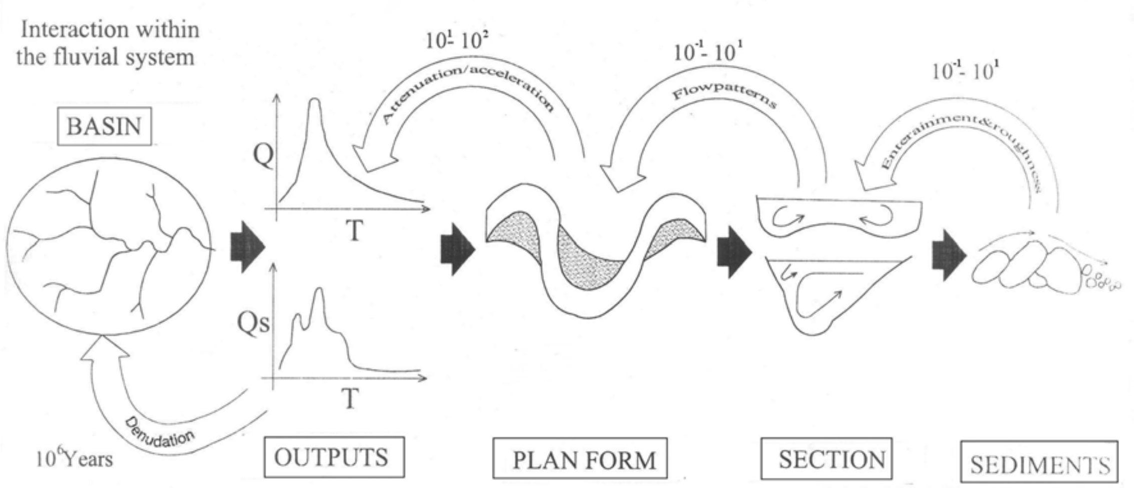


Figure 2.3 Links between the different scales of river geomorphology (after Sear 1996).

2.4 Sediment storage in rivers

The continuity of sediment throughput within the catchment is illustrated in Figure 2.4 through the knock-on effect of upland catchment activity. The continuity of cause and effect is disturbed by periods of sediment storage within the land and river phases of the sediment system. The residence time of sediments within these stores is very variable and 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
- Distance from channel (as opportunity for subsequent storage is increased)

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 & 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). Over shorter timescales, (say 1-100 years), river corridors store large amounts of sediment. Phillips (1989) for example, noted that 29 -93% of the sediment reaching streams was stored in alluvial wetland or channel environments. The channel network has a buffering capacity between headwater and lowland reaches that is manifested in decreasing sediment yield as storage opportunity increases with catchment area. However the stability of these stores (e.g. flood plain or channel bars) may change so that sediment yield may also increase downstream as sediment is supplied by erosion of former stores of deposited headwater sediments (Trimble 1992, Church & Slaymaker 1989).

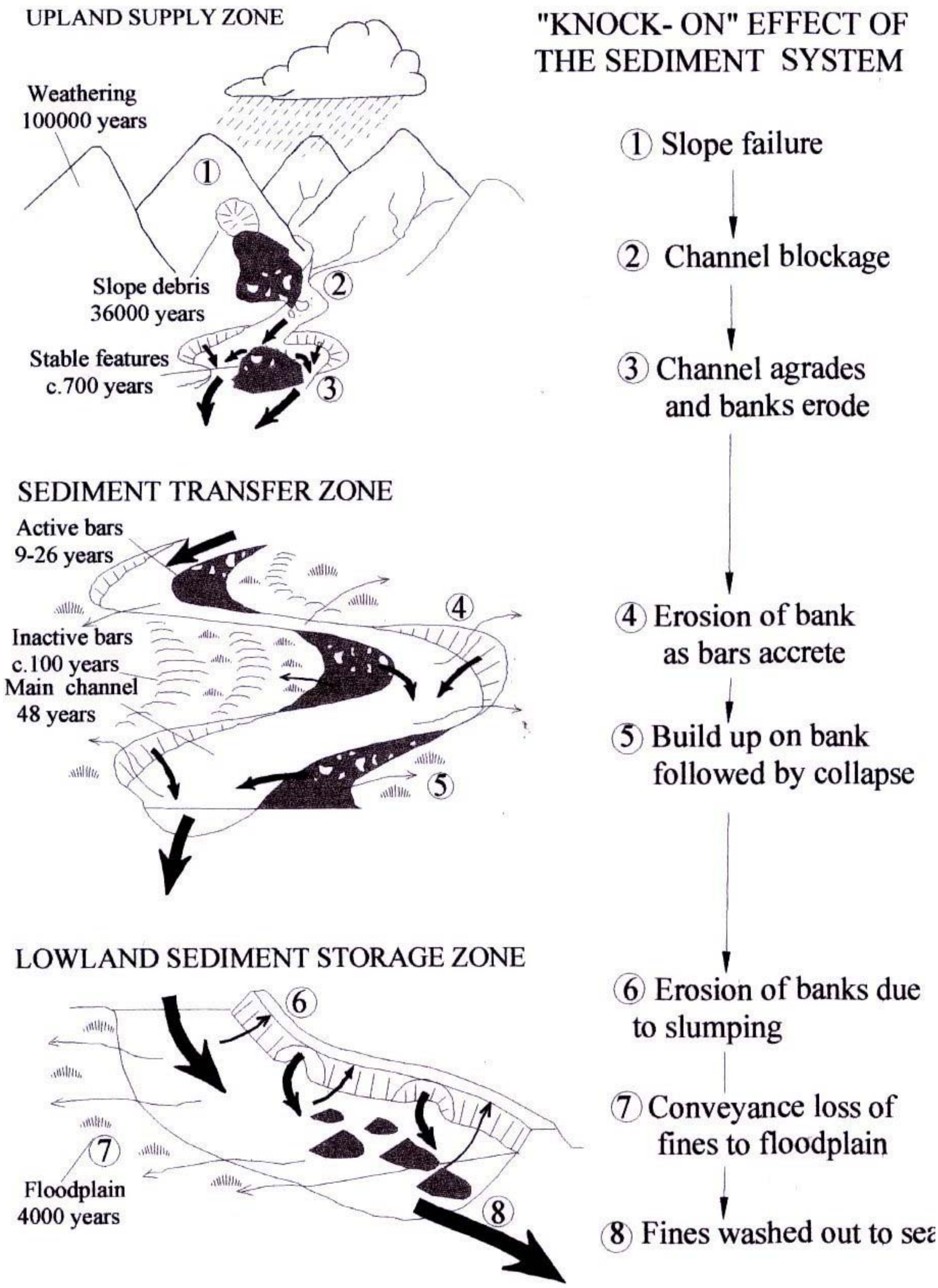


Figure 2.4 Sediment connectivity in the fluvial system (after Newson & Sear 1993).

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, becomes an important contribution to catchment-based river management.

2.5 Sediment transport in rivers

With increasing distance between the problem reach and the headwaters and valley sides of the catchment, the river manager is dealing with increasing timescales between cause and effect. In part this is the effect of sediment storage within the catchment slopes and channel network but it is also a function of the controls on sediment transport. Sediments are transported in three broad phases:

Dissolved load	Ionic solutes carried in the water of no direct morphological significance but can affect morphology indirectly by their affect on plant growth (nutrients and eutrophication) and influence on the erodibility of cohesive sediments.
Suspended load	load dominated by silt and clay though sand can be included at peak discharges. Sediment is maintained in the water column by turbulence and loads increase with discharge to the point at which supplies become exhausted. Important for construction of floodplains and infilling regions of low velocity flow. Important component of gravel siltation.
Bedload	Dominated by sediments coarser than fine sands and transported along the river bed. Bedload transport is responsible for the creation of bed morphology such as bars or riffles. Bedload transport is frequently limited by supply, which complicates simple relationships between discharge and sediment load.

Sediment transport varies with discharge over time and in space within a river network. Sediment transport is controlled by the rate of entrainment, the amount of sediment available for transport in a reach and by the transport length of individual particles. The rate of entrainment and availability of sediments in a reach are controlled by factors such as the number of particles in a reach, particle size, the packing of particles on the river bed, and the distribution of the velocity field over the river bed. These factors change over the course of a single flood event and more progressively over time as channel form and/or grainsize changes.

The length of travel of a sediment particle over time provides important information on the opportunity for linkage between different reaches of a river channel. However, variability in channel characteristics and limited ability to predict sediment transport makes it difficult to predict travel distances. Field evidence is generally limited to studies of individual flood events so that long-term evidence of transport distance is rare. Bunte & MacDonald (1995) published information from mountain streams that suggest the following average annual transport distances:

suspended loads	10 000 m year^{-1}
sand	1 000 m year^{-1}
gravels	100 m year^{-1}

These figures suggest that for many smaller river networks, suspended sediments may pass through the catchment provided that storage opportunities are few and short-lived, but that coarser sediments are likely to remain in the system for long periods, and are derived from relatively local sources. The latter point is significant; fine sedimentation problems such as those associated with salmonid habitats, are most likely to be derived from diffuse and catchment scale sources, requiring a very different management response from the treatment of local coarse sediment problems. It is however, important to note that these figures are averages, are based on a limited database, and that the connectivity between reaches of river may be increased during periods of relatively high flood frequency, during an extreme flood event or following channel modification that increases sediment conveyance through the river network.

Historical analysis at the scale of the river basin have shown that sands and suspended sediments may be moved through quite large river basins (c. 2 500 km^2) over the course of a few decades (Walling and Leeks 1999). Gravel transport may take much longer owing to the more frequent periods of storage in between transport, nevertheless it is clear from historical analysis that wave like movement of coarse sediments may effectively link widely separated channel reaches in periods of less than 50 years (Macklin and Lewin 1989).

2.6 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 & 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 propensity for a given channel state to adjust to a change in hydrological or sediment regime is termed “Sensitivity”. The ability for a given channel state to accommodate a change in hydrological or sediment regime, is termed “Resilience”. The two terms are subtly different; resilient channels may exhibit threshold adjustment as part of their response to change, whereas channel sensitivity refers to the rate and magnitude of that response. It is therefore possible to have resilient and sensitive river channels. Clearly, the management of such channels and their requirements in terms of environmental and social attributes, are very different to channels that are insensitive or less resilient. One of the challenges facing geomorphology has been to identify the attributes of river channels that exhibit differing sensitivity and resilience.

The notion of sensitivity and resilience can usefully be extended to the river catchment, since it is largely the catchment processes that will control the longer-term changes in hydrological and sediment regimes. Sensitive catchments may therefore be viewed as ones that will respond rapidly and dramatically in terms of driving variables Q and Qs. Resilient catchments are those that can adjust to external controls on hydrology and sediment generation, ultimately returning to a new state of dynamic equilibrium. Conceptually we can identify a matrix of catchment:channel types that define the fluvial environment (Table 2.2). Such a table lacks detail (i.e. no channel morphology), and indeed any of the channel states may occur within any one of the catchment states. Nevertheless, in terms of climate change, one can begin to identify a range of possible environmental scenarios.

Table 2.2 Possible scenarios for landform sensitivity to environmental change

Catchment	**Channel**	**Landforms**	**Sensitivity**
Sensitive	Sensitive	Responsive	High
Sensitive	In-sensitive	Robust	Low
In-sensitive	Sensitive	Robust/Responsive	Moderate
In-sensitive	In-sensitive	Robust	Low

The detail of a definition of sensitivity is provided for four types of channel (excluding catchment) in Table 2.3. Taking measures of the driving and resisting variables, it can be shown at least qualitatively that system sensitivity can vary according the nature of the boundary materials. However, whilst this provides some guidance, it is not specific enough to determine what a given treatment might be. For example, does fencing alone switch a channel from a sensitive to a less sensitive state? In reality, more information would be necessary on the dominant processes at a site; for example, incision driven bank erosion would not be treated by fencing the bank line. The implication is that more detailed information will be needed to support local definition of channel sensitivity, a concept that underpins the Geomorphological Assessment Procedure (See Chapter 6.0).

Table 2.3 The potential sensitivity of a fluvial system to climate/landuse change under a given set of driving and resisting variables.

	Upland Confined	**Upland Confined**	**Piedmont**	**Piedmont**
Sediment Supply	Episodic (High)	Episodic (High)	Moderate-High	Moderate-High
Maximum stream power:critical power for sediment movement	High	Low:moderate	Moderate – High	Moderate – High

Boundary Material	Alluvium Colluvium	Bedrock Colluvium	Alluvium	Alluvium
Bank Vegetation	Negligible	Negligible	Low – Moderate	High
Planform Curvature & Sinuosity	Low-Moderate	Low-Moderate	Moderate – High	Moderate – High
System Sensitivity	High	Moderate – Low	V.High	Low-Moderate

Geomorphologists have derived through empirical and theoretical treatments, qualitative models that attempt to relate channel morphology to changes in hydrological and sediment regime (Table 2.4). These however, are largely derived from studies of sand bed, alluvial channels (Schumm 1977). The response of some other river types are less well documented (for example, bedrock gorges). What is absent from these qualitative models is any guidance on the relative magnitude of changes in external drivers that might trigger a change. In part this is because the magnitude of change required to initiate an adjustment is known to vary according to channel sensitivity.

Table 2.4 Qualitative predictors of channel responses to environmental change (after Schumm 1977)

INCREASE IN DISCHARGE ALONE
$Q+ \rightarrow w+\ d+\ F+\ L+\ s-$

DECREASE IN DISCHARGE ALONE
$Q- \rightarrow w-\ d-\ F-\ L-\ s+$

INCREASE IN SEDIMENT YIELD
$Qs+ \rightarrow w+\ d-\ F+\ L+\ s+\ P-$

DECREASE IN SEDIMENT YIELD
$Qs- \rightarrow w-\ d+\ F-\ L-\ s-\ P+$

BOTH INCREASE TOGETHER (e.g. construction/afforestation/stormy climate)
$Q+\ Qs+ \rightarrow w+\ d+-\ F+\ L+\ s+-\ P+$

BOTH DECREASE TOGETHER (e.g. downstream of reservoir)
$Q-\ Qs- \rightarrow w-\ d+-\ F-\ L-\ s+-\ P+$

DISCHARGE INCREASES AS SEDIMENT YIELD DECREASES
(e.g. increasing humidity in the semi-arid zone)
$Q+\ Qs- \rightarrow w+-\ d+\ F-\ L+-\ s-\ P+$

DISCHARGE DECREASES AS SEDIMENT YIELD INCREASES
(e.g. increasing abstraction and land pressure/ climatic drying)
$Q-\ Qs+ \rightarrow w+-\ d-\ F+\ L+-\ s+\ P-$

Key

Q = streamflow
Qs = sediment yield
w = width
d = depth
F = width/depth ratio
L = meander wavelength
S = channel gradient (reach)
P = sinuosity

The existence of river reaches that although morphologically similar, may have different responses to a given change in *Q* or *Qs* 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 morphology that can guide the river manager, and in the context of this study, 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 land form 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. The advice is that it is often increasingly difficult to establish what the driving cause of a given change actually is, and secondly, that adjustment time (relaxation time) is often longer than the frequency of environmental change. The implication, is that UK rivers are seldom in equilibrium (dynamic or otherwise) with prevailing sediment and hydrological regimes. The corollary of this view is that we must expect constant adjustment and a suite of responsive landforms over geomorphologically relevant timescales (50+ years?). This is self-evidently not the case for the whole of the UK where in the lowlands of central and southern England at least, channel incision and fill, are minimal at present, and channel planform at least, 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:boundary resistance may mitigate against large scale channel adjustment. Nevertheless, over longer timescales, these channels are shown to respond to phases of landuse change and climatic instability, through aggradation and incision of floodplain sediments (Macklin & Lewin 1994).

2.7 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 sediments, that interacts with the biological and chemical 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 also helps 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!

An important part of fluvial geomorphology is to classify these forms and sediments and relate them to the processes responsible for their formation. For the river manager, being able to infer process from river morphology and sedimentology, provides a potentially useful diagnostic tool for interpreting system behaviour. Since it is possible to identify past channel morphology and sedimentology from analysis of historical information (maps, air photographs) or from analysis of valley floor sediments, fluvial geomorphology can also be used to reconstruct the sequence of past processes and form. However, in many cases the links between form and process are qualitative and the further back in time, the less information exists; correct interpretation and diagnosis is then highly dependent on the professional experience of the surveyor.

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. 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 (for example woody debris or post-glacial flow and sediment regimes), helps to explain the lack of adjustment and natural re-creation of past features. 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 often re-introduced 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* (Newson and Newson 2000, Church 1992). The precise significance of these features to 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. Furthermore, it is becoming clear, that past channel processes have been 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:

1) Understanding the link between morphology and processes (this helps to decide if the processes exist to create the morphology)

2) Understanding the link between morphology and the sediment system (this helps to diagnose problems from channel form, but also the implications of creating different morphology)
3) Understanding the link between morphology and physical habitat/ecology (this provides the link between biodiversity goals and geomorphology)

The following section will provide guidance on some of the more common landforms associated with UK rivers, and establish 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.

2.7.1 River catchments

At the heart of sciences like 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. 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 all the available sediment sources 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), hydro-climatology, 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. 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 (EA 2001). Such information is vital in attempting catchment scale management of a diffuse sediment problem.

2.7.2 River network

On of the most significant features of the river catchment is the extent of channels that comprise the river network. The River network is the main routeway for the transmission of water, sediments and nutrients and organic matter in the river ecosystem, yet is definition is seldom considered in all except flood routing and hydrological modelling. The form of the drainage network is largely conditioned by catchment geology and relief; indeed the shape of the river network can provide important clues as to the structure of the geology of an area. Figure 2.5 depicts the influence of geology on drainage network at regional, and catchment scales. One of the most important measures of the river network is the density of channels per unit area of 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). 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. 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.

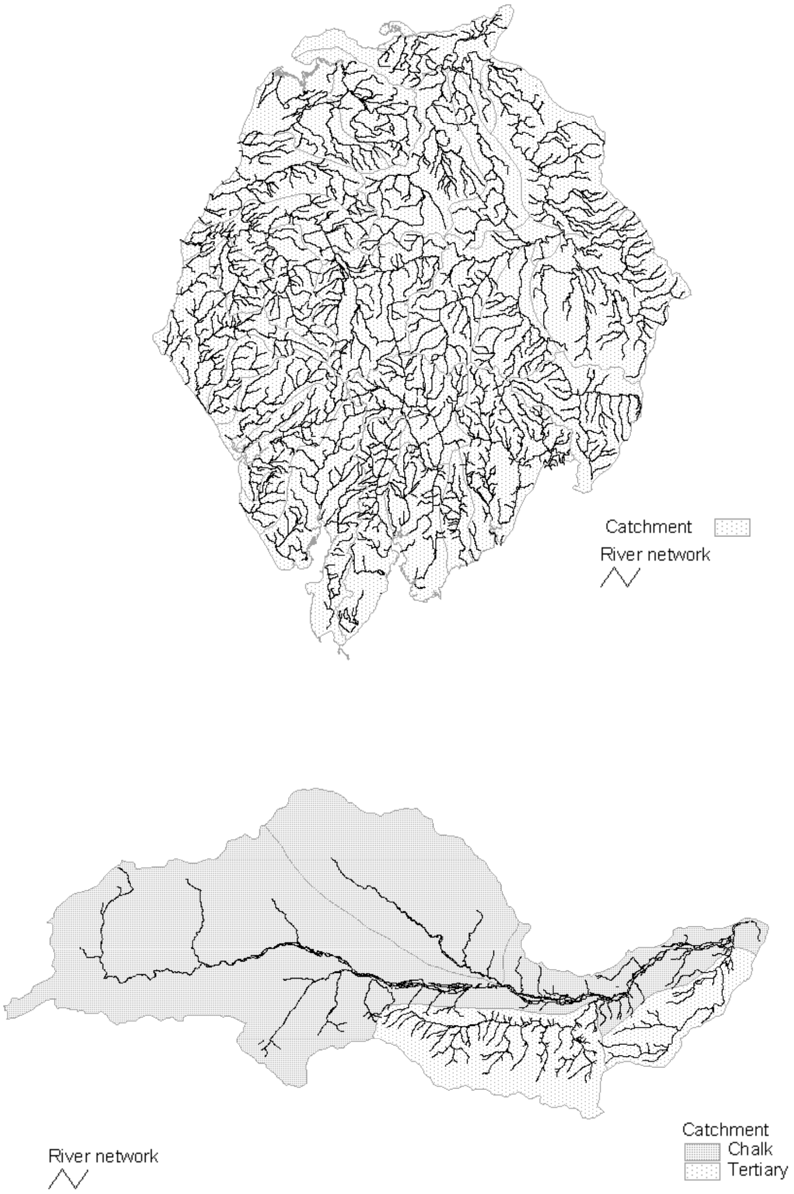


Figure 2.5 Drainage Networks: a) Geological controls on regional drainage networks and b) geological controls on drainage network; River Kennet catchment, UK (courtesy of GeoData Institute).

2.7.3 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 2.6 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. What is also apparent in the diagram, is that the form of the valley is the significant control on this connectivity, and that this is itself controlled by the local geology and longer-term evolution of the catchment. 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. The long profile of a river is defined by the shape of the elevation:distance diagram (Figure 2.7). 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 Figure 2.7. What is clear in UK rivers is the influence of past changes in uplift and sea level, that have “moved the goal posts” 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 full of easily eroded 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 gradients increase 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 & Rumsby 1994).

The form and downstream changes in the valley floor and long profile, provides 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.

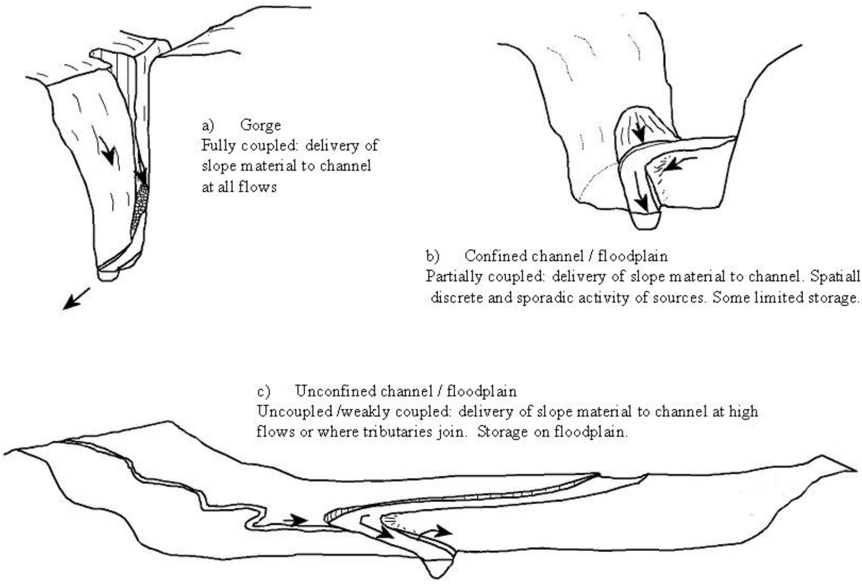


Figure 2.6 Valley form and its control on connectivity between the catchment surface and the river network.

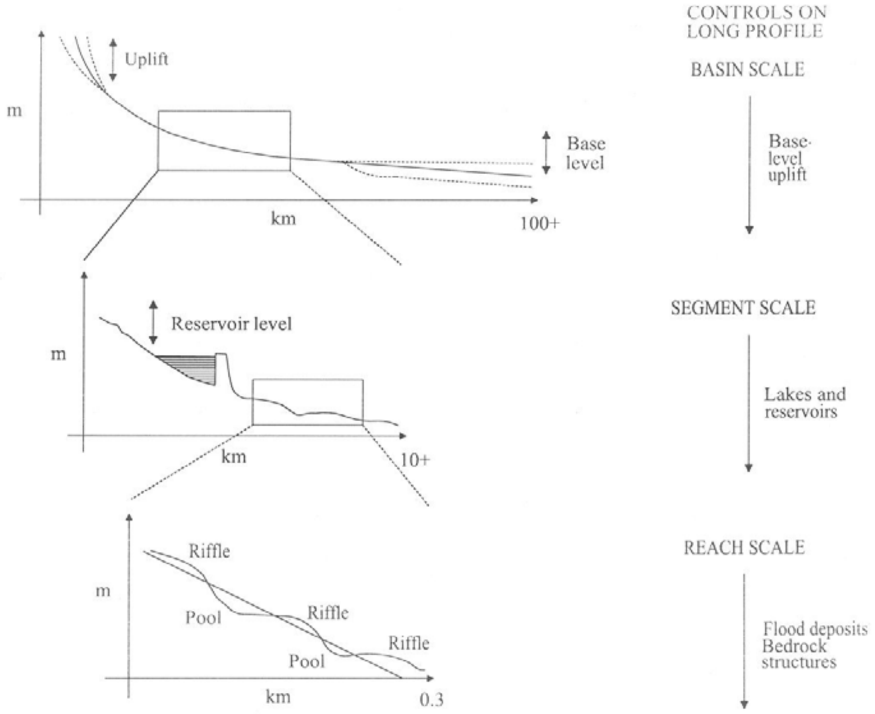


Figure 2.7 The long profile of a river; illustrating geological and base level controls on valley gradient (after Sear, 1996).

2.7.4 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.

As a result, there has been much investment in defining the indicative floodplain for UK rivers as a means of providing decision support for flood protection. 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 & Clayton 2002). Mapping floodplain geomorphology using high quality large scale air photography has been advocated in support of planning and development control;

though it remains problematic in the more intensively managed lowland areas of the UK where topography has been “ploughed” out.

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, whilst also storing sediments brought into the reach from the upstream catchment. 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. Similarly, the breaching of flood embankments can result in either deposition or erosion of the floodplain surface (Gilvear *et al*. 1994).

Figure 2.8a-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.

Figure 2.8 a) High-energy floodplain; b) high-moderate energy alluvial floodplain, c) Low energy floodplain; d) low-moderate energy forested floodplain

High energy floodplains (Figure 2.8a)

In steep upland channels, floodplains are typically narrow and are frequently re-worked by high magnitude floods. The floodplain is highly connected to the valley side and receives sediment from slope processes. The channel is also coupled to the valley sides at points of impact, and this leads in the absence of incision, to high rates of floodplain formation and destruction. Much of the floodplain sedimentology is coarse, but with phases of channel stability leading to peat development and finer sediments in abandoned channels. Vertical instability is often clearly evident from terraces or abandoned channels that lie above the elevation of the current river bed. An important control on floodplain (and valley floor) gradient, and therefore vertical adjustment in upland areas is the presence of rock outcrops in the valley floor. In upland channels, the floodplain is often re-worked through processes of avulsion where the river becomes choked with sediment (or woody debris) and a new course is cut into the floodplain. Alternatively the same end point can be achieved through the cutting back upstream of a channel that occurs when floodplain flows re-enter the channel.

High – moderate energy alluvial floodplains (Figure 2.8b)

The formation of alluvial floodplains in moderate energy valley systems occurs largely through lateral accretion of point bars as meandering or wandering channels move across the valley floor. Rates of channel adjustment are typically high, and are frequently associated with the margins of mountain or upland areas. Sediment delivery to these valleys over time is variable and this results in phases of floodplain aggradation and incision. Correspondingly one of the features of alluvial high-moderate energy floodplains is the presence of river terraces of varying elevation, composed of glacial but also alluvial river sediments. Similarly the lateral channel migration associated with these systems creates sequences of palaeochannels and relict bar forms on the lower terraces and adjacent floodplain. Where channel migration is through progressive movement of meander bends, the inside of these can form ridge and trough (swale) topography. Deposition in the form of overbank run-out of fines or gravel sheets can occur during large floods. Abandonment of old channels, and the vertical fluctuations in floodplain elevation over time creates a diverse ecology in the floodplain, with mixes of terrestrial, wetland, temporary and permanent aquatic habitat. Indeed, partially or fully connected channels are known to provide important refugia for fish during floods. Flood inundation processes are heavily controlled by the complex microtopgraphy associated with former channels and terraces, making prediction of flood extent and duration difficult.

Lowland low energy floodplains (Figure 2.8c)

In the UK and most of NW Europe and North America, lowland floodplains are highly disturbed systems with little left of the natural physical processes and ecology. Centuries of river management in support of floodplain reclamation have led to increasing disconnection between river and floodplain processes and habitats. Embankments now form the margins of many lowland floodplains, and floodplain land cover is typically urban or agricultural. Many of the natural features of lowland floodplains have been removed by land management practices. Channel migration rates are typically low and floodplain development is determined by vertical accumulation of fine sediments carried in suspension and deposited during floods. In the presence of embankments, even this process is reduced.

In some river systems, notably those with a high groundwater contribution to flow regime (e.g. chalk / limestone rivers); traditional lowland floodplain management included a phase of encouraging water and fine sediments on to the land surface through a network of channels and hatches. Relics of these water meadow systems still exist in the chalk streams of Southern and SE England; but are unable to function as designed. Instead they provide a floodplain topography that is only picked out in extreme floods such as those of Autumn 2000/2002.

In the natural state before woodland clearance in the Bronze/Iron age (1500BC - 44AD), lowland floodplains were forested, with multiple channels separating vegetated land of similar elevation to the floodplain. Each channel is a separate river, with morphology scaled to the dimensions of the individual channel. Anastomosed river systems such as these are typical of low valley slopes with a sediment load dominated by fine cohesive sediments. Floodplain formation largely occurs by vertical accumulation of sediment during overbank floods; often aided by the presence of debris dams (see below).

Forested floodplains (Figure 2.8d)

The role of debris in the creation of floodplain geomorphology is only now beginning to be realised. In part this stems from the lack of forested floodplains in the UK and elsewhere. However, the significance of debris in watercourses was formerly much greater since, until c. 1 000 BC, most of the lowland UK floodplains were forested. The role of Large Woody Debris (LWD) in the development of floodplain features is twofold;

1) The creation of debris dams in the channel creates stronger coupling between the river and the floodplain – water and fine sediment are more frequently transferred onto the floodplain surface;
2) The overbank flows of sediment-laden water interacts with debris and living trees on the floodplain to create a diverse microtopography and physical habitat.

Of those forested floodplains studied in the UK, the channel planform during high flows is very complex, with networks of channels and backwaters, creating a highly diverse physical habitat. The floodplain surface is characterised by a network of active and abandoned channels, and ridges of organic rich fine sediments that form levees and wakes downstream of obstacles. Flow across the floodplain is focused into channels rather than as diffuse flow across the floodplain surface. Dead wood is trapped by the presence of large debris dams and may be rafted onto the floodplain surface to be trapped against trees and bushes. Downstream export of debris may therefore be relatively small. Good examples of floodplain forest exist in the New Forest (Low-energy system), and the River Spey (High-energy system).

2.7.5 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 (Figure 2.9). 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.

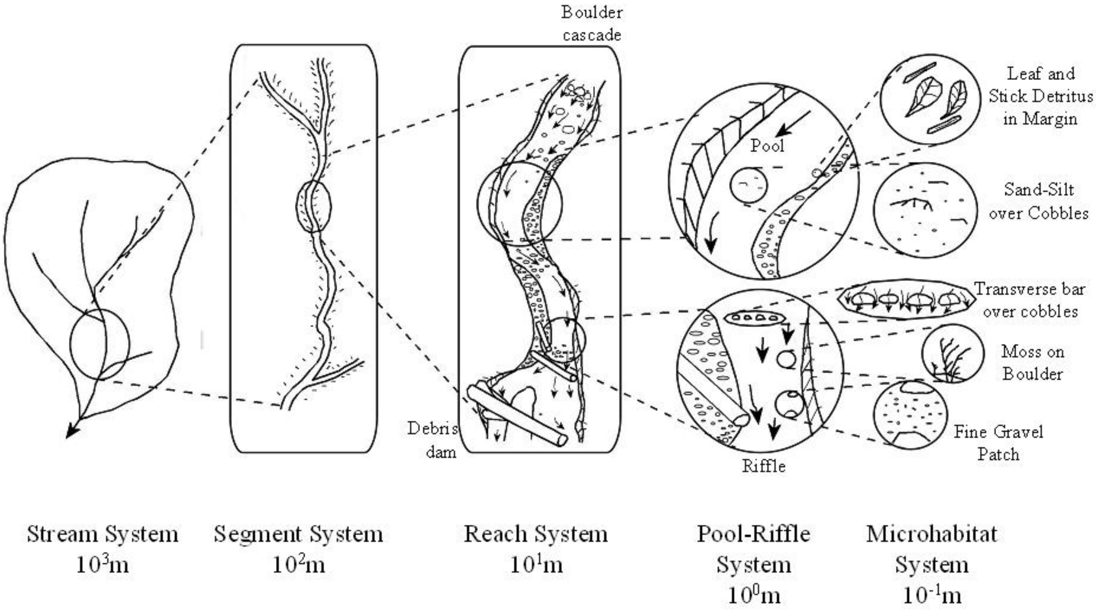


Figure 2.9 The hierarchy of scales in the river system (after Frissel *et al.* 1996)

A river channel may be defined in terms of three dimensions: the cross-section form, the planform, and the long-profile down the reach (Figure 2.10). 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 *River Habitat Survey* or C*atchment Baseline Survey*. Figure 2.10 illustrates the measures generally needed to 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. Clearly the presence of two-staged channel cross-sections or incised gorge like reaches make 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

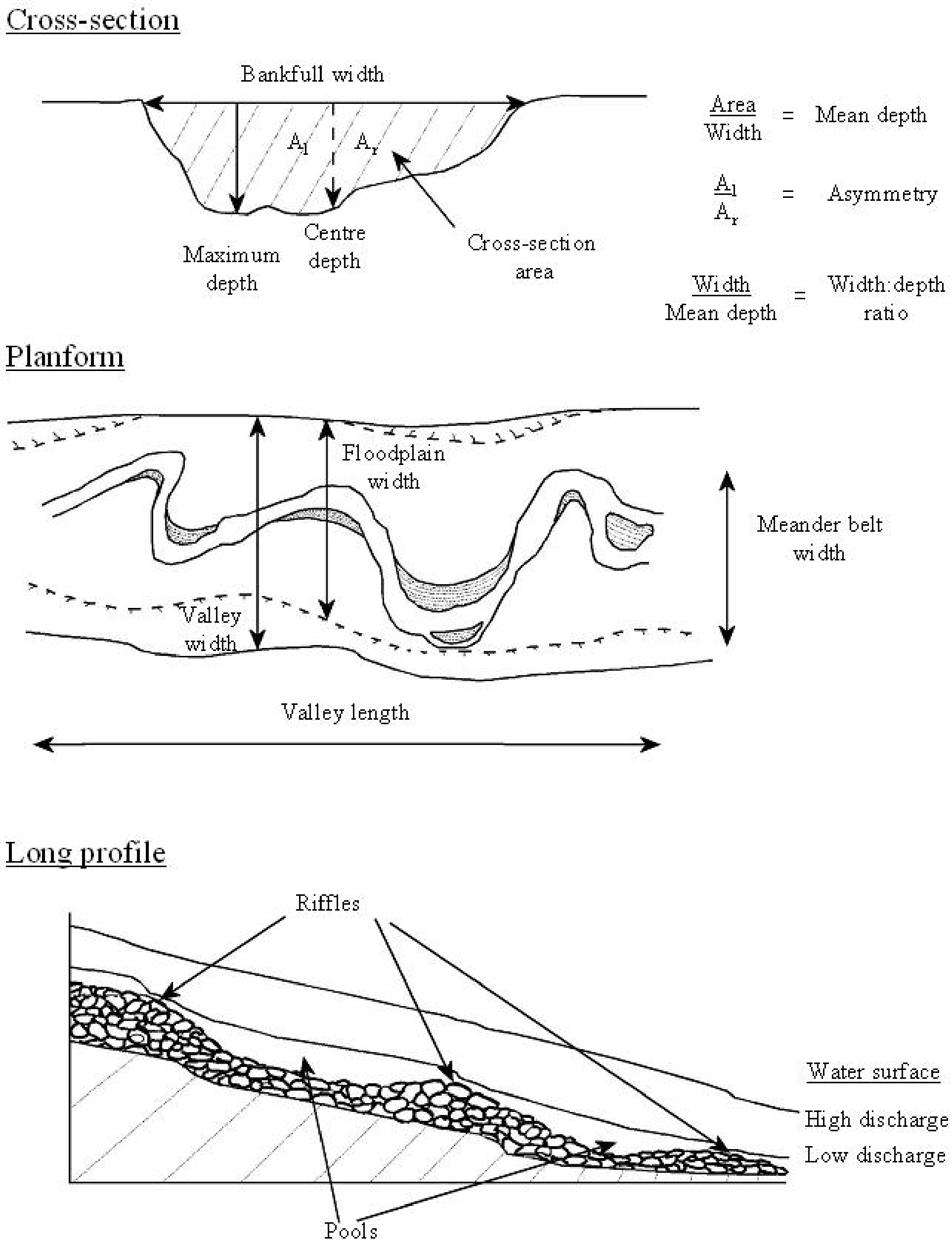
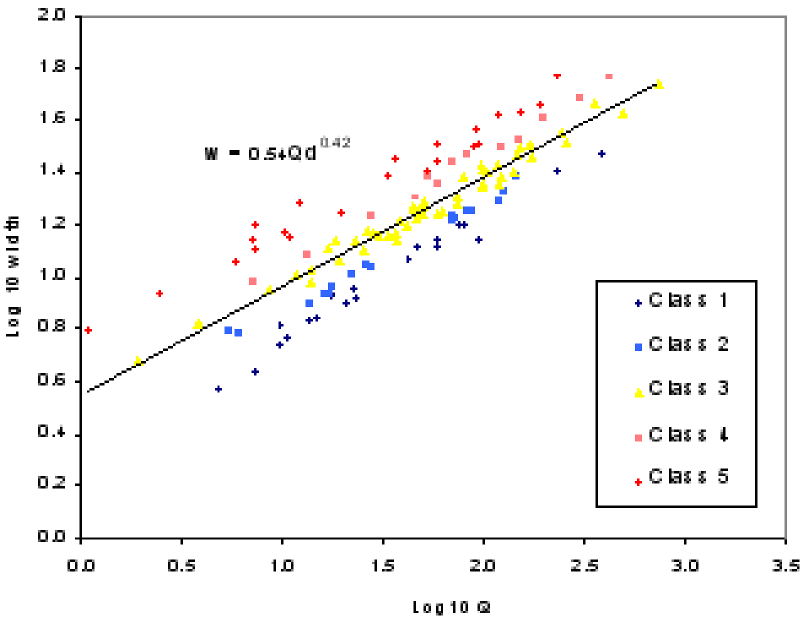


Figure 2.10 The 3-Dimensions of river channel form

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 2.11 illustrates this point, demonstrating that channel width increases with bankfull discharge at similar rates but offset according to 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 – <u>one design will not fit all</u>!



Class 5 silt/sand bank materials – slumping Class 4. bedrock dominated bed, fine materials in banks Class 3. mixed bed or cobble bed. Class 2. sand/gravel banks dominant. Class 1. chalk streams;clay/silt banks dominate.

Figure 2.11 Variation in channel width as a result of bank material and hydrology (after Dangerfield, 1999)

2.7.6 Channel planform

One of the most important features of a river channel is the planform. The planform controls the local stream gradient; affects the 3-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, a straight reach is most likely the result of channel management.

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”. Therefore modifications 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 centuries of past management, rather than natural processes of channel adjustment.

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 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 (Figure 2.12). In the UK, all four types of river occur, although the number of braided and anastomosed channels is small relative to meandering and straight.

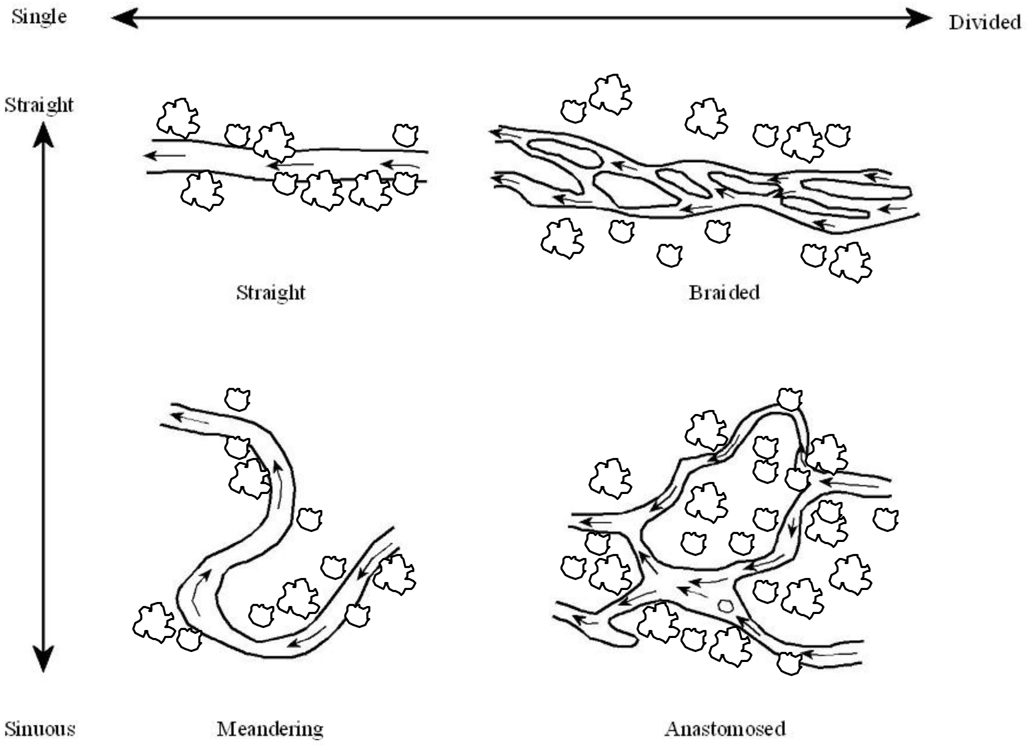


Figure 2.12 Definitions of channel planform (after Rust, 1978).

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 (Figure 2.13).

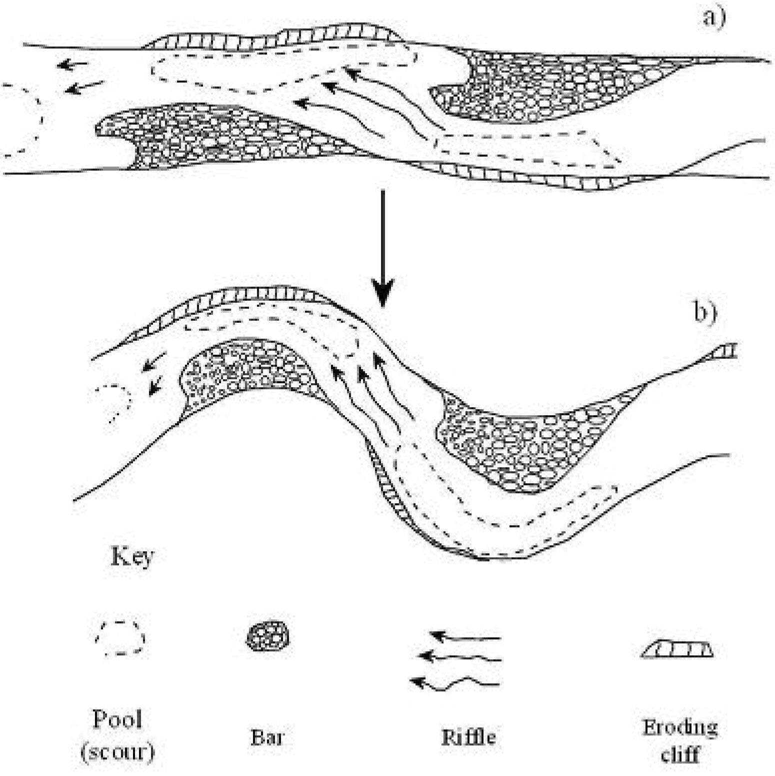


Figure 2.13 The role of alternate bars in the development of meandering in alluvial rivers (after Lewin, 1976).

Meandering channels are those with a sinuosity greater than 1.5, 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, displaying a vertical earth cliff, but in fact are kept clean of vegetation by weathering processes (e.g. 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 was adjusting planform and bedform simultaneously (Thorne 1997).

The geometry of meandering channels may be defined by a specific set of quantitative measurements (Figure 2.14). 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 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.

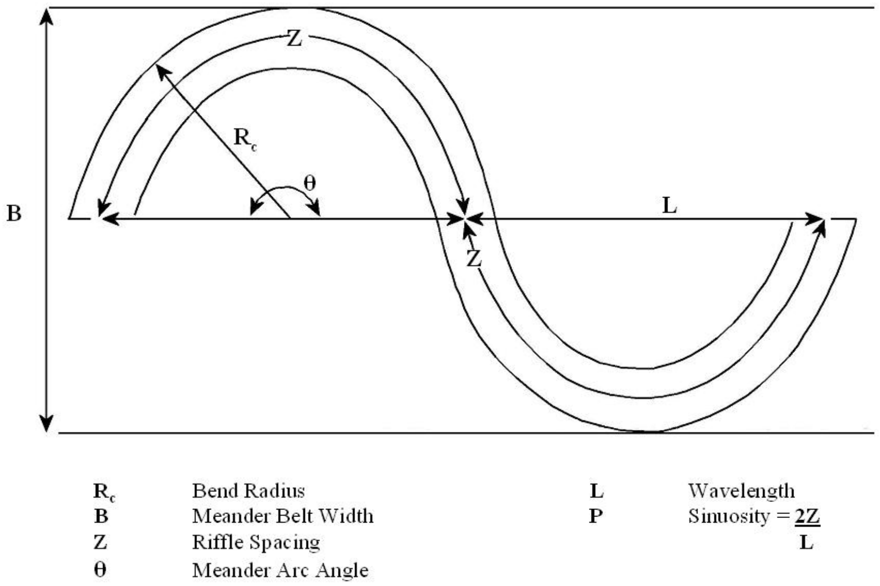


Figure 2.14 Variables used in the definition of meander bend geometry (after Thorne, 1997).

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 (Figure 2.15). The additional mass of water at the outer bank creates a downward pressure that 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.

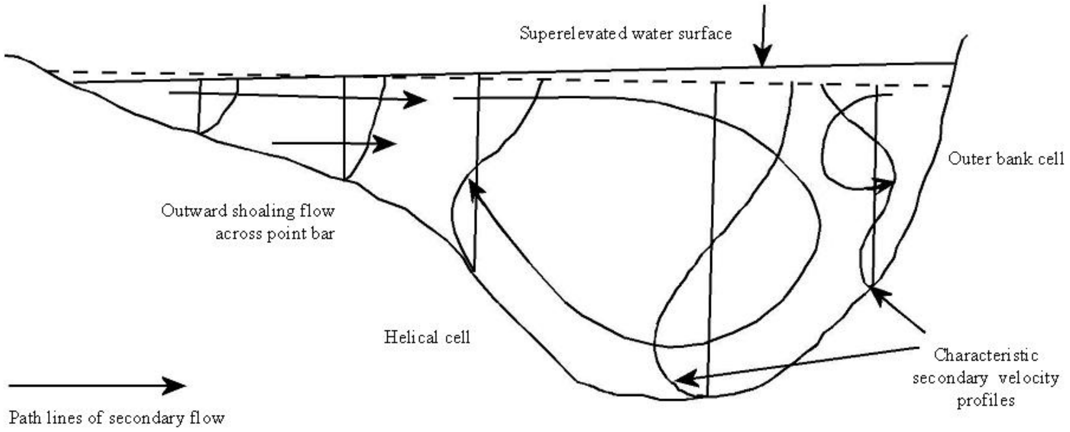


Figure 2.15 Secondary flow structure in a meander bend and its relationship with scour the form of the channel cross-section (after Thorne, 1997)

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. 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.

Braiding

Braiding occurs when the transport capacity of a river is exceeded by the sediment supply, or when transport rates are typically very high (Figure 2.16). 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 grainsize of the bed material in transport. Steep braided streams are characterised by relatively large grainsizes; lower gradient braided rivers tend to form in sand sized bed material.

Figure 2.16 Braided River Reach; River Swale, Yorkshire. Note multiple channels flowing between active gravel shoals within a channel bounded by a vegetated and elevated floodplain surface.

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. 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. Channels that exhibit this switching of planform morphology are termed wandering, and are close to the threshold of channel planform change.

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 Woody Debris helps create bars and islands by acting as local sites for sedimentation.

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:

1) The channels are separated by vegetated surfaces of the same elevation as the floodplain (and in fact form the floodplain surface)
2) Anastomosis occurs in low gradient valleys experiencing long-term aggradation of fine sediment.

3) 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.
4) The planform activity of anabranched channels is typically low
5) 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.

2.7.7 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:

$$A_* = \frac{A_r - A_l}{A}$$

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_l 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 (Hey and Thorne 1986, Charlton *et al.* 1978) 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).

2.7.8 Predicting channel form

Given that the controls on channel cross-sections are likely to change downstream it is reasonable to assume that rivers will exhibit variations in channel cross-section within the catchment. Geomorphologists have made a particular study of the rate of adjustment in cross-section form with increasing catchment area; termed *Hydraulic Geometry*. Hydraulic Geometry when applied in its downstream mode, provides a framework for establishing and predicting the variations in channel width, depth, capacity and mean velocity for bankfull (or a given recurrence interval) flow as this changes through a channel network. The equations for the best-fit lines derived from this analysis have coefficients and exponents that vary according to the influence of other controls on cross-section form; e.g. bank material, hydrological regime etc.) (Figure 2.17). Nevertheless, locally derived downstream hydraulic geometry relationships can be used in support of river restoration and channel design; where sufficient semi-natural watercourses can be found to provide the necessary data. In the absence of field data, channel width:catchment area relationships can be derived from large-scale historic maps for periods prior to substantial channel modification. However, there are cartographic errors associated with this approach, and sediment loads and discharge regime may have changed significantly since the river was mapped.

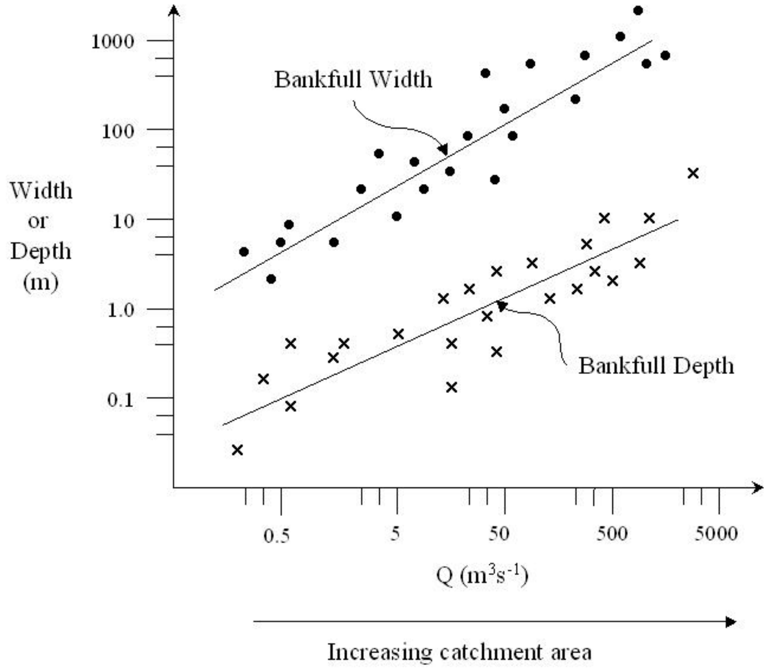


Figure 2.17 Downstream hydraulic geometry

An alternative approach, though with a similar theoretical basis termed “Regime” theory, has been used to explain and predict cross-section form in alluvial rivers. Regime theory (like Hydraulic Geometry) assumes that the channel cross-section represents a balance between the discharge and sediment load conveyed by the channel. The equations of regime theory are typically derived from a sample of similar river types from the same physical environment (e.g. gravel-bed rivers from UK). Field data on the width depth etc. are collected together with local estimates of sediment transport, discharge, bed and bank materials and vegetation. The hydraulic geometry equations are extended to include other descriptors of channel form, and to include other controlling variables. A set of Regime equations has been developed for dynamically stable (i.e. they will adjust their cross-section and planform but retain their average dimensions) gravel-bedded UK alluvial rivers, from which it is possible to determine the broad meander geometry of a design channel for restoration or flood conveyance purposes (Table 2.5). While these equations are for a specified range of rivers types, they have been shown to perform at least as well as theoretical relationships. Recognition that local information on the nature of the bed and bank materials, bankfull discharge and bankfull sediment transport rate is required before selecting a given equation cannot be stressed enough. Further details of their application may be obtained from NRA (1993) and Hey and Thorne (1986).

Table 2.5 Regime equations for the design of gravel bed rivers (dataset from UK)

Channel Geometry	Equation
Bankfull Width (*W*)	$W = 4.33Q^{0.5}$
Bankfull mean Depth (*d*)	$d = 0.22Q^{0.37}D_{50}^{-0.11}$
Bankfull Slope (*S*)	$S = 0.087Q^{-0.43}D_{50}^{-0.09}D_{84}^{0.84}Q_s^{0.10}$
Sinuosity (*P*)	$P = S_v/S$
Meander Wavelength (*L*)	$L = 12.34W$
Inflexion Point (Riffle) Spacing (*Z*)	$Z = 6.31W$
Bend Curvature (R_c)	$Rc = 2$ to $3W$
Scour Depth at Bend (BD_m/XD_b)	$BD_m/XD_b = 2.07 - 0.19 \log_e((R_c/W) - 2)$

Q = bankfull discharge; Q_s = sediment transport rate, D_{50}, D_{84} are the 50th and 84th percentile grainsizes of the bed material; S_v = valley slope, BD_m = maximum scour depth at a bend, XD_b is the mean depth at an inflexion point.

2.7.9 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 (Figure 2.18). 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 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 back to its original form, although it may occupy a different location in the floodplain. Sediment waves, and sedimentation zones are most commonly found in 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 grainsize 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

Figure 2.18 A sedimentation zone on the River South Tyne, Northumberland (Photo courtesy of Northern Echo).

. 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 Figure 2.13).

Figure 2.19 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 (Figure 2.19a). 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 (Figure 2.19b).

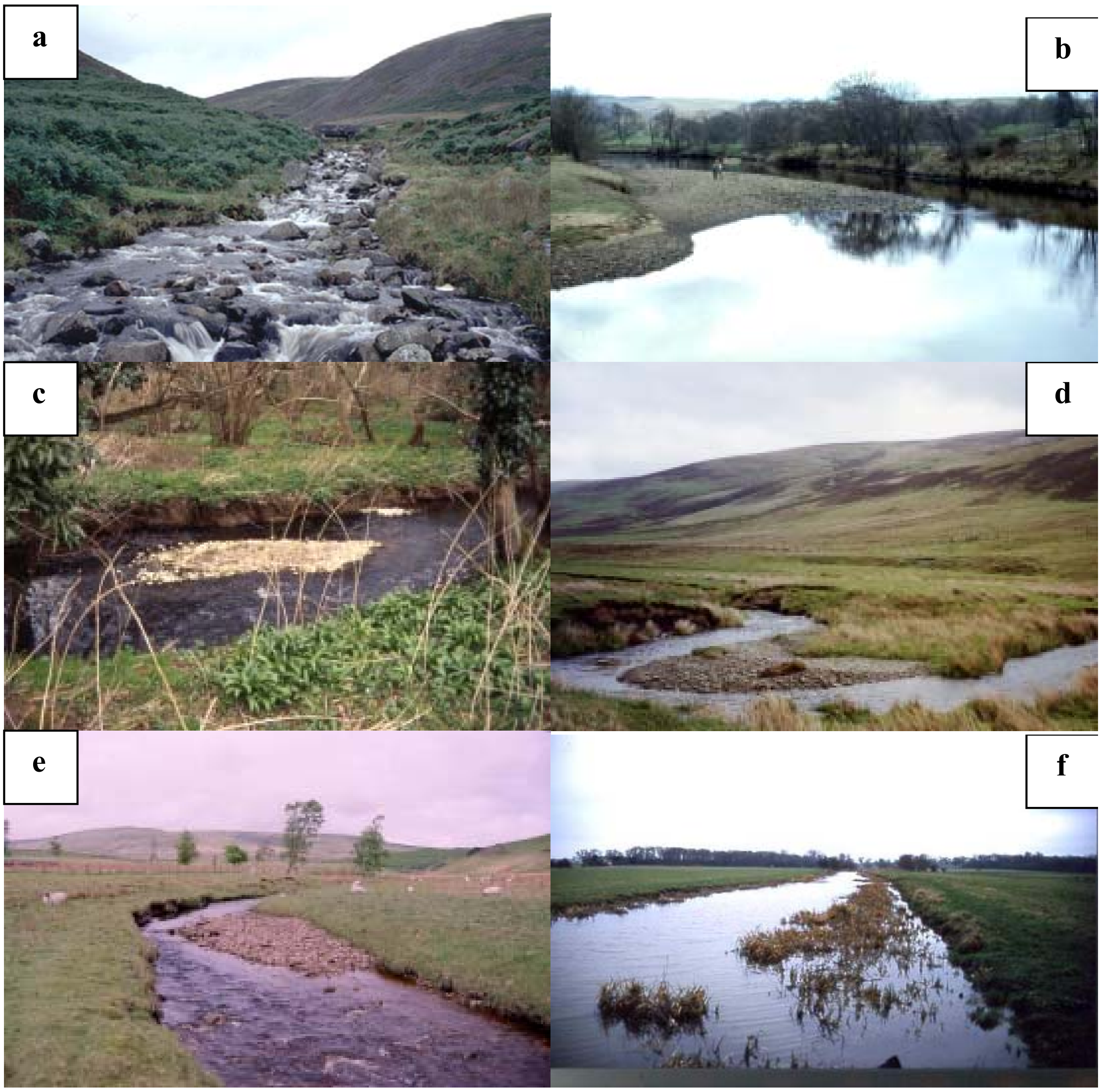


Figure 2.19 Some typical sediment deposits in UK rivers: a) Chaotic boulder channel b) tributary confluence bar, c) Mid channel bar, d) point bar e) side bar f) fine sediment berm

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 (Figure 2.19c). 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 (Figure 2.19d).

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 (Figure 2.19e). Mid-channel bars form under three basic mechanisms;

1. deposition on a riffle following high flows and scour of the upstream pool;
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 (Figure 2.19f). 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.

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 (Figure 2.19g). 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. 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.

2.7.10 Pool-riffles and the geomorphology of river long profiles

The reach scale (< 1 km) long profile of rivers conveying coarse sediment (> 8mm) 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 (Figure 2.20a). The steps can contribute significantly to the 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 (3 –4 channel width). Sediment transport is typically from pool-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.

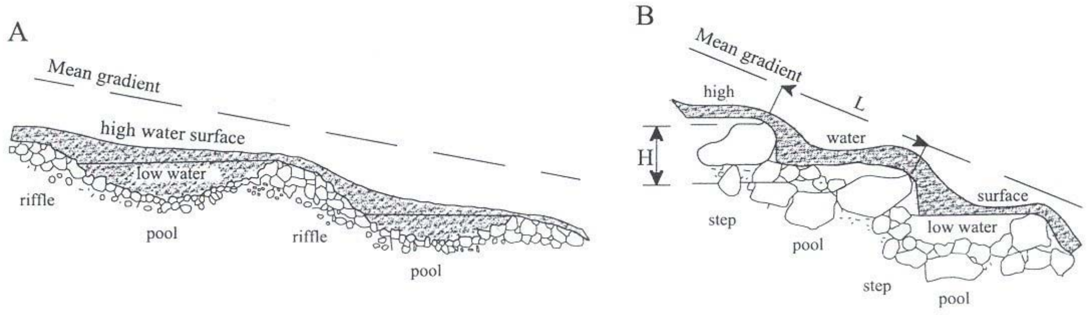


Figure 2.20 Variations in the local long profile: a) Step Pool sequence in steep coarse sediment channels and b) Riffle-pool sequence in alluvial cobble and gravel-bedded rivers.

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 (Figure 2.20b). 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 re-construction 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:

1) 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;
2) A weir or debris dam where the scour pool again creates a riffle/bar;
3) 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:

1) 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;
2) 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;
3) 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;
4) 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-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 in 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 2.6 highlights the possible limitations to achieving the desired function of a riffle rehabilitation programme, and highlights some solutions.

Table 2.6 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 &/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 & 6
Hydraulic diversity at low flows	3 & 4	1,5 & 6
Aeration at low flows	3 & 4	1,5 & 6
Salmonid spawning ground	2 3 & 4	1,5 & 6
Cyprinid spawning ground	2(?), 3 & 4	1,5 & 6
Invertebrate habitat	3	1,5 & 6
Aesthetic feature	4	1,5 & 6

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 friction and in their contribution to the diversity in physical habitat.

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. Runs are associated with Salmonid spawning habitat. Glides and runs are typical of chalk streams, the runs replacing riffles as the local step in the long profile.

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 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.

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 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).

Scour pools occur in response to local increases in sediment transport capacity. These may include deflection of flows by 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 – 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 debris dams or 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.

2.7.11 Vegetation and the role of woody debris

It has become clear that clearance of riparian woodland and centuries of channel management have largely removed woody debris from UK watercourses. Research to date makes it clear that the role of Large Woody Debris (LWD), or Coarse Woody Debris (CWD) 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. Locally and in some river systems extensively, LWD significantly influences the morphology and associated physical habitat. 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 LWD, debris dams may form that block the channel and provide local points at which water and fine sediment are directed on to the floodplain. However, in larger watercourses, where channel dimensions are larger than LWD, the role is frequently that of influencing patterns of channel sedimentation and bank erosion. Deposition of LWD is part of the formation of islands in wider alluvial rivers. A classification of debris dams has emerged that recognises their variable influence on low flow hydraulics, sediment transport and channel morphology (Figure 2.21). Clearly 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, debris dams may be spaced as frequently as every three bankfull channel widths.

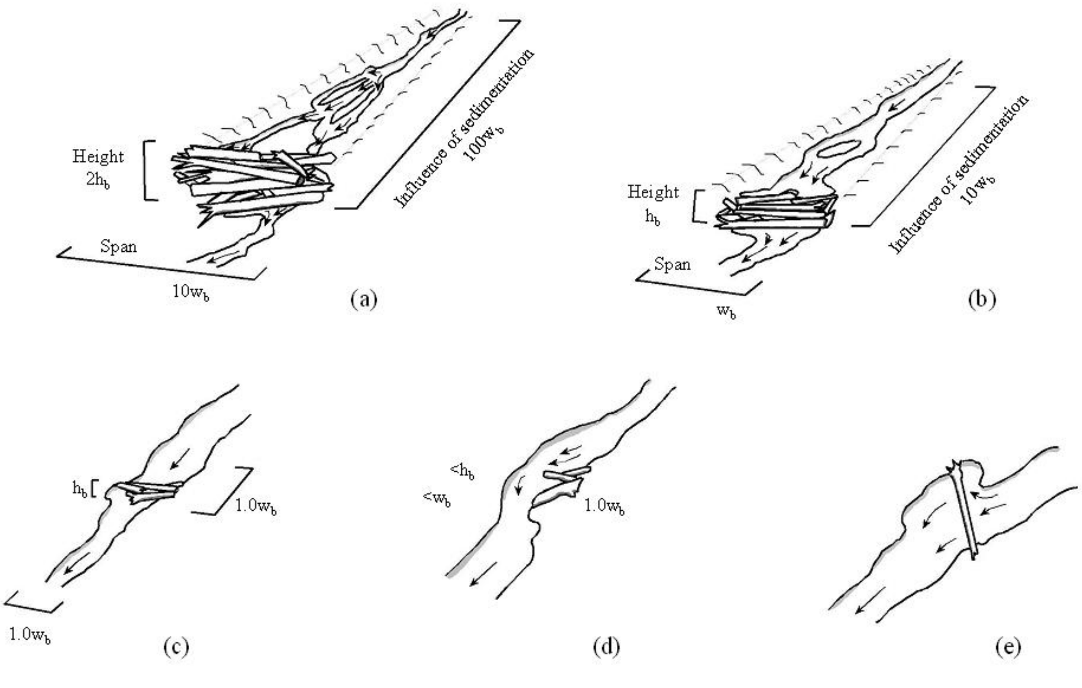


Figure 2.21 A classification of debris dams and their relationship to channel morphology (after Hogan *et al*. 1998).

River management practices focused on flood protection remove LWD accumulation 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. Whilst caution is required, it is possible to consider LWD and floodplain forestry as an appropriate method for increasing upstream flood storage in the intermediate reaches of river catchments. Furthermore, it is almost certain to be the major missing element of the natural habitat of chalk rivers.

2.8 The role of river classification and typology in river management

One of the main tools employed by natural scientists to bring order into the variety of nature is classification. The same approach is used in fluvial geomorphology. Classification is then the ordering of objects into groups based on common characteristics, and attaching labels to the groups. There are two main objectives for river classification: (1) to support scientific understanding of how rivers function, and (2) in support of river management practice. In practice two broad distinctions can be made of existing classifications; those based on channel features, and those based on channel processes. Channel feature classifications include the River Habitat Survey, Rosgen Classification (Rosgen 1996) and the SEQ_{Phy} system of France. 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;
- 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, misapplied, has led to some spectacular river management problems (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.

3 DRIVING PROCESSES 1: UNDERSTANDING RIVER SEDIMENT DYNAMICS

3.1 Introduction

During the 1990s, sediment-related maintenance cost the Environment Agency in excess of £10 million annually (Environment Agency 1998). Usually, sediment-related work involves mechanical removal or re-distribution of sediment that is both expensive and environmentally insensitive. Such approaches tend, in practice, to treat the *symptoms* rather than the *causes* of the problem. The result is that solutions are, at best, temporary because the problem recurs and, at worst, risk triggering further problems through the ‘knock on’ effects of disrupting the relationship between sediment sources, transfers and stores within the river-floodplain system.

Sediment movement is seldom considered in the design of capital works for flood defence, land drainage or navigation. Annual expenditure on flood defence projects exceeded £230 million prior to the Millennium Floods, and it has risen sharply (to around £400 million per annum) since. Available evidence reveals that most engineered flood defence channels require sediment-related maintenance to preserve their design capacity or prevent erosion that threatens infrastructure and assets (HR Wallingford 1987). The requirement under the Water Framework Directive to maximise habitat and biodiversity in channels will dictate that new capital schemes will have to include more natural sediment features. Experience suggests that the whole-life costs of schemes could be reduced, and their environmental value enhanced, if the causes of sediment-related problems and drivers of sediment processes were better appreciated (Environment Agency 1998).

At the heart of the issue is a prevailing view amongst river engineers that the sediment load of a river remains relatively constant along significant portions of its course, at least over engineering timescales (20 to 50 years). In fact, the supply of sediment, transfer paths, and patterns of sediment storage vary significantly at the reach scale over periods of less than 5 years (Environment Agency 1998). This fundamental misunderstanding of the temporal variability and spatial connectivity in the sediment transfer system can best be addressed through geomorphic investigation and analysis of fluvial sediment dynamics.

Despite decades of research on sediment transport theory, engineering-geomorphic methods to predict sediment loads and patterns of sedimentation remain poorly developed and difficult to apply to practical problems. Consequently, there is no engineering handbook of standard techniques to which reference can be made. Instead, practitioners must rely on sound judgement in the selection of methods appropriate to the case in point. Such sound judgement must be based on a thorough grasp of the mechanics of sediment erosion, transport and deposition coupled with an appreciation of connectivity and linkages in the sediment transfer system. It is in this spirit, that this chapter describes these *driving processes* of morphological stability, adjustment and response to engineering intervention in rivers.

3.2 Fluvial Processes

3.2.1 Significance of the Sediment System

Rivers convey sediment as well as water and yet, despite this, the processes responsible for sediment movement in rivers have received far less attention than those involved in water 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 produce and alter the three-dimensional form of the channel (see Figure 2.1). The channel parameters that adjust to changes in the driving variables or boundary conditions have been described as the 'degrees of freedom' which the channel may adjust through time (Hey 1982). Typical links between channel parameters and controlling variables are listed in Table 3.1.

Table 3.1 Degrees of Freedom of the river channel

Degree of Freedom (Dependent variable)	Controlling Variable
Mean velocity	Flow regime
Hydraulic radius (mean and max. depth)	Sediment load
Wetted perimeter (channel width)	Bed material characteristics
Channel slope	Bank material properties
Planform sinuosity	Riparian vegetation
Meander arc length (wavelength)	Valley slope

However, while there is considerable capability to quantify and model the flow of water (through catchment hydrology and channel hydraulics), no equivalent facility exists to predict sediment loads or route them through the drainage network. In fact, it is often difficult even qualitatively to identify the sediment pathways and link sediment sources to sinks. This lack of capability is significant because it limits the potential for river scientists and engineers to identify *causal links* between problems at different locations in the same river system, thereby limiting the scope for sustainable river engineering, conservation and management for the five reasons listed in Table 3.2.

Table 3.2 Significance of sediment dynamics

No.	Impact	Significance
1.	Long-term 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 drainage network is episodic and the sediment transfer system has been described as a 'jerky conveyor belt'. Individual particles travel from headwater source to coastal sink through a series of short duration, but relatively rapid transport events, separated by much longer periods of storage in channel sediment features and floodplain sediment bodies. Nevertheless, long-term continuity of sediment transfer means that any alteration or interruption of the system will result in tangible effects downstream (through elevated or depressed sediment supply) and upstream (through slope and/or planform adjustment).

The sediment transfer system is complex and involves multiple linkages between the flow regime and sediment dynamics as well as complex interaction between these driving variables and the sedimentary features present in the channel (Figure 3.1). Before further considering the sediment system as a whole it is, however, necessary to understand the operation of its component parts: erosion, transport and deposition.

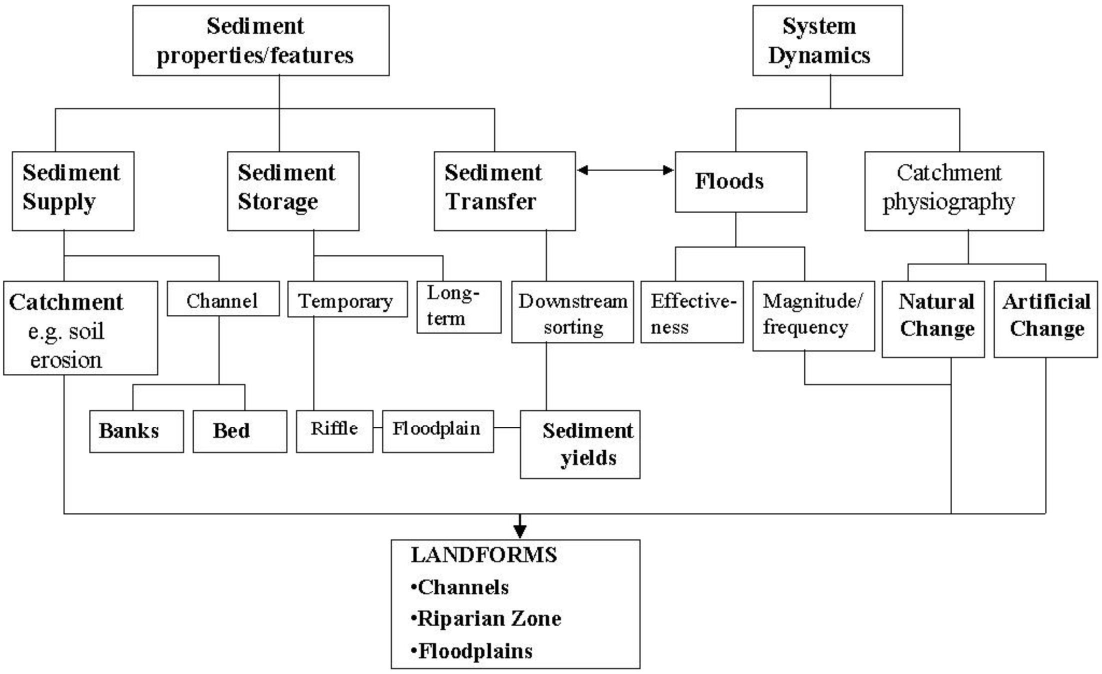


Figure 3.1 Links and interactions between sediment processes and fluvial landforms

3.2.2 Erosion

Catchment Erosion and Sediment Yield

The original source of all sediment in the river network is catchment erosion. Sediment is derived from a variety of processes, operating at different scales and in different parts of the drainage basin. Some sources are localised and site specific; for example an unstable hill slope prone to landslides. Other sources are broad-scale and diffuse, such as soil erosion by surface runoff. Catchment erosion is a natural process that is active to some degree in every landscape but, in developed nations, the intensity and extent of erosion may be increased due to 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 erosion. Urbanisation also increases erosion during the construction phase, although sediment supply may be reduced to below natural levels once urban areas become fully established.

The characteristic types of catchment erosion vary spatially between upland, piedmont (middle course) and lowland regions and Table 3.3 lists the sediment sources that may typically be found in each area of a catchment.

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	

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 fact, only a fraction of the material detached 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. The relationship between catchment erosion and sediment yield depends mostly on two factors: first, the efficacy of 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 carried by these processes.

Typically, either gravity or overland flow drives surface processes responsible for bringing sediment to the channel; for example, rockslides and sheet wash, respectively. The capacity of these (and many other) transport processes to carry eroded sediment increases in a non-linear fashion with the gradient 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. 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 systems.

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 erosion processes are able to operate directly on intact rocks and promote further erosion to produce a supply of coarse particles. The overall result is that, at least in natural systems, catchment sediment yield is usually highest and coarsest in the upland headwaters of the basin. Additionally, the harsh climate and steep terrain of an upland area makes it particularly sensitive to accelerated erosion due to development and primary industries, with over-stocking and forestry ditching well known as causes of elevated sediment yields in headwater catchments in the UK.

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) valley fills, together with coarse sediment input by steep tributary streams that continue to supply catchment-derived sediment from adjacent hill slopes. 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 than the uplands.

Catchment sediment yields in the middle courses of natural drainage systems are lower than in the headwaters as a result of reduced rates of erosion and delivery, although this may not hold for catchments affected by human occupation. Activities such as intensive pastoral and arable farming, and mineral extraction (especially gravel mining) are known to have elevated catchment sediment yields in the middle reaches of UK rivers.

In the lower course, relief is low, soils are deep and the channel is located within a wide valley – limiting opportunities for direct inputs of eroded 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 most lowland catchments in the UK for thousands or tens of thousands of years and so catchment processes are 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, forestry, other primary industries or urbanisation. UK lowlands are heavily developed for arable farming and urban/industrial landuse, leading to elevated yields of clay and silt carried to the channel through extensive drainage networks and by aeolian processes where arable fields are left open to wind erosion for significant periods.

It follows from these descriptions that the characteristics of sediment in the river system are sensitive to changes in catchment landuse and channel management. Indicative channel sediment responses to such changes are listed in Table 3.4.

Table 3.4 Possible changes in catchment sediment characteristics due to changes in landuse or channel engineering

Landuse Change	**Sediment Quality**	**Sediment Size**	**Sediment Compaction**	**Size (+20 years)**
Forestry	0	-	-/+	-
Road construction	-	-	?	+/-
Channelisation	0/-	+	+	+
Urban runoff	-	-	+	+
Accelerated erosion	-	-	-/+	-
Channel Management				
Narrowing/Embanking	0/-	-	+	+
Widening	0/-	-	-	-/+
Downstream of a dam	0	+	+	+
Downstream of sediment trap	0	+	+	+

+ = increase - = decrease 0 = little change

While catchment sediment yield may be influenced by any human activity, it 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:

1. the relationship between rainfall and runoff generation: with drainage density increasing as moisture losses to interception, evaporation and transpiration decrease;
2. infiltration capacity: with drainage density increasing 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 catchment erosion (denudation), 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 artificial drains and ditches effectively extend the drainage network, massively increasing drainage density and 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 marked increases in catchment sediment yield.

It is clear from this brief review of catchment erosion 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.

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 grains' submerged weight and friction between adjacent grains. In theory, motivating and resisting forces are exactly balanced just prior to the erosion 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 sediment in the bed of a river, the bed shear stress is often used as a surrogate measure of flow intensity. Bed shear stress is the 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.

A dimensionless form of the 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, a middle value of 0.047 is often applied as the critical dimensionless shear stress necessary to mobilise bed material under conditions typical of alluvial rivers.

In practice, 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 short duration, high magnitude peaks in the bed shear stress that are actually responsible for the detachment and entrainment of individual grains. Consequently, the precise conditions under which a particular grain will be eroded from the bed of a channel are impossible to predict mechanically and 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 artificial structures in the river. Table 3.5 lists the types and locations of bed scour commonly observed in dynamically-stable, alluvial streams.

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 re-deposited 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 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.
Confluence scour	Bed lowering where two (or more) flow streams merge to form a single stream. Scour occurs due to macro-turbulent eddies generated at 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 2, can cause extreme scour under some circumstances. Prediction of bend scour requires information on bend geometry, approach channel dimensions, discharge, sediment load and bed material composition.
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 such as 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 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 greater than any produced by a single scour process operating alone.

The susceptibility of bed material to scour depends mostly on its size, 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. This *armour layer* acts to protect finer, looser material beneath it, tending to limit bed scour and restricting the transport of gravel downstream. Disturbance of an armour layer during, for example, dredging or de-silting 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 involving the destruction of gravel armour layers have been linked to bed scouring and increases in sediment supply to lowland reaches since the 1960s.

Channel Bank Erosion

In addition to material derived from bed scour, channel-derived sediment may also be obtained in dynamically stable channels through erosion of the banks. Bank erosion in these circumstances 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. While rates of bank erosion and lateral channel shifting in the UK are low on a global scale, falling into the range 0 to about 3 m/yr, the yield of sediment can still be significant. In fact, 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. 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.

While the results of much of the R&D related to river geomorphology conducted during the 1990s were never published in widely available handbooks or guides, that was not the case for work on bank erosion. A joint initiative between the Environment Agency, British Waterways and the Broads Authority brought together the findings of a series of geomorphologically-led R&D projects, together with material from engineering reports, books and practical manuals, to produce a comprehensive guide to the assessment and management of bank erosion (Environment Agency 1997). As this document is readily obtainable, there is no need to reproduce here the detailed and fully illustrated treatment of bank erosion it contains. However, a brief overview is still included for completeness.

In UK rivers, serious bank retreat and the input of significant amounts of sediment to the fluvial system rarely results 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:

i. Bank erosion processes which detach, entrain and transport individual particles or assemblages of particles away from the surface of the retreating bank;

ii. Bank failure mechanisms which lead to collapse of all or part of the bank;

iii. Weakening processes, which operate on or within the bank to increase its erodibility and reduce its geotechnical stability.

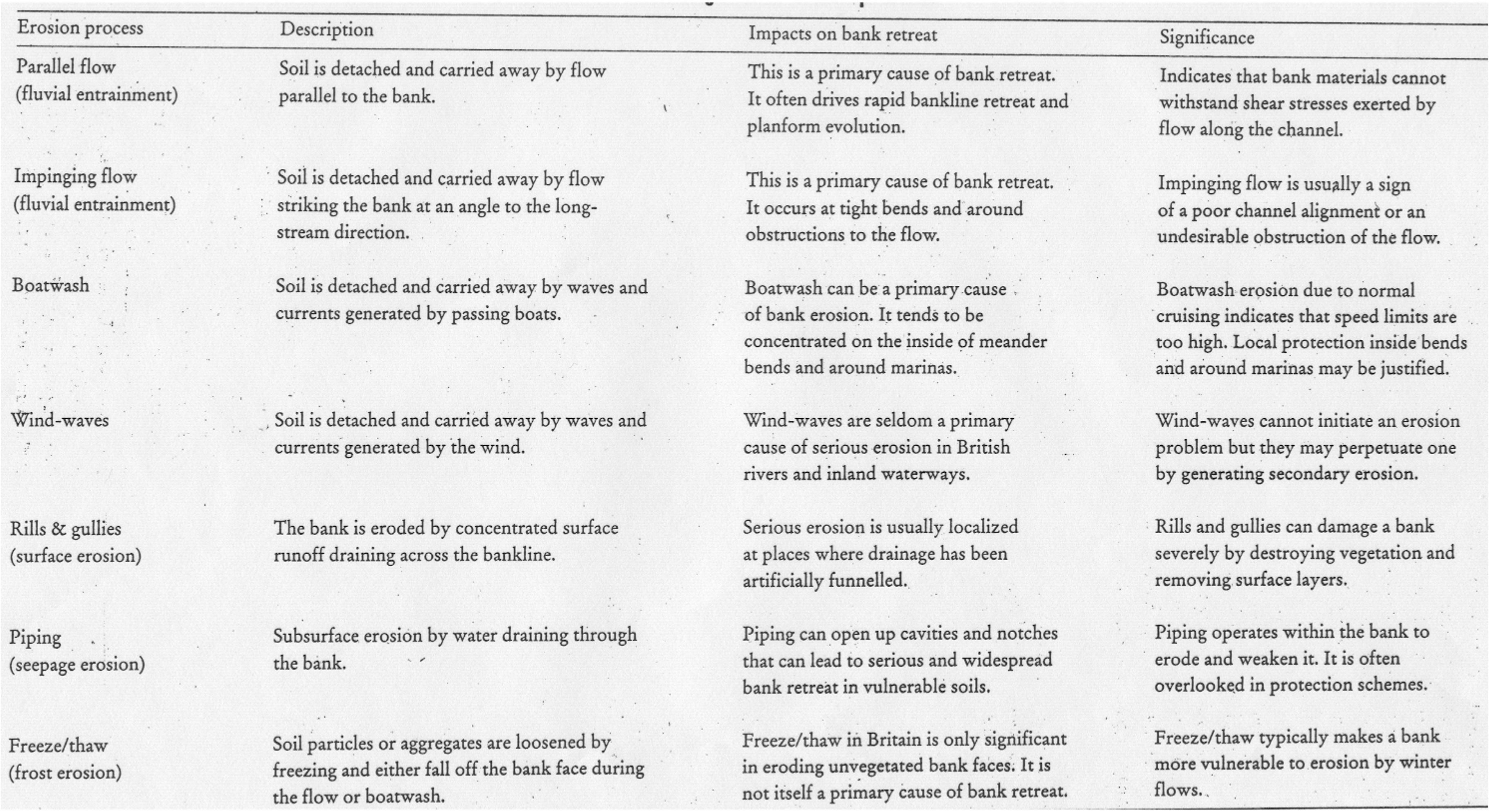
While in nature these processes and mechanisms usually act together, it is useful when describing them to consider them separately. However, in order to appreciate the causes of serious and sustained bank retreat it is necessary to consider how the bank profile responds to different combinations of erosion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

In R&D Report 28 (NRA 1996) seven categories of bank erosion process, seven types of bank failure and six bank weakening factors were identified as having the potential to contribute significantly to serious bank retreat in UK rivers. The description, impact and significance of each of these processes, mechanisms and factors are summarised in parts I, II and III of Table 3.6, respectively. Figure 3.2 illustrates and outlines some of the more commonly observed modes of bank failure schematically.

When analysing bank instability it is useful to desegregate the effects of different processes, mechanisms and factors because they are each influenced by different process drivers (Table 3.7). Understanding the nature of the geomorphological processes driving erosion, is the first step towards explaining how retreat relates to climate, fluvial and soil conditions at the site. In turn, this explanation of process-form linkage underpins the ability to predict response in the degree of instability and rate of retreat to changes in catchment conditions, human activities, 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 bank erosion. 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 *cause* of a bank erosion problem.

Table 3.6 I. Classification of bank erosion processes (NRA 1994a)



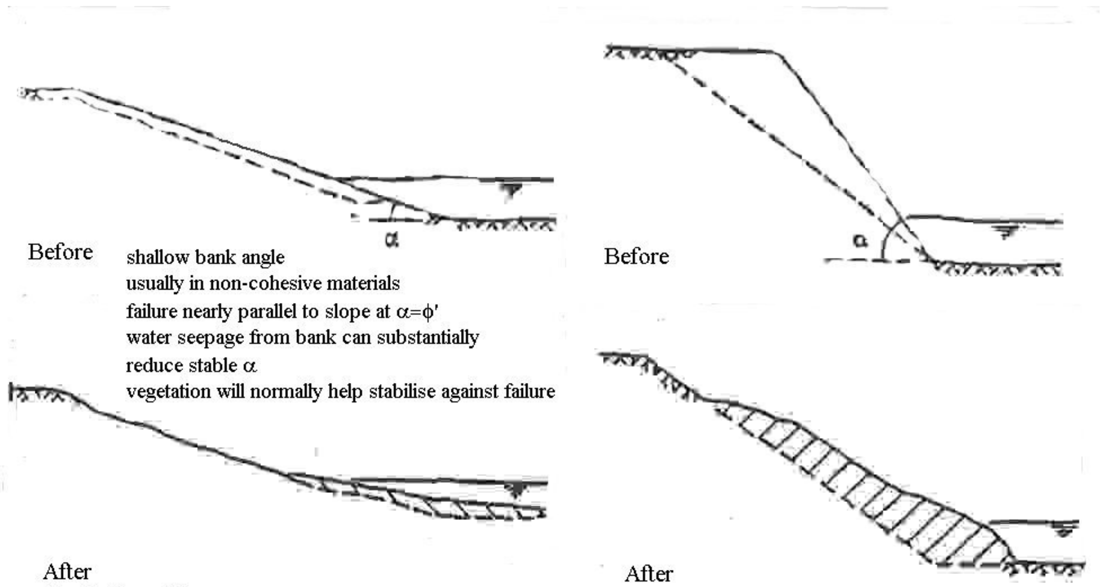
Erosion process	Description	Impacts on bank retreat	Significance
Parallel flow (fluvial entrainment)	Soil is detached and carried away by flow parallel to the bank.	This is a primary cause of bank retreat. It often drives rapid bankline retreat and planform evolution.	Indicates that bank materials cannot 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 & gullies (surface erosion)	The bank is eroded by concentrated surface runoff draining across the bankline.	Serious erosion is usually localized 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 fall off the bank face during the 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.

Table 3.6 II. Classification of failure mechanisms (NRA, 1994a)

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 a 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 into 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 pore water 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 stabilization must include enhanced subsurface drainage.

Table 3.6 III. Classification of weakening factors (NRA 1994a)

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	Occur 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 electro-chemical bonds.	Loosens soil crumbs on exposed bank surfaces during hot summers.	Significance is limited to river cliffs and other places where vegetation is absent.



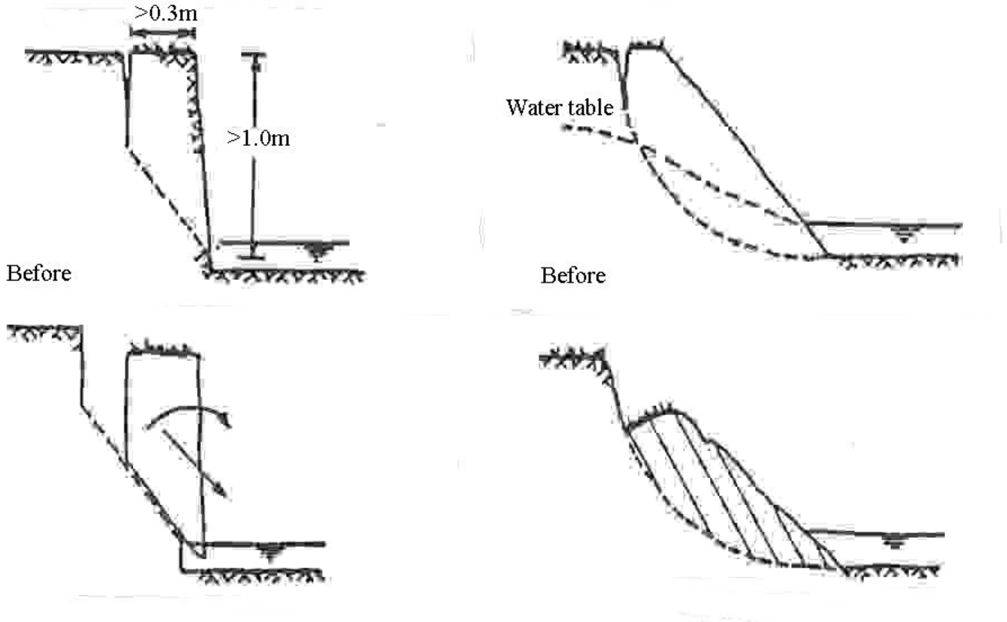
shallow bank angle
usually in non-cohesive materials
failure nearly parallel to slope at $\alpha=\phi'$
water seepage from bank can substantially
reduce stable α
vegetation will normally help stabilise against failure

(a) Shallow failure

shallow bank angle
usually in non-cohesive banks
failure nearly parallel to slope at $\alpha=\phi'$
water seepage from bank can substantially
reduce stable α
vegetation will normally help stabilise against failure

(b) Planar failure

steep or vertical bank angle
frequently (but not always) in non-cohesive banks
water table/channel water level usually low relative
to total bank height



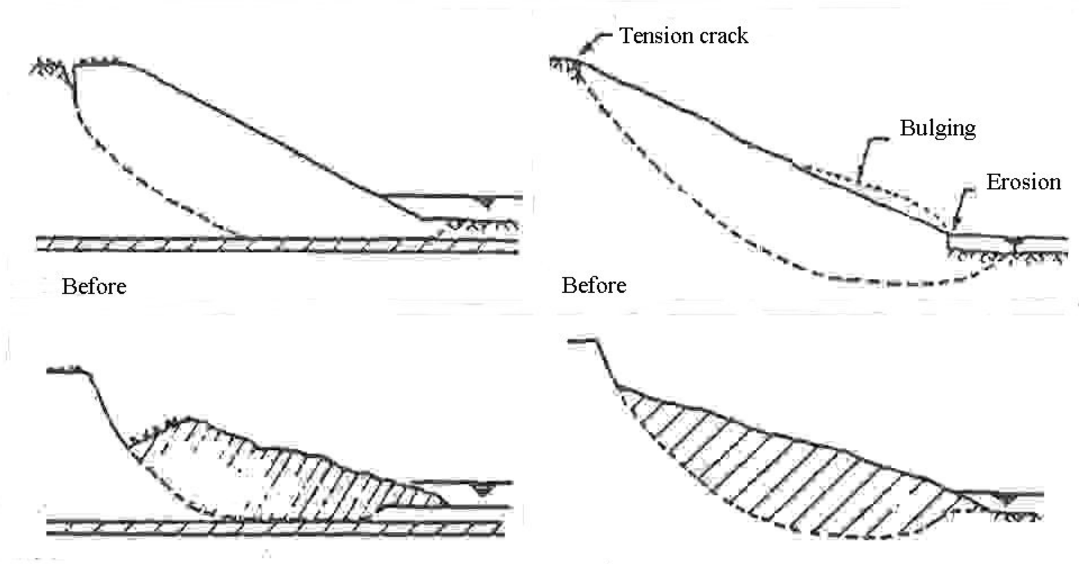
(c) Planar/slab failure

steep or near vertical banks
deep tension cracks
failure occurs by sliding and/or toppling
failure more likely if crack fills with water
little affected by groundwater table

(d) Rotational failure in homogenous material

usually on moderately high or steep banks
ususally in cohesive material
tension cracks reduce stability particularly
when water filled
significantly affected by position of water table

Figure 3.2 Commonly observed modes of bank failure (NRA 1994a)

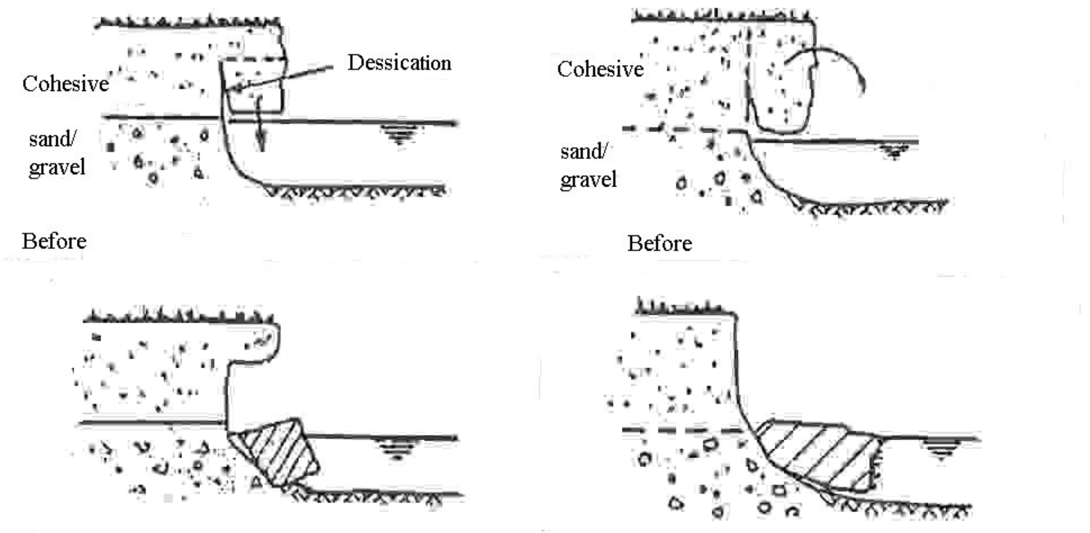


After
(e) Rotational failure with weak zone

failure surface dictated by position of weak zone
see also comments for type (d)

After
(f) Massive rotational failure/landslide

erosion of river bank threatens stability of whole valley side
very large volume of slipped material
tension cracks up valley side, bulging above toe, or noticeable movement are signs of potential failure



After
(g) Failure of composite bank (in tension)

occurs only where upper cohesive layer overlies erodible sand/gravel
failure by tension of lower part of overhanging block

After
(h) Failure of composite bank (as beam)

occurs as type (g)
failure with upper soil tension, followed by rotation
after failure block usually remains intact with vegetation towards river
failure can also be by shear

Figure 3.2 Commonly observed modes of bank failure (NRA 1994a)

Table 3.7 Process drivers influencing bank retreat

Category	Process/mechanism/ factor	Driver
Erosion	Flow erosion	Intensity of near-bank flow – represented by bank shear stress or stream power and influenced by channel form, flow deflection, flow impingement and flow curvature effects (secondary currents).
	Boat wash	Wave height and frequency – controlled by vessel design, speed, and distance from bank, navigation traffic density and shape of channel.
	Rills and gullies	Concentration of water draining over bank – influenced by floodplain topography, land drainage and stock access.
	Piping	Concentrated sub-surface drainage – caused by adverse bank stratigraphy, compaction, and land drainage.
	Freeze/thaw	Freezing temperatures and frost – influenced by microclimate and lack of vegetation cover.
Mass Failure	Shallow slide	Over steepening of bank by fluvial undercutting due to intense near-bank flow.
	Rotational slip	Over high or steep bank due to fluvial scour at toe due to intense near-bank flow usually combined with surcharging, intense precipitation, adverse drainage.
	Slab failure	Over high or steep bank due to fluvial undercutting due to intense near-bank flow usually combined with soil cracking.
	Cantilever failure	Instability in an overhanging bank due to fluvial undermining, soil cracking and high saturation.
	Soil fall	Loss of soil strength caused by action of weakening factors (see below).
	Earth flow	Saturation and positive pore water pressures caused by adverse drainage conditions liquefy soil.
Weakening	Leaching	Concentrated sub-surface drainage. Loss of minerals due to soil seepage flow in areas of.
	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.
	Pore water pressure	Restricted or adverse drainage coupled with long periods of bank inundation and/or heavy precipitation.
	Desiccation	Intense drying of bank material due to lack of precipitation, lack of shade, and bank orientation.

To explain the concept of basal endpoint control, it is necessary to visualise the sediment movement system in the near bank zone of the channel (Figure 3.3). Sediment may be supplied to near bank zone from upstream and/or from the bank itself – due to either erosion or failure of the bank. Sediment may be removed from the near bank zone either to downstream, by the main current, or laterally towards the centre of the channel by secondary currents or wave action. These sediment fluxes allow three states of sediment balance or imbalance 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 the three possible states of basal endpoint control (Table 3.8).

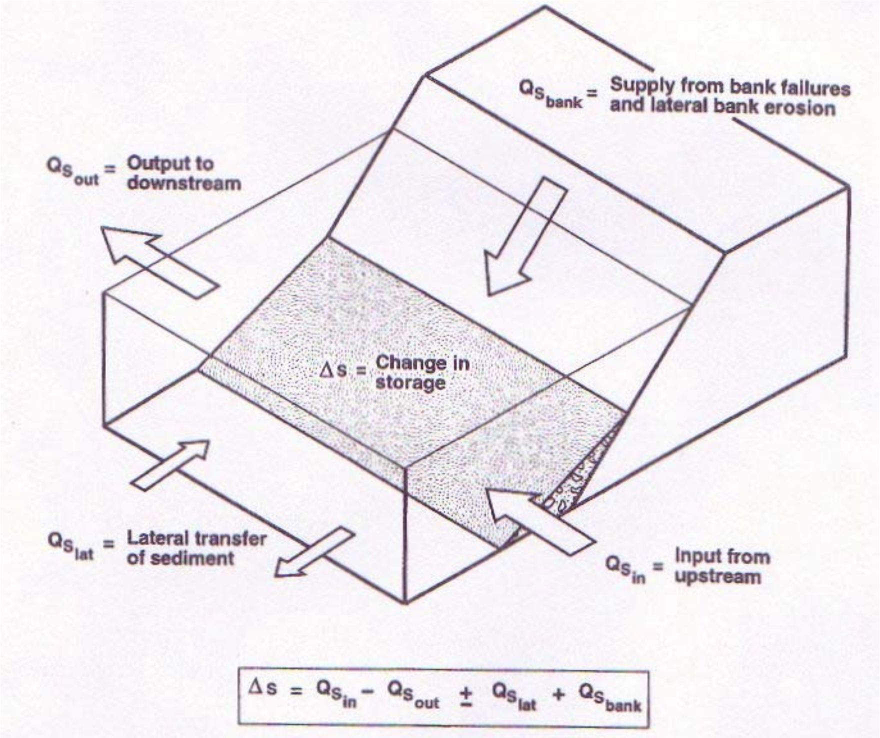


Figure 3.3 Sediment fluxes in the near bank zone (after Thorne 1997)

Table 3.8 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 reduced, triggering mass failures that increase sediment supply to bank base. Rate of bank retreat accelerates, tending towards 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 at base of bank. Rate of bank retreat matched to rate of sediment removal by currents and waves. Bank retreats through parallel retreat (i.e. bank profile does not change through time) at rate governed by rate of sediment removal from base.
Impeded removal	Rate of sediment removal lower than rate of supply (output < input). Sediment accumulation at base to account for difference, forming low angle beach, wedge or berm. Accumulated sediment protects intact bank behind it from erosion and tends to stabilise bank, reducing rate of sediment supply. Rate of bank retreat decelerates, tending towards state of unimpeded removal with rate of bank retreat adjusted to match rate of sediment removal at the base of the bank.

Sustained, long-term retreat of a river bank depends on the near bank flow being able to remove sediment and bank debris from the foot of the bank at the same rate that it is generated by bank erosion and failure. This demonstrates that while the processes and mechanisms responsible for bank instability may not be directly related to flow 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 that retreat. The effect is to reveal that long-term bank retreat is tied inexorably into the wider sediment system as an integral component of sediment transfer and exchange in reaches that are active laterally.

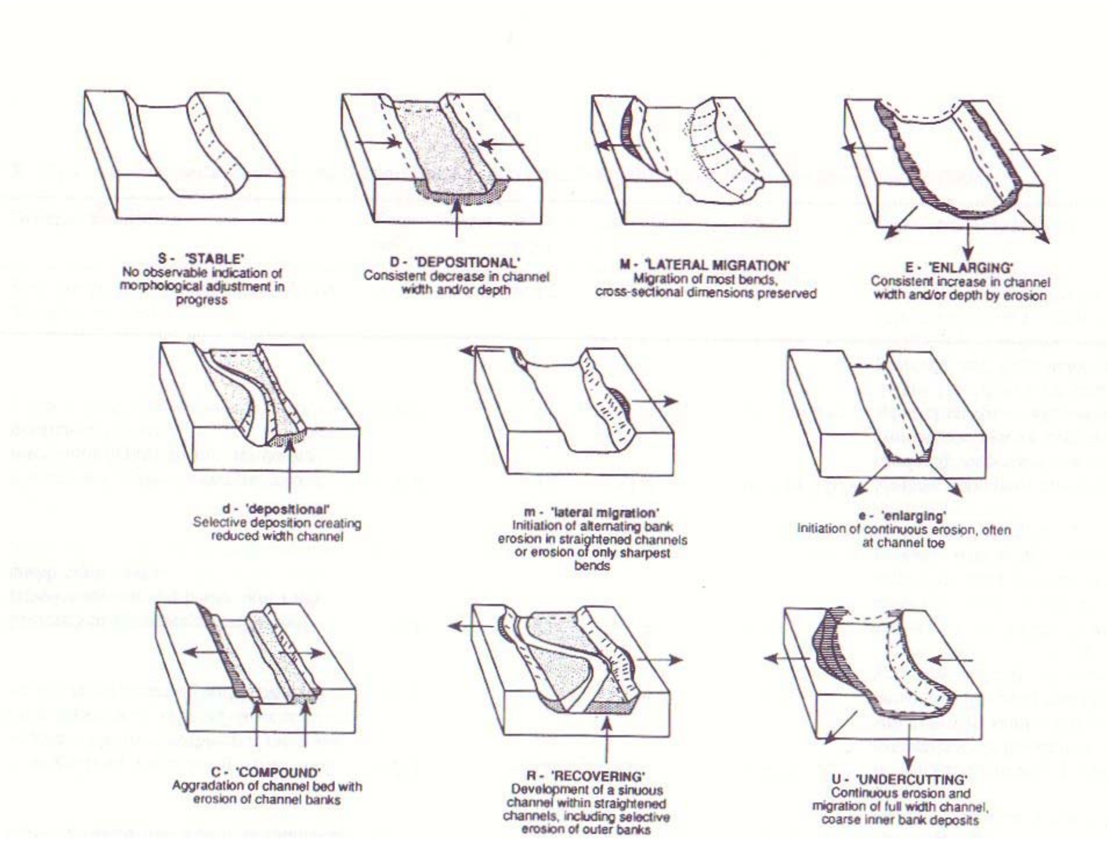
In light of this, useful insights can be gained when examining an eroding bank by inspecting the bank profile and the sediment balance at the foot of the bank to identify the state of basal endpoint control. This will this allow the observer to appreciate how closely the eroding site is coupled to the catchment, river and reach-scale sediment systems and so place. Also, it will help guide selection of an appropriate response where continued erosion poses unacceptable risks to properties of infrastructure.

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, 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 supply this to downstream reaches, usually 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 processes whereby the elevation of the channel bed increases 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, 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 mutual adjustment in bed elevation, cross-sectional geometry and planform pattern. The balance between changes at the bed and the banklines strongly affects both the amount and the calibre of sediment derived through channel adjustments in an unstable channel.



S - 'STABLE' No observable indication of morphological adjustment in progress

D - 'DEPOSITIONAL' Consistent decrease in channel width and/or depth

M - 'LATERAL MIGRATION' Migration of most bends, cross-sectional dimensions preserved

E - 'ENLARGING' Consistent increase in channel width and/or depth by erosion

d - 'depositional' Selective deposition creating reduced width channel

m - 'lateral migration' Initiation of alternating bank erosion in straightened channels or erosion of only sharpest bends

e - 'enlarging' Initiation of continuous erosion, often at channel toe

C - 'COMPOUND' Aggradation of channel bed with erosion of channel banks

R - 'RECOVERING' Development of a sinuous channel within straightened channels, including selective erosion of outer banks

U - 'UNDERCUTTING' Continuous erosion and migration of full width channel, coarse inner bank deposits

Figure 3.4 Types of Adjustment commonly observed in Unstable Channels (after Downs 1995)

Neither is change confined to the channel itself. Significant erosion of the floodplain may occur during out-of-bank events to remove sediment from long-term storage in the deposits filling the floor of the valley. Such instability may produce marked changes in floodplain topography and alter the location and planform pattern of the river. Table 3.9 lists the main types of scour in unstable rivers, including both in-channel and over bank processes.

Table 3.9 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 and, if it destabilises the banks, it also boosts the yield of fine sediment and threatens 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 and morphological evolution.

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 three in just a few years and produce very high inputs of fine sediment to downstream reaches.
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 over bank 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 avulsion (see below).
Avulsion	Is the abandonment of the channel along a substantial length of river and adoption of a new course at another location on the floodplain. 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 with serious implications for channel stability both up and downstream
Planform Meta-Morphosis	Defined by the switching of the channel from one planform pattern to another in response to the crossing of an intrinsic geomorphic threshold. 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 lowland sedimentation. Conversely, metamorphosis of a braided channel into a meandering channel could result in much greater scour depths in the resulting, single channel, elevating downstream supplies of coarse bedload.

3.2.3 Sediment Transport

Transport Mechanics

Transfers of material in the fluvial system take place through the transport of sediment downstream from erosive source to depositionary sink. It is, therefore, sediment transport that links up 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 the 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, but the quantity of sediment actually in motion is restricted by its availability, the sediment load is said to be *supply limited*. Generally, in UK rivers 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.

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 motion episodic. This fact may be demonstrated by reference to long-term bed material trapping records from sediment traps in Lake District streams (NRA 1994a). Figure 3.5 shows the maintenance record for a gravel trap on Coledale Beck, illustrating that the great majority of the 5,958 tonnes or gravel trapped during a 50-year record was actually transported during just four flow events that occurred in June 1952, May and October 1954, and June 1956 (months 130-170). Conversely, the relatively low yields associated with floods in 1960s and 1970s (months 370-480) may indicate that gravel transport was supply limited due to exhaustion of available storage areas by flow events during the 1950s.

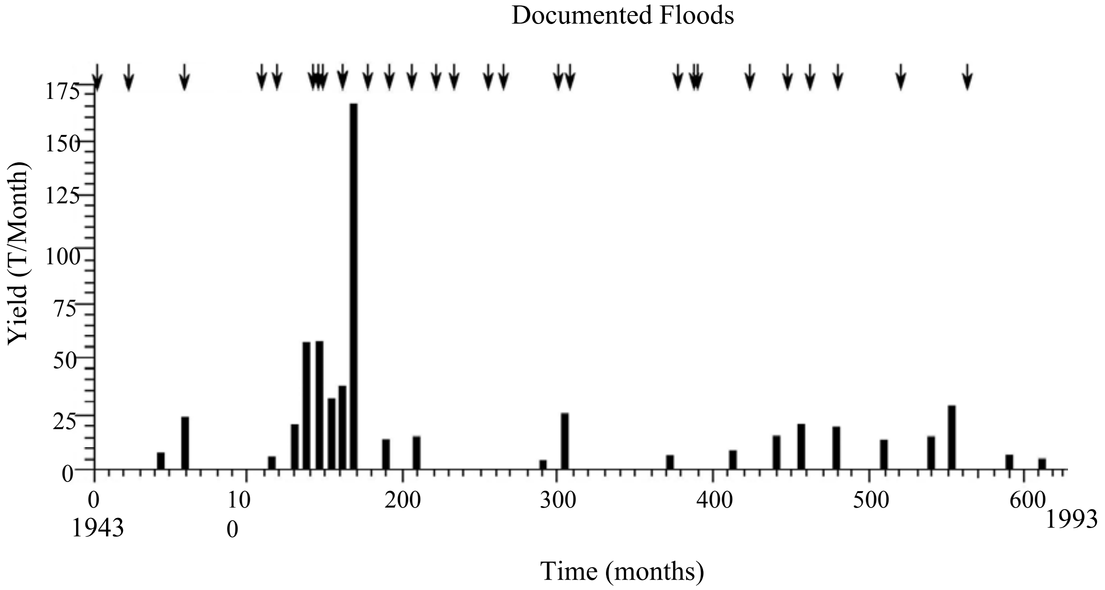


Figure 3.5 50-year record of gravel yield (in-trap accumulation) in a gravel trap on Coledale Beck in the Lake District. Arrows indicate occurrence of flood events (NRA 1994b).

The distribution of sediment transport through time and space during a particular transport event is also unsteady and non-uniform. Data obtained from gravel traps fitted with equipment to record the accumulation of material at frequent intervals demonstrate that bedload characteristically moves in pulses, so that the shapes of the water and sediment hydrographs do not correspond to one another (Figure 3.6). While it is believed that bedload pulses like those in the record for Turkey Brook are ubiquitous to gravel-bed rivers and may be explained in part by dynamic adjustments to the make up and fabric of the armour layer, no complete theory exists to allow their explanation or prediction.

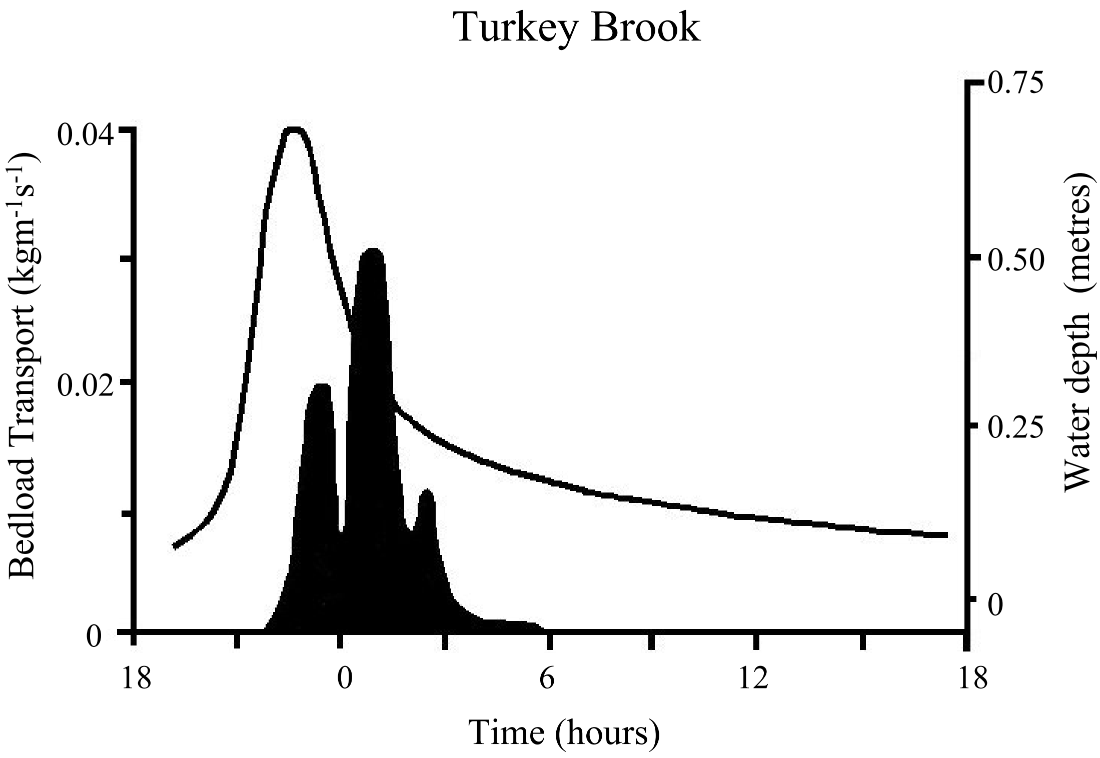


Figure 3.6 Storm hydrograph and sediment hydrograph showing pulses of bedload movement out of phase with variation in stream flow (after Reid & Frostick, 1985).

This short review of the variability and complexity of sediment transport through time and space illustrates why it is problematic to attempt to predict sediment loads based only on contemporary flow hydraulics and a simple measure of sediment size. It also indicates that knowledge and understanding of additional factors (including: sediment availability, particle arrangement and bed fabric, and a record of recent and historical transporting events) are also required to make accurate predictions.

Classification of the Sediment Load

Erosion of the catchment takes place through the removal of soil and rock material that is dissolved in the river water (the solute load) and the 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 systems for classifying the sediment load (Table 3.10).

Table 3.10 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.

	Wash load	Sediment mainly supplied by catchment erosion and which is finer than that found in substantial quantities in the bed of the channel.
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 using conventional equipment and techniques.

The existence of multiple bases for classifying and accounting for the sediment load is the source of a great deal of confusion concerning sediment dynamics and their morphological significance. This arises because terms such as 'bedload' and 'bed material load' are *not* inter-changeable, 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 3.11 illustrates the relationship between the different constituents of the sediment load definitively, and frequent reference to such a diagram is recommended whenever sediment transport and the make up of the sediment load are being discussed.

Table 3.11 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="3">Bed material load</td></tr>
<tr><td rowspan="2">Unsampled load</td></tr>
<tr><td>Bedload</td></tr>
</table>

Bed material grading, armouring, sorting and fabric

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. Poorly graded sediments consist of a mixture of widely differing sizes of material. For example, in an upland stream the bed may be made up of a particles ranging from boulders (material with a median diameter larger than 256 mm) to sand (material finer than 2 mm). In studies of sediment transport, the mobility of a grain has been found to depend not only on its actual size, but also on its size relative to that of other particles making up the channel bed. 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, the largest grains tend to protrude above the bed and be over-exposed when part of a mixture. 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 size.

The effects of grading are most pronounced in cobble and gravel-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. Grading is accounted for in sediment transport equations like that of Ackers-White by calculating the transport rate for each size fraction (D_{10}, D_{20}, D_{30}..etc.) rather than using a single size parameter (such as the median grain diameter, D_{50}). In sediment routing by size fraction, the model must keep track of the size distribution 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 a flood the smaller grains are entrained earlier and transported further than the larger ones, with important impacts on the composition of the bed, sorting of the sediment load and downstream sediment transfer.

Selective entrainment of the smaller grains in a mixture leads to development of a coarse surface layer composed preferentially of the larger, less mobile grains. In extreme cases, where there is no re-supply of mobile gravels from upstream, a stable, immobile surface layer termed a '*pavement*' develops. Paved beds are found downstream of dams and in degraded reaches where the bed has scoured away all the mobile bed 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 termed an *armoured bed*. Armouring further reduces the mobility of finer grains by its macro-hiding effect on the finer, underlying substrate, but it does not eliminate bed material motion entirely.

Research in fluvial geomorphology has demonstrated the huge significance of armouring to bed material loads, bed scour and benthic habitats in gravel-bed rivers. 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, but these effects are lost if the armour is destroyed due to a large flood, gravel mining or dredging. Hence, downstream sediment loads, bed stability and in-stream habitats in gravel-bed reaches are particularly vulnerable to extreme events, in-channel activities and careless management.

Sorting occurs because the effects of hiding do not entirely eliminate selective entrainment of finer grains from an armoured bed and because the transport distance for a grain increases as its size decreases. The results of sorting are a downstream fining in the size and increased uniformity (that is mixed sediments 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, research demonstrated that this is not a significant contributor to downstream fining in British rivers and that sorting through selective entrainment and preferential transport of finer grains are able to explain observed downstream trends in bed material size.

Fabric 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 an loose packing pattern with relatively open interstices that allow water to flow freely through the gravel matrix. 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 a loose bed. For example, the critical dimensionless shear stress for entrainment of very loose gravel is about 0.03 but this rises to in excess of 0.06 for compacted gravels. Also, with time the interstices of compacted gravels tend to fill with fine sediment that filters down into the bed from the throughput or wash loads. Clogging of gravels by fines further reduces mobility, reduces water flow within the bed and greatly reduces the value of the bed in terms of 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 structure and fabric of the bed is required, as well as data on characteristic sediment size and gradation.

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 reliable data derived from field measurements of sediment load. 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, in error by as much as one or two orders of magnitude. Table 3.12 lists some of the more popular sediment transport formulae, together with some comments on their performance gleaned from R&D reports.

The Ackers-White equation has been used recently 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 river modelling and, somewhat unusually, the findings are available in a substantive academic paper (Walker, 2001).

Table 3.12 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 over predicts.
Bathurst, Graf and Cao (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). Over-predicts 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. Over-predicts.
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 at present.

The transport of coarse sediment derived from the bed of the channel is usually limited by the capacity of the flow and may 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 endorsed in a number of NRA/Environment Agency R&D projects, which have used the Bagnold formula with success. On this basis, it may be appropriate for general usage.

The bedload transport rate per unit width of the active channel bed (in 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 S.I. units. For use in Bagnold's equation, the stream power index is defined by:

$$\omega' = \frac{\rho QS}{w}$$

where, ρ = water density, Q = stream discharge, S = energy slope (usually approximated to the water surface slopes), and w = channel bed width. The critical value of the stream power index 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, the load of fine-grained sediment moving as 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 equations based on flow hydraulics. Much wash load is derived from catchment erosion and Agency R&D projects have demonstrated that a more fruitful approach is to relate fine load to catchment area. This topic is developed further in Chapter 4.

3.2.4 Deposition and Storage

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 (estuary or sea). Consequently, sediment spends periods stored in the landscape in the form of *alluvium*: that is material making up channel bed, channel margin and floodplain sediment features and bodies. The duration of storage varies widely depending on the sedimentary feature involved. For example, in-channel sediment storage in active bars and riffles is usually short-term, while marginal berms act as longer-term stores and floodplain sedimentary units represent 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.

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 due to reduction in discharge on the falling limb of a storm hydrograph;
2. The sediment transport capacity of the river decreases in the long-stream direction due to a reduction in channel slope, a flow obstruction or an increase in flow resistance.

Characteristic in-channel depositionary features include bars (often termed shoals), 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 (boulder and cobble), material recently eroded from steep slopes and valley sides. This is the case because transport in this zone occurs only during short-duration, infrequent storms and because opportunities for deposition in over-bank areas are limited by the narrow width of the valley. Characteristic depositionary features include boulder steps with cobble deposits between them in the channel bed, and boulder berms along the margins.

In the middle course, channel deposition is dominated by the formation of cobble and gravel riffles, shoals and bars. The term 'shoal' is not widely used in geomorphology, but it is used by maintenance and fisheries staff. In this guidebook the terms 'shoal' 'bar' may be used interchangeably. 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 that are beyond the scope of this guidebook. However, Figure 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. These bars and shoals 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 part of the drainage network.

Deposition of relatively coarse sediment moving as bedload and organised into bars and shoals in the middle course of the river is closely associated with erosion of finer-grained sediment from the floodplain through bank erosion. Adjustments to the size and location of bars drive bank retreat and planform evolution that allows the sediment transfer system to *exchange* coarse bedload for finer sediments that are subsequently transported to the lowlands as suspended and wash loads. Sediment exchange often takes place through the growth and migration of bends in meandering channels.

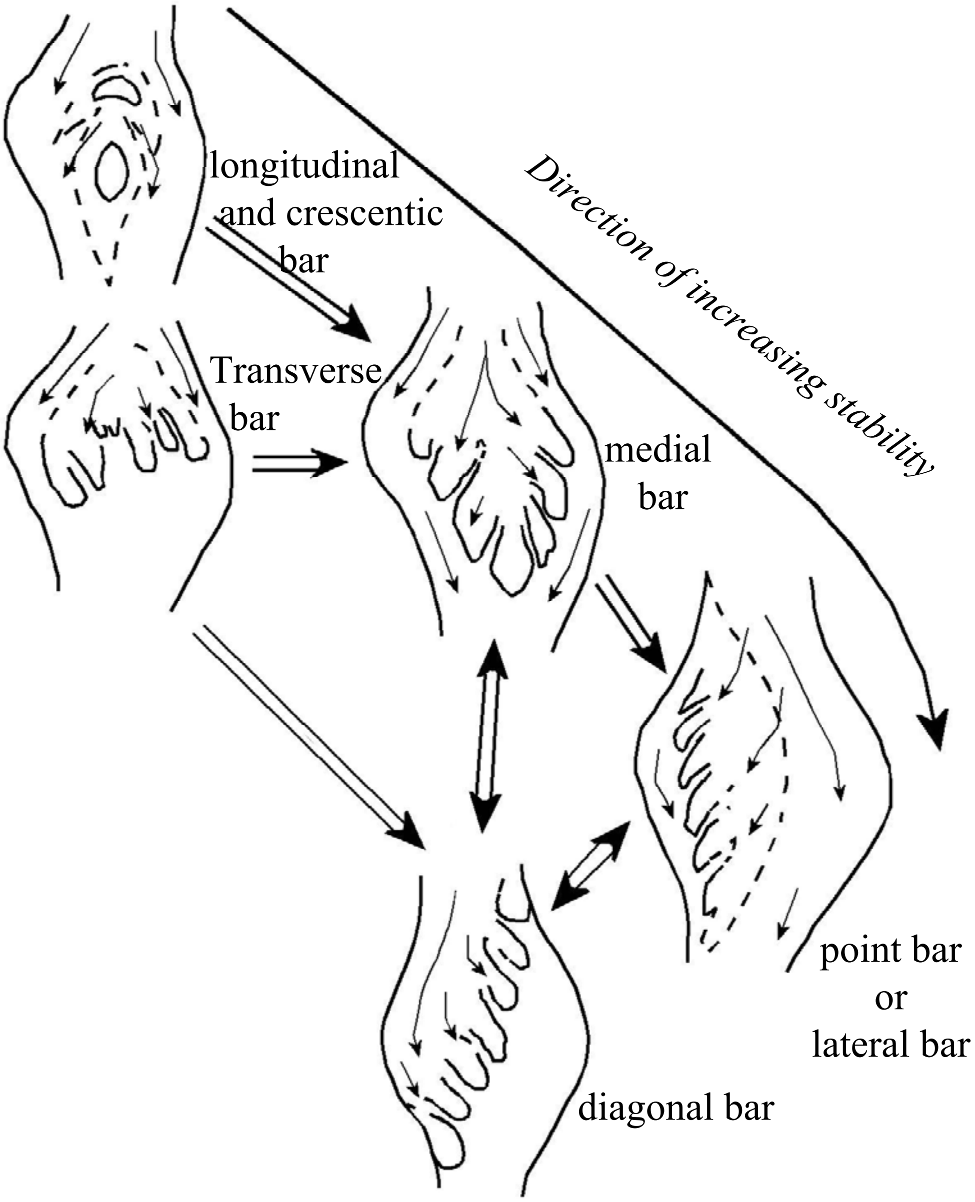


Figure 3.7 Typical channel bars observed in gravel and cobble-bed rivers with active bedload transport (after Church & Jones, 1982)

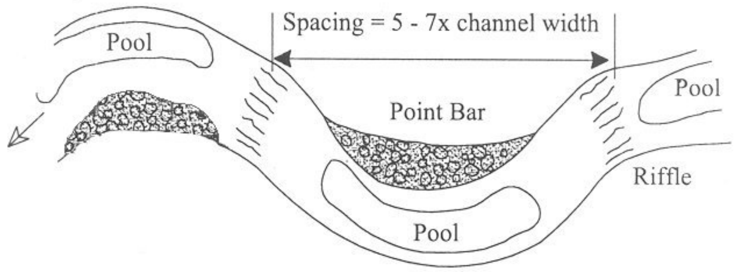
To understand sediment exchange in meandering rivers, it is necessary to consider briefly how water and sediment moves through a sinuous channel (Figure 3.8). Secondary currents, established due to flow curvature effects, heavily influence the distribution of velocity. At bends, fast, surface water is thrown outwards to plunge near the outer bank before return as a near-bed current. Inter-action between the helical cell so formed and the bank sets up a small, counter-rotating cell adjacent to the outer bank. The combined effect of these secondary cells is to concentrate bed scour in the outer half of the channel and attack the outer bank, promoting asymmetry in the cross-section and driving outer bank retreat. Conversely, deposition and bank advance is promoted where secondary flow upwells in the inner half of the channel. Taken together, these processes lead to bend growth and migration.

Figure 3.8 Distributions of surface and near-bed flow, and bedload transport in meandering channel (NRA 1994b)

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 Figure 3.8, sediment transport is concentrated over the point bar and it is predominantly relatively coarse, bed material load that is deposited there. Material eroded from the outer bank travels downstream to the riffle at the inflection point between bends, where it is sorted. The coarsest fraction tends to stay on the riffle; medium sized material is stored on the next point bar (on the same side of the channel), while the finer fraction carries on downstream. 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 change due to contemporary erosion and sedimentation are illustrated in Figures 3.9 and 3.10.

(a) Typical location of riffles, pools and bars



(b) Typical response of channel to an increase in sediment supply upstream

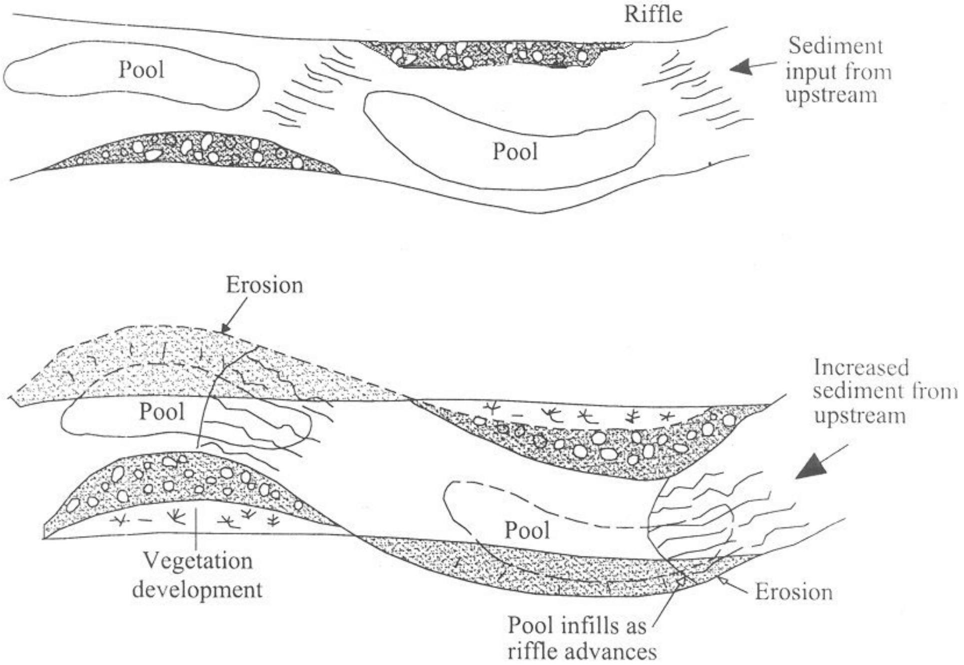


Figure 3.9 Contemporary erosion and sedimentation in the middle course associated with: a) sediment exchange and lateral channel shifting; b) an increase in sediment supply (NRA 1994b)

In the lower course, deposition is usually dominated by fine sediments (sands, silts and clays) and in-channel features are often less significant, in terms of the quantity of material deposited, than marginal and over-bank storage.

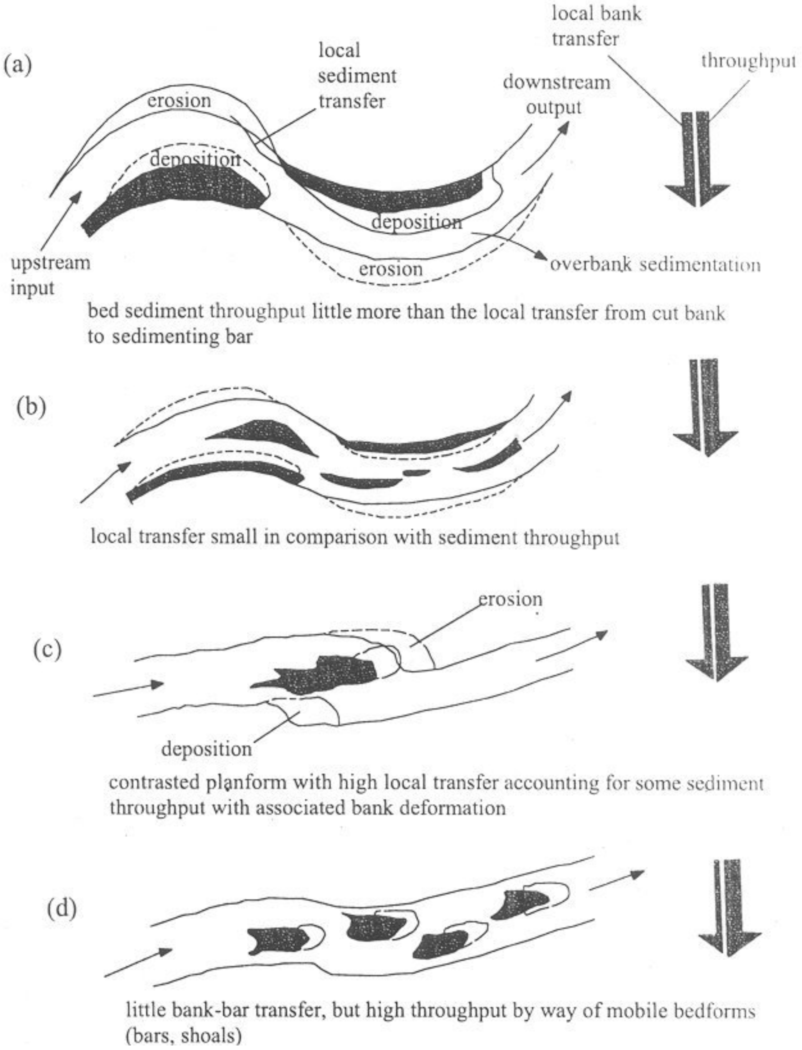


Figure 3.10 Dynamic response in the sediment exchange system to changes in the balance between bank transfer and throughput loads

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 retardance.

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 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 just downstream of the bend apex (where main flow separates and re-circulates), 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 re-circulating eddy).

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.

During major 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 have 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 detail 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, the outcome is generally to concentrate overbank deposition close to the banklines. While sedimentation also occurs on the floodplain remote from the channel due to the export of suspended load that accompanies the export of momentum, deposition decreases exponentially, both in terms of particle size and quantity, with distance from the bank edge. 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.

Innovative research using radio-isotopes deposited during atmospheric testing of nuclear weapons in the 1950s and 60s has established that recent and contemporary rates of floodplain deposition in the UK are not negligible. Typically, floodplain elevations in the Southwest of England are increasing at average annual rates of 3 to 9 mm/yr due to deposition of fine sediment derived primarily from catchment and bank erosion sources (D. E. Walling, personal communication 2002). 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.

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 is comprised of a series of sources, transfer links and stores extending through the drainage network. Consequently, changes to the catchment yield of sediment 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 sediment transfer and exchange. Impacts are transmitted downstream through either elevated sediment supply 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 slope reduction) and planform (changes in sinuosity or metamorphosis between straight, meandering or braided patterns).

However, a change in sediment yield or an episode of reach-scale instability does not necessarily trigger discernible response 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 amplify the impact or to make the channel particularly sensitive (responsive) to destabilisation.

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, coarse substrate sediments, 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 system of its sediment. Typical breaks in the sediment transfer system include lakes and 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 geomorphic insight, the first step to enlightenment.

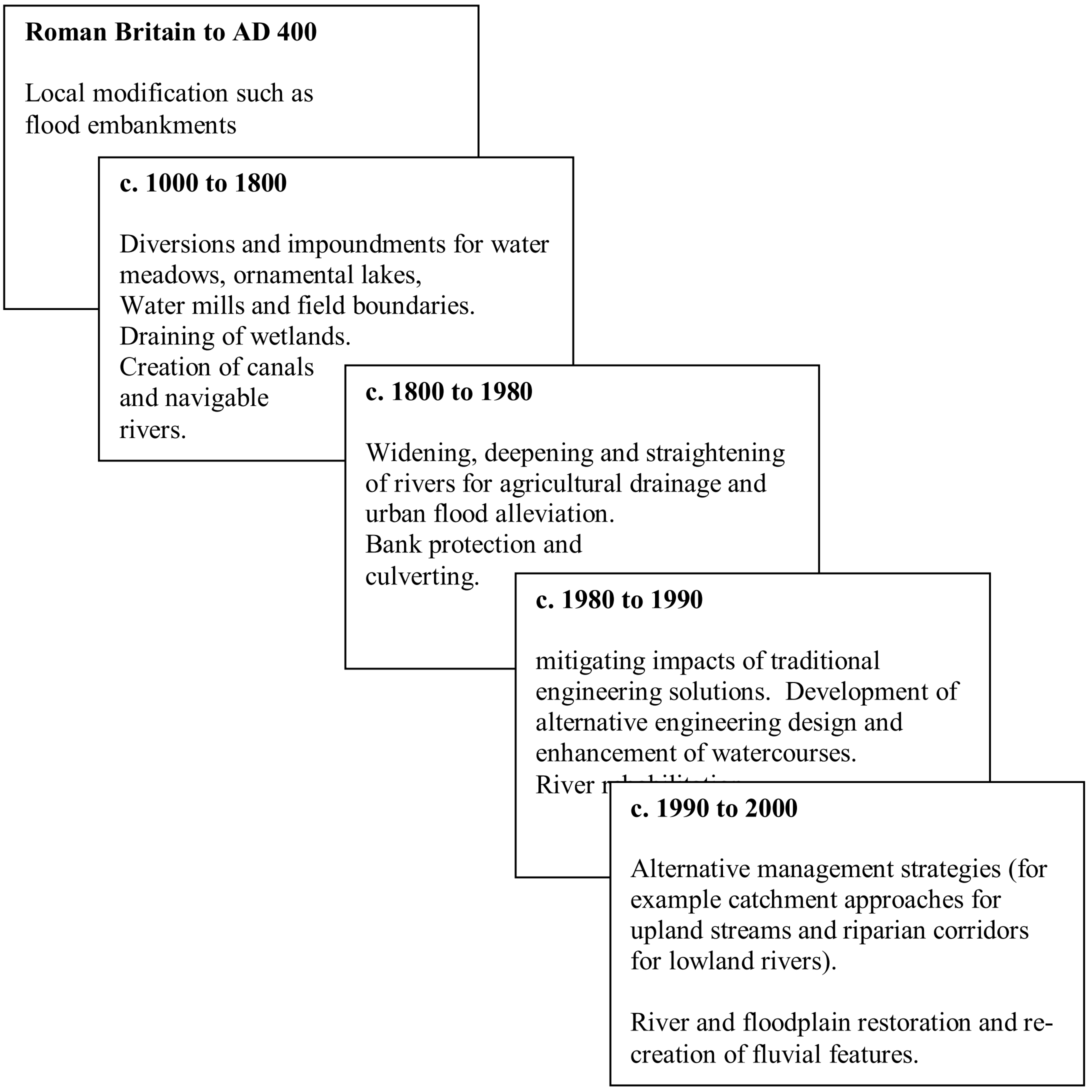
3.3.2 Timescales of Channel Adjustment and Channel Evolution

In the past, policy, planning, and operational horizons in river engineering and management were generally limited to project and budgetary timescales. Adoption of new approaches related to 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 that occur in response to changing environmental conditions. 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 catchment changes, engineering interventions or 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 landuse may take decades or centuries to be completed (see Figure 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 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 large-scale adjustments means 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 simply in the natural and anthropogenic phenomena that can be observed today. Consequently, a historical element to geomorphological investigation and explanation is essential, with information obtained from old 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 1 500 years and it is 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, Figure 3.11 highlights some landmark periods in the history of channel management in the UK.

While the accuracy of historical data may be often 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.



Roman Britain to AD 400

Local modification such as flood embankments

c. 1000 to 1800

Diversions and impoundments for water meadows, ornamental lakes,
Water mills and field boundaries.
Draining of wetlands.
Creation of canals and navigable rivers.

c. 1800 to 1980

Widening, deepening and straightening of rivers for agricultural drainage and urban flood alleviation.
Bank protection and culverting.

c. 1980 to 1990

mitigating impacts of traditional engineering solutions. Development of alternative engineering design and enhancement of watercourses.
River

c. 1990 to 2000

Alternative management strategies (for example catchment approaches for upland streams and riparian corridors for lowland rivers).

River and floodplain restoration and re-creation of fluvial features.

Figure 3.11 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 adjusts to fluvial processes operating under a range of flows with low to moderate return periods. 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. Notwithstanding this, extreme events of high magnitude but long return period can have lasting impacts on the fluvial system. 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 to elevate catchment sediment supply not only during the event but for decades after.

For example, a geomorphological study of Shelf Brook, Derbyshire (NRA 1994a) 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 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 (Figure 3.12). The map, in turn, provided the basis for effective positioning 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 2002 the traps had been allowed to overfill when a flooding event (circa 50 properties in Glossop) occurred.

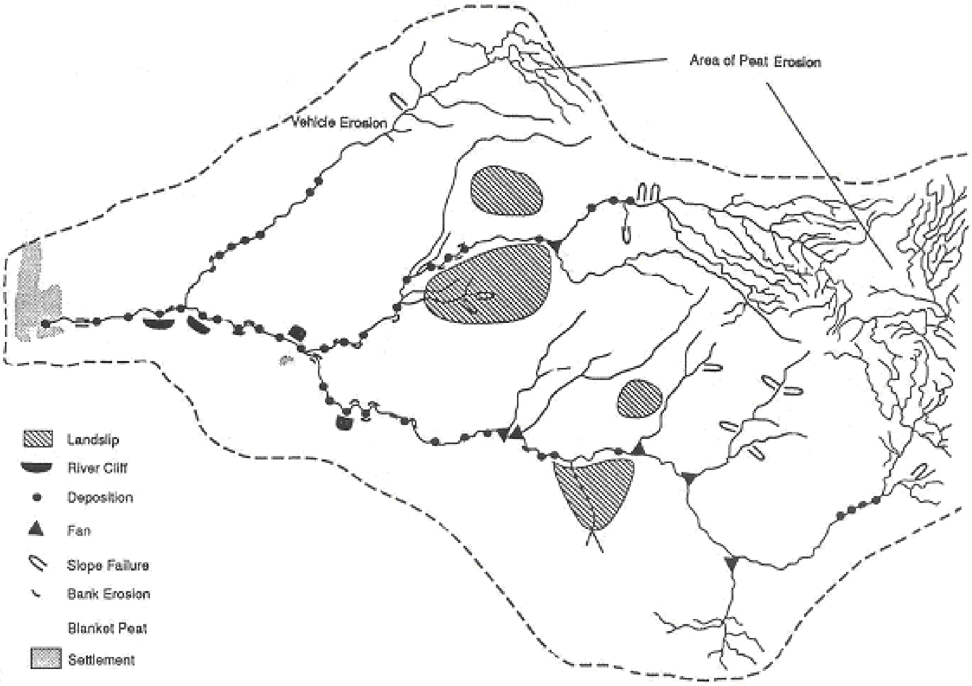


Figure 3.12 Sediment sources and sinks in Shelf Brook, Derbyshire (Sear *et al.* 1995)

3.3.4 System Response to Natural Change and Human Impacts

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, Figure 3.13 illustrates schematically how a wide variety of catchment and river activities that may impact sediment transfer system to elicit morphological responses elsewhere in the river.

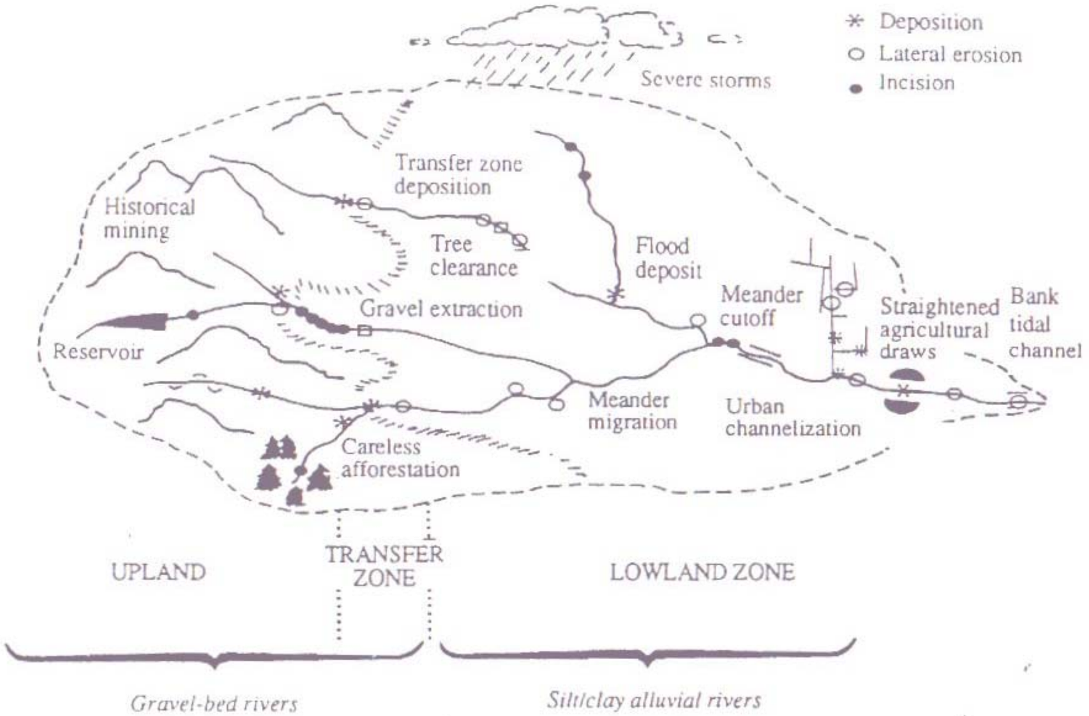


Figure 3.13 Natural and anthropogenic catchment and river processes affecting sediment dynamics (NRA 1991)

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 river problems. For example, overgrazing of a hillside in a headwater catchment can lead to soil deterioration and accelerated sheet and gully erosion. This increases the supply of sediment to headwater streams, increasing in-channel storage and elevating sediment loads supplied to the middle and lower courses to promote shoaling and lateral shifting. More rapid runoff from the hillside due to compaction by animals and gullying increases downstream discharges. Taken together, increased peak discharges and reduced conveyance capacity increase the likelihood of flooding, with serious implications for floodplain dwellers and users.

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

- Providing understanding of the factors which contribute to the stability of natural river channels (for example, 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 (for example, downstream channel response to impounding flow and trapping sediment in a reservoir);
- Developing stable designs for flood defence, capital, maintenance and conservation projects (for example, 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 (for example, pools, riffles, morphological variability, cross-sectional asymmetry).

Catchment Landuse Change

Channel morphology is sensitive to changes in the rainfall-runoff relationship and the catchment sediment yield that result 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 morphological response have been established through empirical studies (Table 3.13).

River Engineering

River engineering, in the form of capital works and operational maintenance, is undertaken in order to solve problems of flood defence, land drainage, navigation and channel instability that threatens 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 3.14).

Many engineering interventions in the form of channel maintenance activities are designed specifically to mitigate problems associated with sediment. Table 3.15 lists and defines common sediment-related maintenance practices.

Table 3.13 Qualitative predictors of morphological response to catchment change (after Schumm, 1977)

<table>
<tr><td colspan="3">Increase in Runoff alone
e.g. increased precipitation
$Q^{+} \sim w^{+}\ d^{+}\ F^{+}\ L^{+}\ S^{-}$</td><td colspan="2">Decrease in Runoff
e.g. reduced precipitation
$Q^{-} \sim w^{-}\ d^{-}\ F^{-}\ L^{-}\ S^{+}$</td></tr>
<tr><td colspan="3">Increase in Catchment Sediment Yield alone
e.g. construction/overgrazing
$Qs^{+} \sim w^{+}\ d^{-}\ F^{+}\ L^{+}\ S^{+}\ P^{-}$</td><td colspan="2">Decrease in Catchment Sediment Yield
e.g. soil conservation/reduced arable
$Qs^{-} \sim w^{-}\ d^{+}\ F^{-}\ L^{-}\ S^{-}\ P^{+}$</td></tr>
<tr><td colspan="3">BOTH Increase
e.g. afforestation/increased storminess
$Q^{+}Qs^{+} \sim w^{+}\ d^{-/+}\ F^{-}\ L^{-}\ S^{-/+}\ P^{+}$</td><td colspan="2">BOTH Decrease
e.g. downstream of a reservoir
$Q^{-}Qs^{-} \sim w^{-}\ d^{-/+}\ F^{-}\ L^{-}\ S^{-/+}\ P^{+}$</td></tr>
<tr><td colspan="3">Runoff Increases & Sediment Yield Decreases
e.g. urbanisation (after construction)
$Q^{+}Qs^{-} \sim w^{-/+}\ d^{+}\ F^{-}\ L^{-/+}\ S^{-}\ P^{+}$</td><td colspan="2">Runoff Decreases & Sediment Yield Increases
e.g. water abstraction/reduced precipitation
$Q^{-}Qs^{+} \sim w^{-/+}\ d^{-}\ F^{+}\ L^{-/+}\ S^{+}\ P^{-}$</td></tr>
<tr><td>Key</td><td>Q = runoff</td><td>Qs = sediment yield</td><td>F = width/depth ratio</td><td>L = meander wavelength</td></tr>
<tr><td></td><td>W = width</td><td>D = depth</td><td>S = channel slope</td><td>P = sinuosity</td></tr>
</table>

Table 3.14 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 3.15 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.
Re-alignment	Relocating and straightening the channel to increase conveyance capacity and/or facilitate development of the floodplain. Usually accompanied by re-grading and re-sectioning.
Re-grade	Large-scale (often grant-aided capital works) modification of channel slope and long-profile based on regime theory or 1-dimensional hydraulic modelling (e.g. HEC-RAS).
Re-section	Imposing or returning channel cross-section to design

	configuration, including re-profiling bed and banks. Usually based on regime theory or 1-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.

During the 1990s, evidence accrued concerning the impacts of river engineering works on fluvial sediment transfer systems and the morphological adjustments of channels resulting from these impacts.

For example, re-alignment has been a widespread practice, both historically to form straight field boundaries and improve agricultural drainage and, more recently, 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. Bed lowering may lead to over-steepening of the banks, and bank retreat (widening). 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. Table 3.16 summarises the geomorphological impacts of channel straightening.

Table 3.16 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 Reduced Conveyance
Bed scour	Bed scour	Increased flood risk
Bank instability	Bank instability	

Capital works may also impact the sediment system in a variety of ways, with implications for the engineering performance, maintenance requirement, environmental value and sustainability of the scheme (NRA 1993).

Channel changes triggered in response to re-alignment 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. Reach-scale bank retreat leads to destruction of the riparian corridor, with many detrimental effects on bank stability, ecology and aesthetics.

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 1994a). Extensive bank instability was reported in the engineered reaches immediately following the works, which involved re-grading and re-sectioning that produced high and steep banks surcharged by spoil taken from the channel (Figure 3.14). Following construction, erosion of the lower half of the bank profile occurred due to enhanced flow erosivity and decreased bank erosion resistance associated with vegetation removal and the undetected presence of a weak sand layer low in the bank that was exposed by re-sectioning.

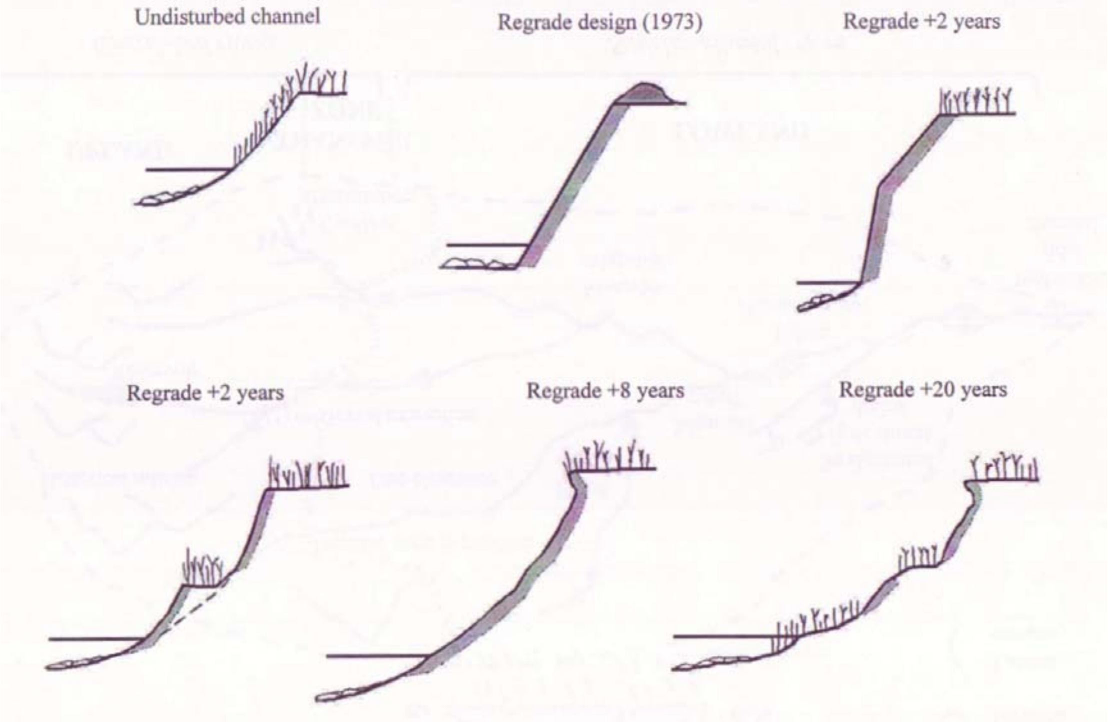


Figure 3.14 Indicative bank profiles from an engineered reach of the River Sence, Leicestershire between 1973 and 1985 (Sear *et al.* 1995)

Erosion then brought the banks to a condition of limiting stability, with wet conditions triggering significant bank retreat through slumping. Further cycles of flow scour and slumping occurred for the next 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, 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. In the River Sence, bank erosion and failure supplied literally hundreds of cubic metres of sediment per year to the river which, in turn, generated deposition and further channel instability downstream.

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 various Environment Agency R&D projects are listed in Table 3.17 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.

Table 3.17 Potential Sediment Impacts and Morphological Responses to Engineering and possible Geomorphological Solutions

Engineering Option	Impact on Sediment System	Channel Response					Timescale	Possible Solution
		W	d	S	D50	C		
Straightening	Upstream: T>Qs = E Downstream: Qs>T = D	+ +	+ -	+ -	+ -	+ -	After first transporting flood. <1 to >50 years	Upstream bed check weirs. Reinstate riffle/pool sequence, put shallow trap below straightened reach. Extend downstream flood way.
Dredging to grade	Upstream: T>Qs = E At site: Qs>T = D Downstream: T>Qs = E	+ + +	+ + +	+ - +	+ +/- +	+ +/- +	After first transporting flood <1 to >50 years	Upstream bed check weirs and gravel trap to prevent siltation. Plant trees on banks. Extend downstream flood way to allow meandering.
Shoal removal	Downstream: T>Qs = E	+	+	+	+	+	After first transporting flood and +100 years	Accommodate shoals by extending floodway or two-stage channel.
Weir removal	Upstream: T>Qs = E Downstream: Qs>T = D	+ +	+ -	+ -	+ -	+ -	After first transporting flood. <1 to >50 years	Bed check weirs in blockstone. Sheet piling in upstream reaches. Downstream dredging or increased floodway.
Widening	Upstream: no change At Site: Qs>T = D	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.
Gravel trap	Upstream: T>Qs = E Downstream: T>Qs = E	+ +	+ +	+ +	+ +	+ +	After first transporting flood. <1 to >50 years	Do not over dig gravel trap. Protect upstream end with bed check weirs. Site trap at riffle. Underpin downstream lip. Do not site upstream of structures.
Bank protection	Downstream: T>Qs = 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>Qs = 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
D = channel depth
S = channel slope
D50 = median bed size
nc = no change
Qs = sediment supply
T = sediment transport
E = erosion
D = deposition
C = bed compaction

Using the stream power device

While it is possible to estimate of the type and direction of channel change likely to result from a given engineering intervention based on qualitative assessment of the type of intervention and post-project channel configuration, confidence is increased if a quantitative element can be introduced to these considerations. Geomorphological theory as well as Bagnold's sediment transport equation, show that the capacity of the flow to do geomorphological work on the channel through the erosion, transport and deposition of sediment may be characterised by its stream power. 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 to water surface slope). A more widely used index of stream power is the specific stream power, or stream power per unit bed area, defined by:

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

Where, w = representative channel width.

In a study of river channel typology conducted under an NRA R&D Project (NRA 1995), River Habitat Survey (RHS) data, combined with estimates of bankfull discharge, were used to calculate specific stream power for a large number of reaches. The study demonstrated that values of specific stream power for UK rivers vary between 2 and 1,815 W/m^2, illustrating their contrasting energy levels and capability for performing geomorphological work through dynamic adjustment of their channels.

The results generally supported an earlier finding that erosional instability is restricted to channels with stream powers in excess of 35 W/m^2. Attempts to relate instability of the bed or banks to stream power and bed material type (silt, sand, gravel, cobble) revealed a trend for the stream power associated with instability to increase with increasing bed material size (Table 3.18).

Table 3.18 Stream power values associated with stability/instability in UK rivers

	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	47.5	13.8-81.1	6	37.8	8-105
Gravel	9	107	12-1766	27	73.3	4-489.6
Gravel/Cobble	4	135.6	58.8-269.1	6	78.8	57.7-482
Cobble	1	n/a	n/a	13	142	7.2-427

However, error margins in the data were too high to support the analyses necessary to establish predictive relationships between stream power 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 high incidence of instability, while stable conditions were observed at some sites with stream powers in excess of 1,000 W/m^2.

Lack of a simple relationship between stream power and channel stability should be expected because by no means all the stream power expended by a river is actually available for geomorphic work through sediment entrainment and movement. In fact, most energy is consumed in overcoming:

- Internal friction through flow shearing and turbulence (related to velocity gradients and large-scale flow structures);
- Boundary friction due to roughness of the bed (related to sediment size and fabric) and banks (related to bank profile and stratigraphy);
- Form drag due to bed topography (related to bedforms such as pools and riffles and channel bars/islands) and irregularities in the bankline;
- Bend losses due to flow curvature effects in meandering and braided channels;
- Retardance by aquatic and emergent vegetation (related to abundance and stiffness of stems and therefore highly seasonal for flexible plants).

In natural channels, these processes of flow resistance consume all but a small fraction of the overall stream power, limiting the ability of the flow to erode the channel boundaries and transport sediment. However, the proportion of energy consumed by the processes listed above varies widely, depending on details of the channel morphology, sediment size, types of sediment features (bars, shoals etc) and vegetation present.

It is highly significant that, in high-energy streams, engineered and heavily modified/maintained channels lack many of the forms and features responsible for energy dissipation listed above. The initially high hydraulic efficiency of newly-constructed engineered and recently maintained channels, makes them prone to instability because reduced power consumption in overcoming energy losses leaves a greater proportion of stream power available for eroding the bed and banks.

Conversely, in low-energy reaches, channels that are significantly oversized experience extremely low specific stream powers that make them prone to siltation because they lack the capacity to transport sediment supplied from upstream.

Recognising these principles, a presentation to NRA Flood Managers (NRA 1994b), reported a general rule linking the type of post-project channel adjustment to specific stream power. Based on the results (which were obtained from engineered river reaches in England and Wales) it was concluded that:

Low energy streams ($\omega < 10$ W/m^2)	-	are likely to experience sedimentation that obscures reinstated features.

High energy streams ($\omega > 35$ W/m^2) - are likely to erode reinstated features.

Laterally- dynamic streams ($\omega > 100$ W/m^2) are likely to recover their sinuosity after straightening (Brookes & Sear (1996)).

The specific stream power cannot be used in isolation to infer the potential for post-project adjustment and the type of instability likely to occur. However, taken together with other qualitative information collected in, for example, a Fluvial Audit, consideration of stream power can prove helpful in predicting system response to human impacts.

Specific stream power may also be used as a device to estimate the likely travel distance for bed material grains carried by the flow. This is useful in establishing the distance-scale for transport steps linking up sediment sources and stores in the sediment transfer system. In R&D Project Record C5/384/2 (NRA 1994a), data for upland streams in different parts of the UK were combined to define a relationship between the excess specific stream power during the peak of a flood event discharge and the mean travel distance for bed particles (Figure 3.15). While considerable scatter is present in the data, an upper envelope for gravel transport distance can serve as a useful guide to the maximum distance over which coarse bed material particles may be expected to move between source and sink during a given transporting event. This effectively scales the step length for coarse sediment moving through the system episodically as bed material load.

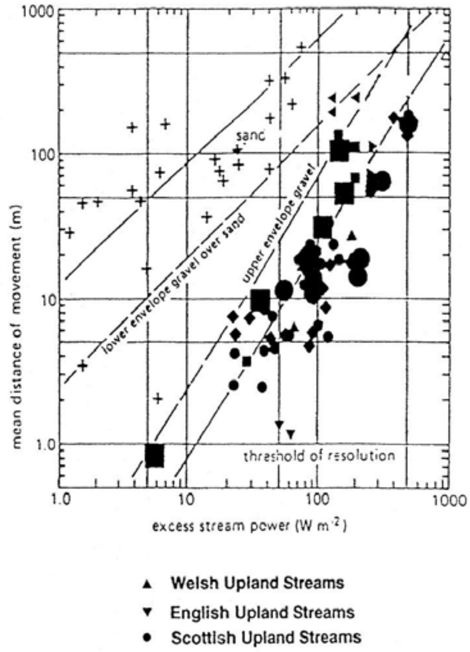


Figure 3.15 Movement distances for bed material particles as a function of excess stream power above the value required to initiate motion (Hassan *et al.* 1992)

4. DRIVING PROCESSES 2: CHARACTERISING AND MANAGING RIVER SEDIMENT DYNAMICS

4.1 Geomorphological Studies

4.1.1 Background

During the 1990s, geomorphology contributed to river channel management and engineering across a range of applications and functions. The inclusion of a geomorphic element to river studies and adoption of geomorphic principles in the design and implementation of schemes (particularly those concerned with sediment management, bank protection, restoration, rehabilitation and the design of environmentally sensitive channels and maintenance regimes) led to the requirement for standardised approaches.

The framework for geomorphological investigations that was developed, involving a series of nested activities that parallel the engineering and environmental aspects of a scheme, was outlined in Chapter 1. Subsequent evolution of the methodological framework within which geomorphological investigations are performed spawned the GA and GAP approaches described in Chapter 1. The procedures, methods and techniques involved in studying the driving processes of morphological change are fleshed out and illustrated in this chapter provided. Coverage here is limited to the suite of methods developed through NRA/EA R&D during the 1990s and summarised in R&D Guidance Note 18 (EA, 1998), however, as later developments have yet to be accepted as 'standard approaches'. Briefing documents to provide guidance for staff performing or contracting standard geomorphological studies were developed in the late 1990s and these are reproduced at the end of the chapter (Section 4.6).

New field techniques are currently under development as part of on-going research funded by the Defra/EA R&D programme. Of particular note is the addition of geomorphological and floodplain components to the River Habitat Survey method, under research led by the Universities of Newcastle and Southampton. As these methods are developmental at present (June 2003) it would be premature to include them in the tried and tested approaches described here. However, reference is made to early findings using new methods in chapters 5 and 6.

4.1.2 Catchment Baseline Survey

A Catchment Baseline Survey (CBS) provides a strategic overview of the geomorphological 'state' of the drainage network. A broad understanding of the network is useful in guiding planning priorities and it enables Environment Agency staff to respond efficiently to requests for information concerning the stability status, geomorphological context and conservation value/sensitivity to disturbance of particular reaches that might be affected by development, capital works or maintenance operations. A commitment to performance Catchment Baseline Surveys to provide underpinning information for all main rivers that would be available prior to and during project formulation would, thus, reduce the prevalence of reactive management. The CBS can be undertaken at one of two levels.

A Broad CBS consists of an assessment of catchment geology, soils, topography, landuse and geomorphology performed through a desk-study using documentary information, supplemented by material obtained through consultation with relevant Agency staff and a 1-2-day site visit to key locations within the catchment. The resultant summary (1-2 pages) of catchment characteristics and issues can be used to provide input to regional and strategic catchment planing studies.

A Detailed CBS (DCBS) includes all the elements of the Broad CBS plus an initial assessment of channels making up the drainage network, with the insights so obtained used to sub-divide the fluvial system into reach-scale, geomorphological components. The detailed assessment methodology centres on a field reconnaissance survey used to supplement knowledge based on the desk-study, by collecting information on the morphology of channels and broadly identifying the dynamics of the sediment transfer system. Geomorphic units are mapped on a catchment map, possibly using a geographical information System (GIS).

The information obtained from a DCBS is often used to classify reaches according to their 'geomorphological conservation value' – which is a measure the channel's 'naturalness' and susceptibility to being degraded by human activities (Table 4.1). It can also be used to gauge the stability status on a reach-by-reach basis, and, in heavily modified watercourses, the potential for the channel to recover towards a more natural state if allowed to do so.

Use of the Table 4.1 in the field has, however, revealed potential for ambiguity and misunderstanding. For example, differences between channels that should score 8, 9 or 10 are difficult to detect. The table presents what is essentially a classification based on 'degree of modification' and this may not correspond directly to susceptibility to disturbance or conservation value.

This is the case because *Susceptibility to disturbance* depends on factors additional to those used in the classification. For example, two rivers with little modification would be classified as having high susceptibility to disturbance. In fact, one river could be an inherently stable system that could effectively absorb the impacts of upstream disturbance by actively adjusting within a broad band of dynamic stability. This stream is, therefore, not necessarily highly susceptible. Conversely, the other river might be marginally stable with the capacity for irreversible morphological response to interventions. This river would be damaged irreparably by artificially induced instability and it is, therefore, highly susceptible.

In terms of conservation value, this depends on the purpose for which the channel is to be conserved. Even a concrete-lined channel may have a conservation value for certain species. Also, conservation value depends on a number of other controlling factors, such as water quality and sediment type, as well as degree of modification. Hence, the real conservation value might differ markedly from that indicated by the degree of modification alone.

The approach espoused in Table 4.1 is useful in defining how much the channel has been modified in the past and gaining an idea of its 'naturalness' and sensitivity. However, a judgement regarding the channel's conservation value and susceptibility to disturbance should obviously not be made on the basis of the degree of reach-scale engineering alone.

Table 4.1 Summary of Environment Agency (1998) scheme for classifying geomorphological conservation value or susceptibility to disturbance

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.

The DCBS element of geomorphological investigation can be viewed as equivalent to a River Habitat or River Corridor Survey, and several elements of the DCBS method are to be incorporated into an enhanced River Habitat Survey methodology that is currently under development (January 2003) in an Environment Agency/Defra R&D project. More information on these developments may be found in Chapter 6.

The product of the DCBS is a valuable, though qualitative, geomorphological overview of the drainage network. To progress beyond this, it is necessary to introduce a quantitative dimension, through the estimation of sediment yields at key points in the river.

4.1.3 Predicting Sediment Yield

The annual sediment yield at any point in the drainage network can, in theory, be predicted by applying a suitable sediment transport equation over the range of flows experienced at that point. Unfortunately, application of conventional sediment transport formulae requires detailed information on channel geometry, discharge and bed sediment size that is seldom available from archives and is expensive to collect. In practice, data necessary to calibrate sediment transport equations are simply unavailable in the UK and it is neither cost-effective nor time-efficient to propose that measurements be made to validate the accuracy of conventional sediment transport calculations. When applied uncalibrated, errors of one or two orders of magnitude in predicted rates may occur. In any case, the load of fine sediment moving in suspension as ‘wash load’ is supply limited rather than transport limited and cannot be predicted on the basis of stream hydraulics and channel form.

An alternative, empirically-based approach that has proven useful in situations where physically-based equations cannot be used due to lack of data, is to predict sediment load as a function of catchment drainage area. In R&D project W5A/i661/1 (EA 1998a), the observed data presented in Figure 4.1 were used to derive separate equations for the annual yields of bedload and suspended sediment in source areas (headwater catchments) and large catchments:

Source areas (headwater catchments) with areas less than 100 km^2:

$$\Psi_{bed} = 5.85A^{1.08} \qquad (n = 33, r^2 = 0.31)$$

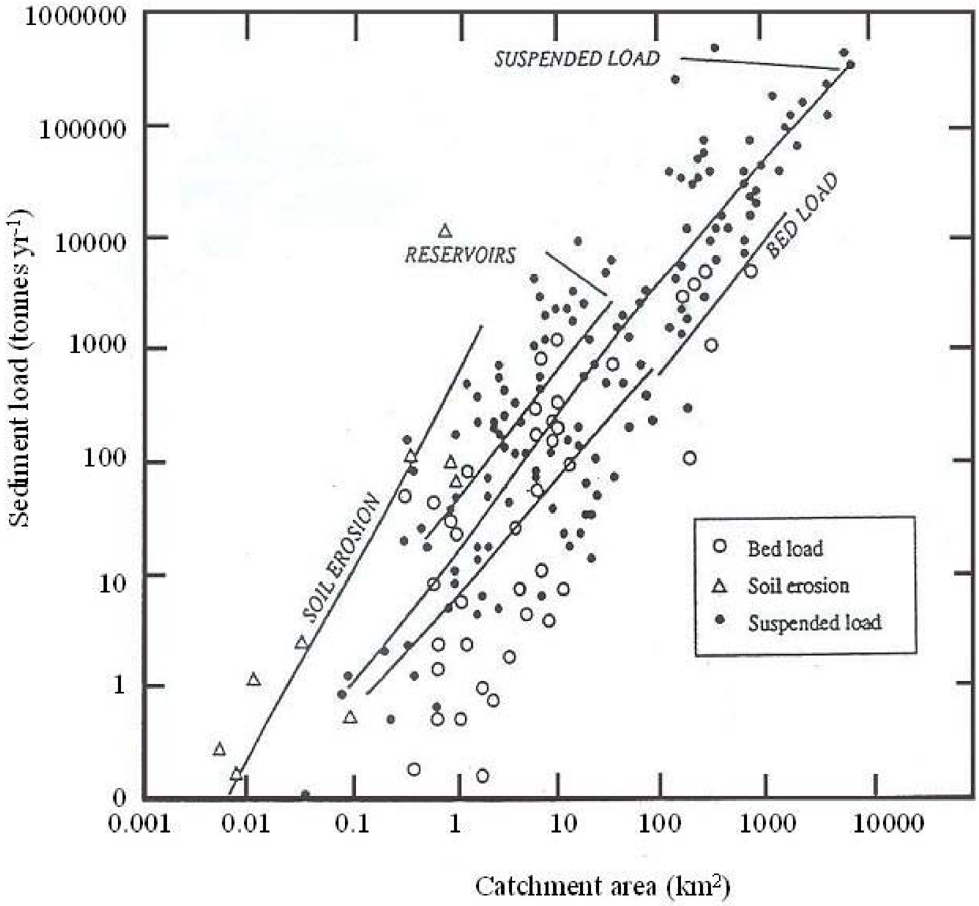
$$\Psi_{susp} = 11.64A^{1.16} \qquad (n = 60, r^2 = 0.63)$$

Large catchments with areas greater than 100 km^2:

$$\Psi_{bed} = 2.50A^{1.16} \qquad (n = 7, r^2 = 0.41)$$

$$\Psi_{susp} = 31.04A^{1.04} \qquad (n = 44, r^2 = 0.48)$$

where, Ψ_{bed} = annual bedload yield (tonnes/yr), Ψ_{susp} = annual suspended load yield (tonnes/yr), and A = catchment area (km^2).



Source areas (catchments <100 km^2)

BED LOAD .... $L = 5.85A^{1.08}$; $n = 33$; $r^2 = 0.31$

SUSPENDED LOAD .... $L = 11.64A^{1.16}$; $n = 60$; $r^2 = 0.63$

Larger catchments (>100 km^2)

BED LOAD .... $L = 2.50A^{1.16}$; $n = 7$; $r^2 = 0.41$

SUSPENDED LOAD .... $L = 31.04A^{1.04}$; $n = 44$; $r^2 = 0.48$

(soil erosion equation not quoted: too dependent on-site conditions)

Figure 4.1 Observed data for sediment yield (bedload and suspended load) as a function of catchment area in UK rivers (NRA 1991)

Clearly, the limited empirical database underpinning these formulae, taken together with the relatively low coefficients of explanation for the regression equations, indicates that they should be used carefully and that the predictions they produce are purely indicative. Nevertheless, the robust form and minimal data requirements of these equations makes them simple to apply when an initial estimate of sediment yield is required.

4.1.4 Fluvial Audit

The Fluvial Audit is the recommended geomorphological data collection and presentation process developed and applied during R&D projects performed by and on behalf of the Environment Agency and its predecessors during the 1990s. For project reaches, or reaches identified in the CBS as experiencing sediment-related problems, a Fluvial Audit is performed to provide the geomorphological basis for a sustainable solution. The Audit technique is intended to incorporate and build on the results of a prior CBS, but it can also stand alone when no CBS has been performed.

The Fluvial Audit relates sediment conditions in the study reach to those prevailing in the wider catchment, paying close attention to sediment transfers between source and sink areas. The method is intended to establish a semi-quantitative or first-approximation understanding of the reach-scale sediment budget, the geomorphological processes operating in the channel and the causes of instability or other sediment-related problems. Setting the context and identifying cause includes a historical dimension as the impacts of past, as well as contemporary events and catchment changes 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 4.2.

Table 4.2 Documentary/Historical Sources used in Fluvial Auditing

Source	Timescale	Location
Maps		
Estate	C16th+	British Library and National Library of Wales
Enclosure	C18th – 19th	
Tithe		
County	1840s	County Archivist
Ordnance Survey		
1:10,560 County Series	1853-1923	Ordnance Survey
National Grid Series	1948+	
Drift geology 1:50,000 Series	10^6 years	British Geological Survey
Soil Survey 1:50,000 Series	10^6 years	Soil Survey
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 –	Archives/British Library
Catchment Board Records	18th	Archives/Environment Agency files
River Board Records	1930+	Archives/ Environment Agency files
Water Authority Records	1946+	Environment Agency files
NRA Reports	1973+	Environment Agency files
Scientific Journals	1989+ C20th+	British Geomorphological Research Group/CIWEM/CEH

In addition to historical and documentary sources, Fluvial Auditing relies on geomorphological field survey and reconnaissance to characterise the study reach and identify the relevant channel forms and sedimentary features. An important component of stream reconnaissance is accurate classification of the stability status of the reach (incising, stable or aggrading), based on recognition of indicative channel features. In this regard, Table 4.3 lists some of the attributes commonly used to assess channel stability in upland, mid-course and lowland contexts.

Table 4.3 Indicators of Channel Stability

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 'over loose' bars Eroding banks at shallows Contracting bridge openings Deep fine sediment	Buried structures Buried soils Large, uncompacted bars Eroding banks at shallows Contracting bridge openings Deep fine sediment overlying coarse	Buried structures Buried soils Large, uncompacted, 'over loose' bars Eroding banks at shallows Contracting bridge openings Deep fine sediment

	overlying coarse particles in bed/banks Many unvegetated bars	particles in bed banks Many unvegetated bars	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

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

1. Time chart of catchment changes that may have impacted fluvial geomorphology.
2. Map of catchment and drainage network indicating sediment sources, pathways and sinks.
3. Geomorphological map of the channel system indicating sub-reaches, key locations and stability status.

These outputs form the basis for identifying the cause(s) of sediment-related problems and identifying sustainable solutions and project designs that treat these causes rather than their symptoms.

Based on the understanding of sediment dynamics and geomorphological adjustments (past and present), a number of secondary products are derived in the Fluvial Audit. First amongst these is a table or list identifying 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 re-activated in the future. These factors, are collectively termed 'Potentially Destabilising Phenomena' (PDPs). A list of commonly encountered PDPs is given in Table 4.4).

Table 4.4 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

4.1.5 Geomorphological Dynamics Assessment

A Geomorphological Dynamics Assessment (GDA) forms the most intensive stage of a study into river geomorphology and sediment dynamics. The method requires detailed, quantitative investigation and analysis of the channel in an individual problem or project reach to assess its form, processes, process-form links and sensitivity to change. The field techniques employed are derived from research-level geomorphological studies and may include measurement and monitoring of channel hydrology, hydraulics, sedimentology, sediment movement and the geotechnical properties of the bank materials.

In designing and performing a GDA, it is necessary to match the techniques and duration of the study to the spatial scale of the problem. For example, in the case of a question concerning bank erosion, different study methods and equipment are appropriate to different scales of time and space (Figure 4.2). For the study of bank erosion at a single problem site, photogrammetry or erosion pins would yield useful information on event effectiveness and average rate of retreat provided that measurements were conducted for a year or, ideally, a few years. Conversely, meaningful assessment of bankline changes at the reach-scale would require evidence collected over a much longer period, probably necessitating the use of historical sources (old maps and aerial photographs), plus interpretation of the spatial distribution of floodplain age and configuration, based on the distribution of plants and sediments (Figure 4.2).

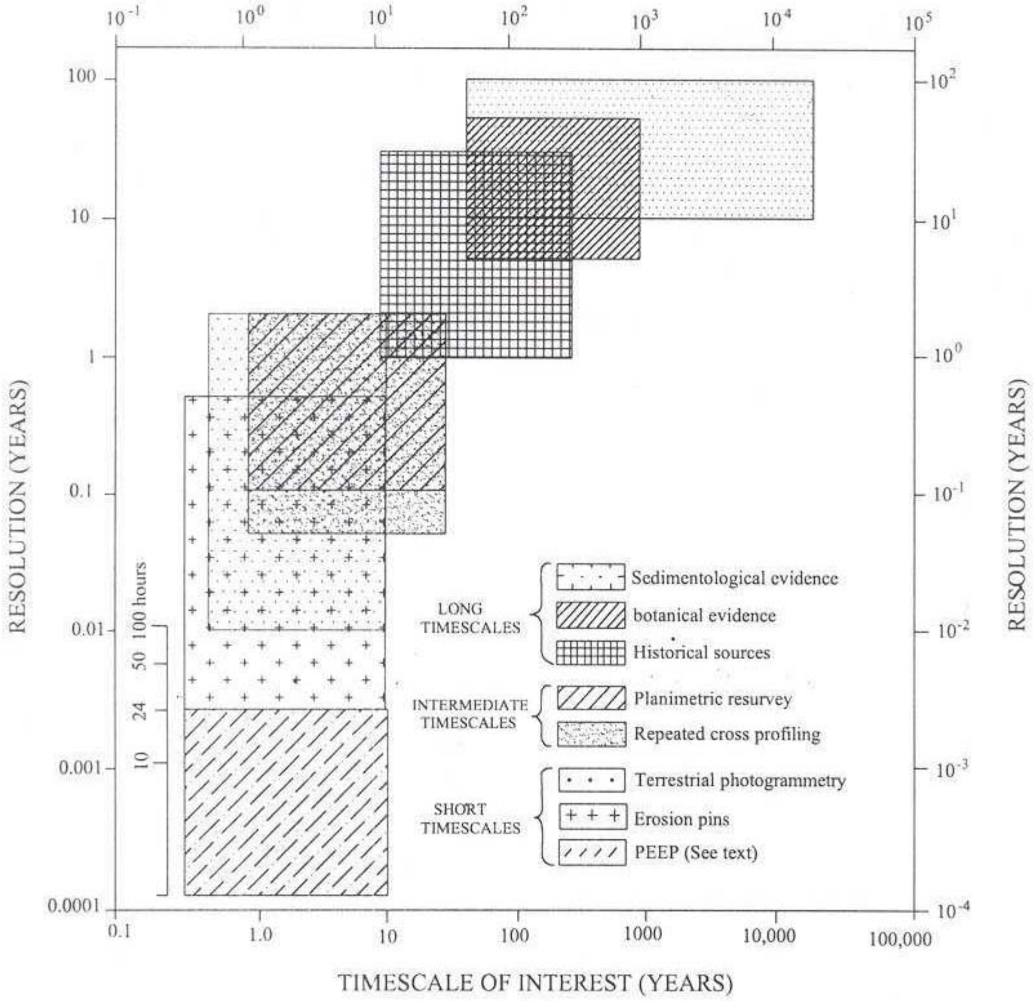


Figure 4.2 Timescales and techniques appropriate to the assessment of bankline change at a variety of spatial scales (after Lawler *et al.* 1997)

4.1.6 Geomorphological Post-Project Appraisal

Post-project appraisal should be an integral component of all capital works and significant maintenance operations. Geomorphological PPA is a particular type of investigation with two major constituents. First, GPPA compares the forms and features of the actual outcome of the project or maintenance operation to those specified in the design and plans (Compliance Audit). Second, GPPA uses systematic monitoring of channel form, morphological adjustments, sediment dynamics and maintenance activities to evaluate the success of the project in meeting its objectives in a sustainable fashion. The results of GPPA are valuable both in supporting adaptive management of the project in question and in contributing to improved project designs for future projects.

A GPPA methodology was developed in research co-funded by the Environment Agency and the University of Nottingham in the 1990s, but the resulting guidance document has not been widely disseminated. Hence, the approach is outlined here and a brief for GPPA is included in Section 4.6.6.

The aim of the UoN project was to provide a standardised approach to assess the performance of environmentally-aligned flood control and channel rehabilitation schemes. The procedure was developed through incorporating some of the main theories of Environmental Assessment processes into a geomorphic framework, in a format that allows its skeletal structure to be adapted to suit the needs of end-users such as project designers assessors.

Application of the GPPA procedure to capital works and maintenance operations should enable an evaluation of the degree of morphological stability or adjustment following construction, indicating whether the scheme has achieved short-term objectives and whether it can be sustainable in the longer-term.

4.2 Managing Sediment-Related Problems

4.2.1 Policy and Legal Context

Sediment-related maintenance is performed when and where necessary to protect structures and assets threatened by bed or bank erosion, and preserve the design capacity of a channel with a flood defence, land drainage or navigation function that might otherwise be compromised by sediment accumulation or siltation. The Environment Agency has permissive powers under the Water Resources Act (1991) to maintain conveyance within the main river network and protect flood defence assets, although these do not impose a duty on the Agency and they are limited to watercourses defined as 'main river'.

4.2.2 Overview

The national distribution of maintenance costs was mapped in 1990s R&D work and is reproduced in Figure 4.3. The results reveal that there are clear geographical variations in maintenance costs and that considerable sums of money are expended annually in dealing with erosion, siltation and weed-related problems.

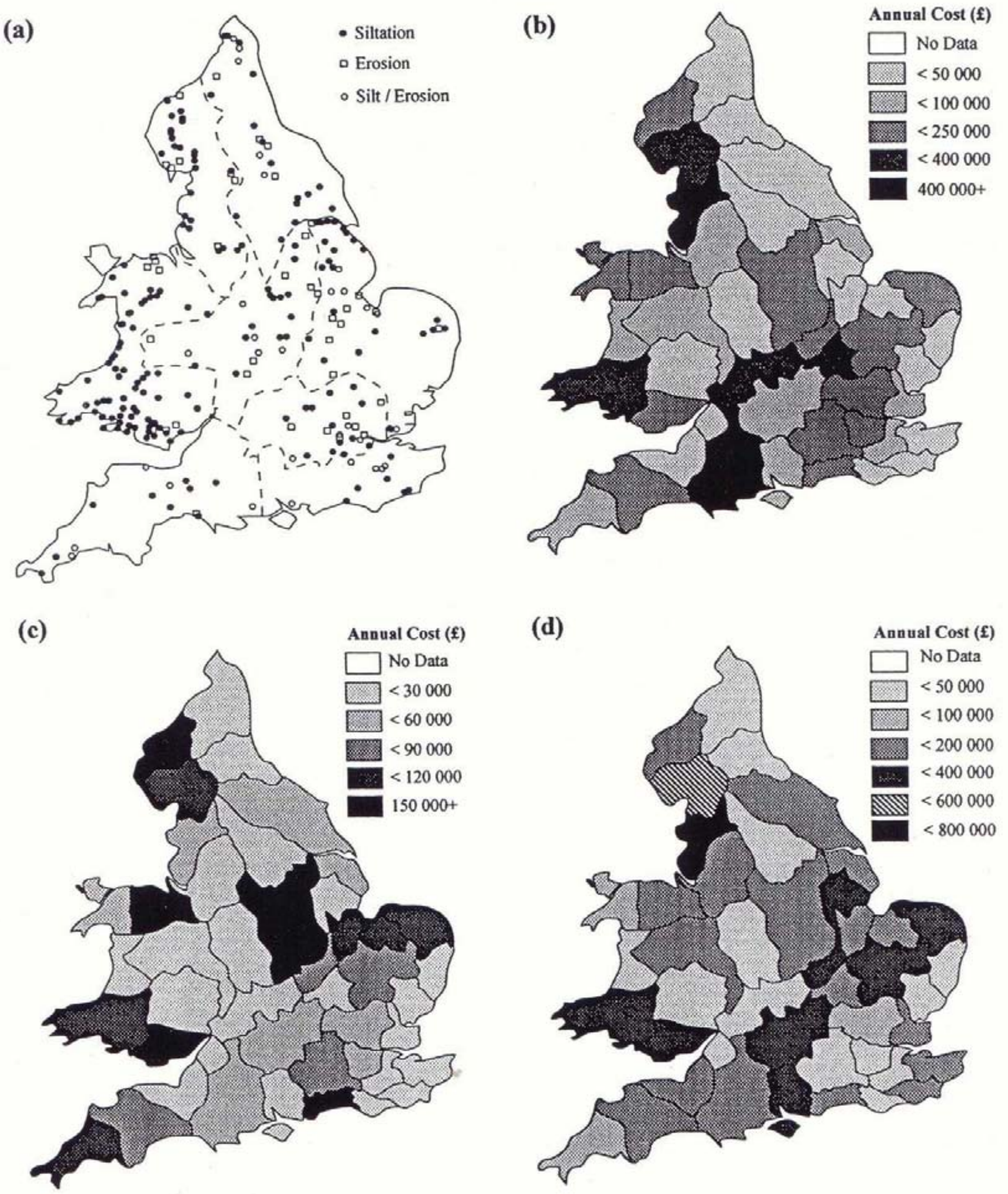


Figure 4.3 Distribution of documented sediment-related maintenance in England and Wales during the 1990s (NRA 1994c)

The major types of sediment-related management and maintenance activities practised by the Environment Agency are listed in Table 4.5. While there is clearly a range of maintenance responses available to address sediment-related problems, in practice during the 1990s most solutions adopted 'traditional' methods. For example, questionnaire surveys reported in NRA and later Environment Agency R&D reports found that 90% of maintenance involved dredging, re-grading and re-sectioning, 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.

Table 4.5 Procedures used to mitigate sediment-related problems

Procedure	Description
Bed Control	Weir or sill structure installed in an incising channel to prevent continued lowering of the bed.
Bank Protection	Protection of an eroding bank where a flood defence structure or other asset is threatened. May employ a variety of materials/techniques ranging from biotechnology (soft) to structural engineering.
Re-grade Bed	Large-scale (often grant-aided capital works) modification of channel slope and bed profile usually based on regime theory or hydrodynamic modelling (HECRAS or iSIS).
Re-section Channel	Large-scale modification of channel cross-section including re-sizing of the area and re-profiling of the banks. Usually intended to increase channel conveyance capacity.
Gravel Trap	Structure installed to prevent downstream movement of coarse sediment where this would threaten the design capacity or stability of a flood defence or land drainage asset.
Dredge	Removal of sediment that has accumulated on the bed and/or banks to the extent that it compromises flood defence or land drainage functions.
Desilt	Removal of less than three years' accumulation of silt (often performed in conjunction with weed clearance).
Shoal Removal	Selective dredging to remove individual sediment features such as bars or riffles where these are deemed to compromise flood defence benefits or navigation in the channel.
Groynes/Deflectors	Structures installed to organise sediment storage in a reach accumulating sediment and so maintain a clear thalweg.

4.2.3 Catchment Sediment Source Control

Given that sediment-related problems in rivers are often driven by catchment sediment yield and changes therein, it follows that controlling sediments input to the river system at source may be a viable solution. Control at source may involve changes to landuse and sediment management, or controls introduced to headwater streams (non-main river) reaches and tributaries.

The control 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 or burned 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/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 have 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 co-operation 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 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,
- drilling instead of ploughing,
- planting of field and riparian buffer strips

The use of buffer strips to trap elevated sediment supplies *en route* to the channel system has received much attention. Buffers are known to reduce not only sediment yields but also nitrate and phosphate loadings. The design of strips is to some degree site-specific but common features include:

- Buffer width typically 5 to 10m for small channels (w < 5m);
- 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;

4.2.4 Bed Controls

Bed controls are structures installed in the channel bed to prevent incision, arrest the upstream migration of a knick-point or headcut, or promote aggradation. Weirs are not included here although they may act as bed controls because the primary purpose of a weir is usually to pond flow for the purposes of flow 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 usually 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. 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. A single sill will seldom be sufficient to stabilise the bed in a channel that is prone to significant scour and in practice a series of sills is used to protect a reach. The invert of each sill is set to be flush with the bed, so that there is no afflux or back-water effect upstream and the elevations of a series of sills should match the gradient of the bed at the reach scale.

Grade control structures differ from sills in that they are more heavily constructed and are able to withstand both general scour and incision. Usually, the invert of a grade control structure is set above the level of the bed to raise the base level for the 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 downstream.

Check dams are similar to grade control structures but are structurally more robust and are usually installed on steep streams with coarse sediment loads. They are designed to trap and retain sediment and debris (to protect the system downstream), as well as arresting the movement of knick-points or headcuts migrating upstream and providing a stable base level for the channel upstream.

Bed controls may be constructed from a variety of materials including timber (in small rivers), rock, gabions and concrete and to a variety of designs. R&D Note 154 (NRA 1993) presented four different sill designs (Figure 4.4) and noted that sills 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.

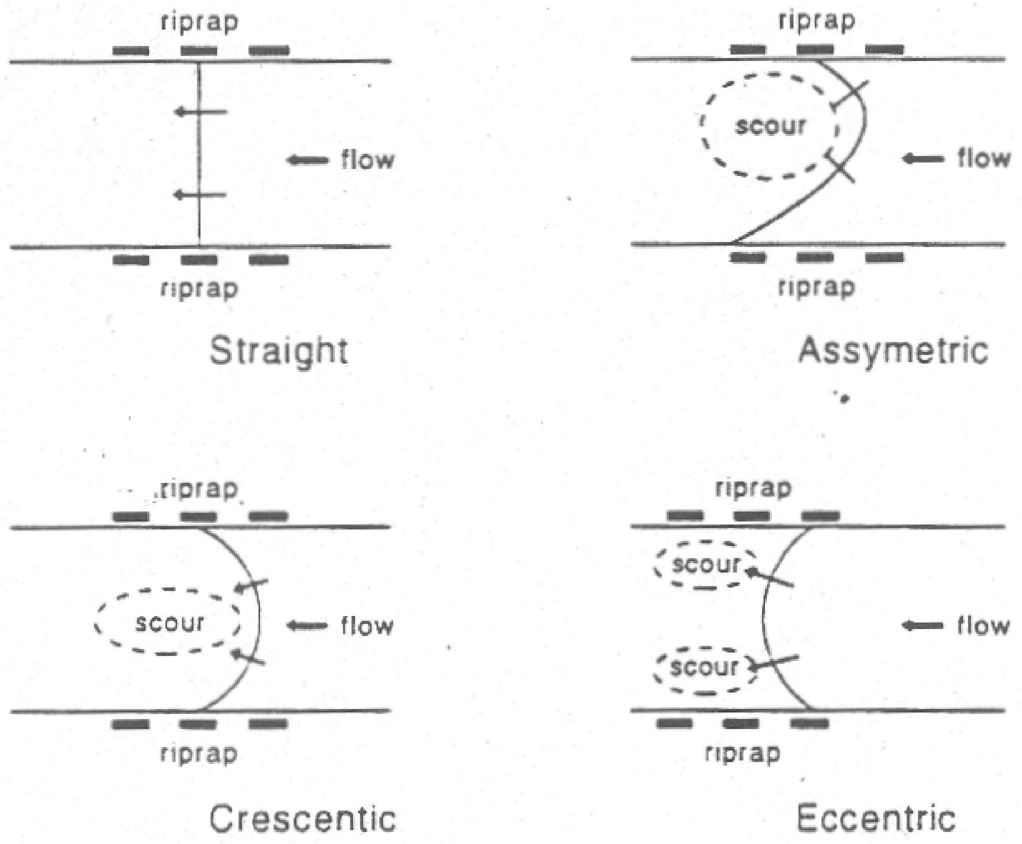


Figure 4.4 Alternative designs for Bed Control structures (NRA, 1993)

Additionally in R&D Note 154 it is recommended that sills be spaced along the channel at no more than three times the width and a number of general construction guidance notes applicable to all bed controls are provided. These include:

- 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. Further strengthen the structure using reinforcing rods piled into the bed.
- 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 conveyance capacity of the channel.
- 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 4.2.5).
- Use riprap to the sides of the structure to prevent outflanking.

4.2.5 Bank Protection

Policy

Agency policy on bank erosion stems from a meeting of the Land Drainage Advisory Committee in April 1974 and a subsequent MAFF Decision letter of 1984 and states:

- 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 in 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.

Selecting a Solution

Selection of appropriate solutions to bank erosion problems based on geomorphological assessment and characterisation is covered at great length in the guide referred to in the section on bank erosion in Chapter 3 (Environment Agency 1997). It is, nevertheless, appropriate to re-state the guiding principles underpinning the selection process here, because these principles spring directly from the geomorphic approach promulgated during the 1990s in the preceding series of geomorphologically-led R&D projects on bank erosion assessment (Table 4.6).

Table 4.6 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.

Examples

Consideration of two case examples serves to illustrate the utility of taking a geomorphic approach and applying the guiding principles of bank protection listed above.

During the 1970s landowners voiced concern about the loss of farmland associated with erosion at the outer banks of actively migrating banks of the River Severn between Llanidloes and Newtown, Powys. Detailed investigation of the fluvial system, made 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 3.2.4a, 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 sediment exchange and disturb reach-scale sediment continuity, triggering morphological response. It was concluded that 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, leading inevitably to stabilisation of much of the reach, with considerable capital and maintenance costs, as well as serious environmental impacts.

Application of a geomorphological assessment of the underlying causes of bank erosion led to the conclusion that intervention would be expensive, unproductive and unsustainable. Consequently, a policy of allowed natural adjustment of the banklines and planform of the river was adopted.

The second example comes from the River Sence in Leicestershire (referred to earlier in section 3.3.4b of Chapter 3). R&D Project Record C5/384/2 (NRA 1994) reported that capital works were performed on the River Sence between 1973 and 1985. Work involved re-grading and re-sectioning to produce 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 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:

1. Increased sediment supply as a result of bank failure following reg-grading;
2. Livestock poaching of collapsed banks;
3. Locally reduced sediment transport capacity as a result of channel widening;
4. Maintenance working upstream that enhances siltation;
5. Massive weed growth exacerbated by siltation and increased nitrate loadings.

In suggesting options to mitigate siltation, it was recognised that control of sediment sources rather than seeking to transport excessive sediment downstream was preferred. 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 Geomorphological Dynamics Assessment, revealed the role of mass instability due to increased bank height and angle following re-grading. A bank stability diagram was produced using field observations of bank height, angle and stability condition (Fig. 4.5). 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 re-grading had in some places exposed a weak sand layer in the flood plain at the bank toe, further reducing bank stability.

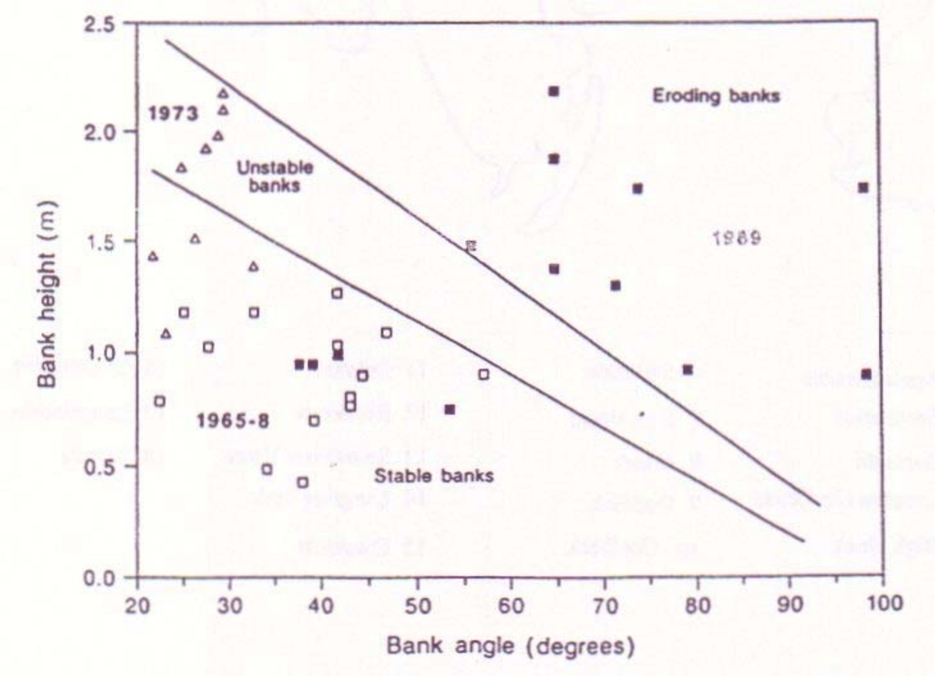


Figure 4.5 **Bank stability graph for the River Sence, Leicestershire (Sear *et al.*1995)**

Identification of the causes, driving processes and factors affecting bank instability led to recommendations for mitigation through that included elements of active bank management and structural protection:

1. Re-profiling of banks to reduce bank heights and angles sufficiently to prevent mass failure;
2. Encouraging farmers to fence off vulnerable banks and prevent livestock access at least until riparian vegetation has re-colonised eroding bank faces and slip surfaces;
3. Use of biotechnical protection (willow spiling) where the weak sand layer is 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.

4.3 Managing Sediment Transfers – Sediment Traps

A sediment trap may be used to mitigate or prevent the transfer of excessive amounts of sediment that would otherwise have to be removed further downstream in the river system by dredging. Traps are operated in many Regions, and have a particularly long history in the North West Region, 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 the reach hydraulics as well as data on the quantity, calibre and transport mechanism of the sediment load. Experience from long-term monitoring of traps in the North West Region has demonstrated that sediment yield is highly variable through time, depending on flood frequency and the occurrence of sustained periods of wetter or drier than average weather. This makes it almost meaningless to attempt to derive a single, representative sediment yield for design purposes. Clearly, the benefits of the trap only accrue during high runoff events associated with 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.
2. Effective trap efficiency of traps located away from natural deposition sites is only 66% of that for traps sited at locations of natural deposition.
3. Convenience of access for emptying the trap is vital for efficient operation and ease of entry is therefore a major design parameter.
4. Downstream impacts of reducing the sediment load may include: bed scour, armouring, bar erosion and, compaction. Consequently, the implications of the trap for downstream habitats and spawning areas must be considered.
5. Traps promote downstream bed scour and can enhance degradation. Hence, 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.
6. Traps must be stabilised to protect them against destabilisation by incision downstream and head cutting upstream.
7. The stability status of the host reach must be established prior to trap installation. Traps should not be installed in reaches prone to degradation as they may exacerbate channel local instability.

In addition, if the purpose of the trap is to limit the delivery of sediment to a downstream reach, the designer must also understand the relationship between sediment transport in the trap reach, sediment transfer to the target reach and morphological response in the fluvial system. For example, the use of a gravel trap in a headwater stream will only be successful in reducing the dredging requirement in a flood control channel downstream provided that:

1. the trap interrupts what was a significant transfer of sediment between the two reaches;
2. the river does not substitute new gravel (derived from morphological adjustment in intermediate reaches) for that trapped, to maintain 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 R&D Project Record C5/384/2) since the 1930s. Figure 4.6 shows the locations of traps and Table 4.7 lists their characteristics. Traps consist either of simple boulder weirs reinforced by iron piles or more complicated concrete and pitched stone structures with drains to facilitate emptying.

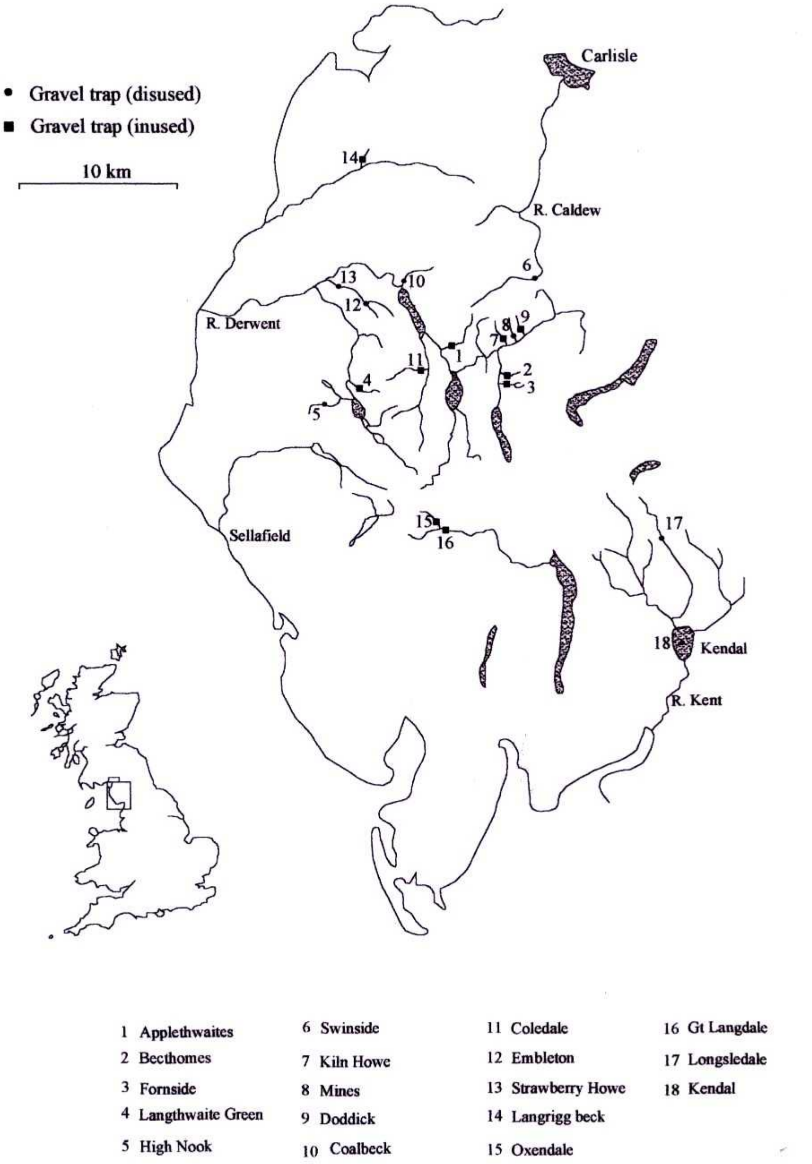


Figure 4.6 Location of gravel traps installed in the English Lake District (NRA, 1994b)

Table 4.7 Gravel traps installed in the English Lake District (NRA, 1994b)

Site	NGR	Date Built	Volume (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

- *Gravel trap currently in operation
- SKS/S = Skiddaw Slates and Sandstones
- A = Alluvium
- An/R/T = Andesites, Rhyolites and Tuffs
- LD = Land Drainage
- FC = Flood Control
- Mine = Mining in upstream catchment

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 be starved of coarse load, with the bed being scoured to make up the deficit. Records for several traps revealed that bed erosion protection had to be installed downstream following trap construction and it is desirable that trap efficiency be sufficiently below 100% that some gravel is let through to mitigate 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. Fig. 4.7 depicts the sedimentary structure and grain size of the bed of Coledale Beck up and downstream of a long-established gravel trap. Notable impacts include:

1. The bed upstream of the trap has a bimodal grain size distribution with considerable amounts of shingle (~2 to 8 mm). The bed downstream lacks this material and is dominated by cobble sized material.
2. The bed upstream includes a high percentage of particles that are unstable and exposed. 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 bed load movement, channel adjustments, spawning gravels and a wide range of benthic habitats. Consequently, downstream impacts and the risk of ‘over-trapping’ must be fully investigated when considering the use of a sediment trap to manage sediment transfer.

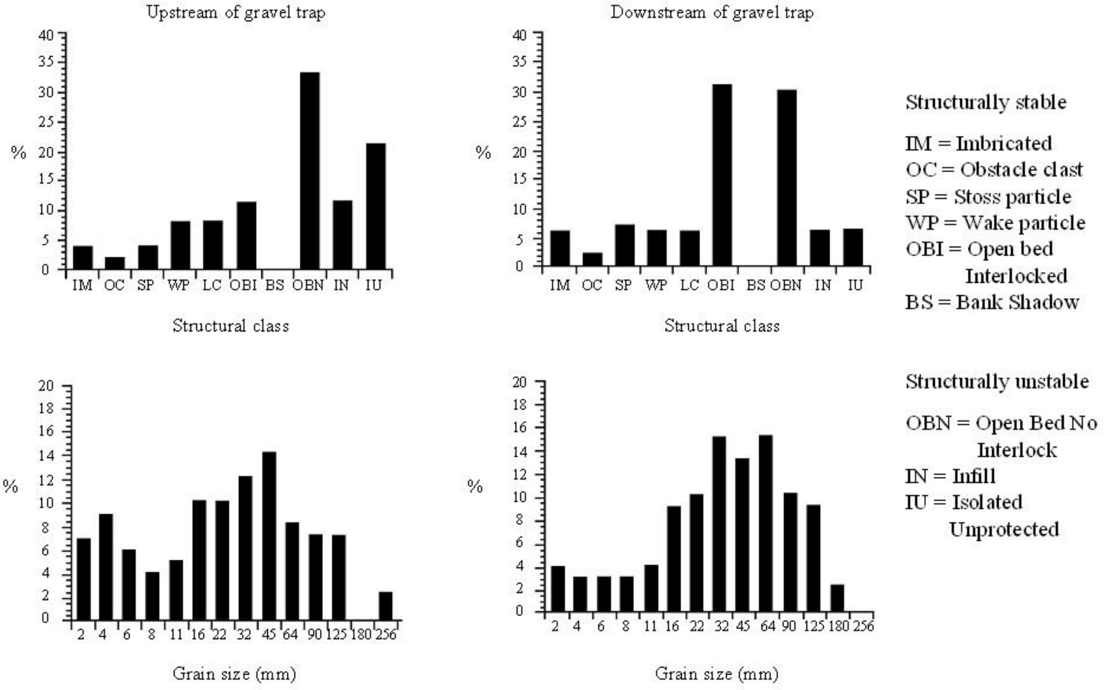


Figure 4.7 Sedimentary structure and grain size of the bed of Coledale Beck up and downstream of a long-established gravel trap (NRA, 1994b)

4.4 Managing Deposition

4.4.1 Background

The permissive powers for the removal of sediment deposits within a channel come under Section 165 of the Water Resources Act 1991 and Section 14 of the Land Drainage Act 1976. In addition, Local Authorities can serve notice to remove siltations under Section 259 of the Public Health Act 1936 where these pose a statutory nuisance.

However, under Section 614 of the Land Drainage Act 1991, the Agency has an obligation 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.” Large-scale maintenance works are also eligible for Environmental Impact Assessment and Statutory Instrument 1217 applies. Hence, there are environmental and conservation issues concerning the management of deposition that cannot be ignored.

The option to accommodate a siltation problem, rather than continue to suppress it through repeated dredging or desilting, deserves serious consideration. This approach may involve extending the floodway to allow in-channel storage, reconnecting the channel to its floodplain to increase overbank storage or reinstating a more appropriate channel morphology to improve sediment transfer through the reach. Two common options in rehabilitating channel morphology involve reinstatement of pools and riffles and the use of flow deflectors to increase sinuosity and marginal storage capacity for fine-grained sediment.

4.4.2 Reinstatement of Pools and Riffles

In a gravel-bed river, reinstatement of a pool-riffle sequence in a uniform, over-wide, channelised reach 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. The gravel deposited in pools is temporarily stored, being available to be re-eroded during the next transporting flood. Reinstatement of pools and riffles not only helps to solve the deposition problem, but enhances the conservation and recreation value of the reach.

When reinstating pools and riffles, care should be taken to mimic the characteristics these features typically display in natural channels. Specifically:

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 material overlain by fines during low flows.
- Are located at bends (around or just downstream of bend apex) in meandering streams.
- 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 refuges.
- Add to recreation and aesthetic values of river.

Riffles

- Occupy 30-40% of the river length.
- Are seldom spaced at a distance less than 3 and more than 10 times the channel width and are often spaced at between 5 and 7 times the width.
- Project ~0.3 to ~0.5m above the mean bed level.
- Are up to 25% wider than associated pools.
- Display high velocities with coarse bed grains breaking the surface to give a ‘riffled’ flow.
- Possess nearly symmetrical or slightly asymmetrical cross-sections, even in meandering channels.
- Have a bed composed of a coarse, tightly-packed surface armour layer underlain by a mixed substrate gravels and sands.
- Are located at crossings (around or just downstream of inflection point) in meandering streams.
- Tend to accumulate sediment during high, 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.

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 naturally and in such streams pools and riffles must be reinstated artificially. Construction of a riffle-pool sequence should then bear in mind that:

- The choice of material for riffle construction is important. Ideally 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 from pool to pool via temporary storage on the riffles. Hence, changes and adjustments of riffle position and morphology should be expected. The use of over-large material, while ensuring stability, may produce unnatural bed conditions that do not provided good benthic 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 some allowance made for natural 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 up to the point midway between the bend apices. Riffles should be located between bends, around or just downstream of the meander inflection point.
- In straight channels, pools should be excavated on alternate sides of the channel, separated by riffles.
- Riffle spacing should be 3 to 10 times the bankfull channel width, but regular spacing should be avoided.
- Spacing should be closer in steeper reaches and longer spacing in flatter or more sinuous reaches.
- Pools should be at least 0.3m deep.
- 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.
- Pools and riffles cannot usually be installed successfully in ephemeral streams, in channels with steep gradients, where there is high sediment transport or where the banks are unstable.

4.4.3 Use of Deflectors

Deflectors act to deflect low flows to one or other side of the channel to create flow asymmetry. Cross-sectional asymmetry develops as a result, through local acceleration and bed scour on side of the channel opposite the deflector and slack water deposition and storage of fine-grained sediment at the channel margin downstream of the deflector. Where deflectors are used on alternating sides of the channel, a sinuous low flow channel develops to increase the range of in-stream habitats and add to the conservation value of the river.

Deflectors should be built in the form of groynes or spurs constructed from timber, rock or gabions, depending on the energy level of the flow and the environment within which they are situated. A wide variety of designs are available including triangular, wing and spur configurations. Detailed design guidance is available in R&D Reports by Hey and Heritage (1992, 1993).

4.5 Catchment Approach to Sediment Management

4.5.1 Catchment Sediment Management Concept

Stream systems in the UK respond to natural events and human activities. Over a long period, weirs and dams, diversion and abstraction structures, flood embankments, in-channel works and the straightening, widening, deepening, and clearing of channel systems have all been employed to provide water power, water supply, flood control, navigation, channel stability and sediment management, recreation, and fish and wildlife habitat improvement. The cumulative impacts of these activities, combined with catchment changes such as de-forestation, afforestation, intensification of agriculture and urbanisation have significantly disrupted the dynamic equilibrium of stream systems and the ecosystems within them.

Channel erosion may cause serious on-site problems but it is increasingly recognised that the sediments generated channel instability are carried downstream through the system to cause sedimentation problems in flood control channels, damage wetlands and lakes, adversely impact fish and wildlife habitats, degrade water quality, and adversely impact infrastructure. In extreme cases, sedimentation itself may initiate further accelerated stream instabilities.

Historically, the focus of management activities in UK rivers has been on construction of capital works and performance of operational maintenance. However, in the twenty-first century the focus is shifting to the design of drainage networks on a catchment basis, particularly with respect to flood and sediment management. Progress is hampered because there is little published guidance for accomplishing effective catchment sediment management and a shortage of reliable and comprehensive data sets with which to investigate and understand the driving processes of sediment erosion, transfer and deposition at the catchment scale.

To address these limitations it is recommended that high priority be given to strategic research in catchment sediment management and field monitoring of sediment processes in order to:

1. Clearly establish the nature of basin-wide linkages in the sediment transfer system,
2. explore those linkages quantitatively,
3. identify and avoid the circumstances under which sediment and morphological responses or adjustments in the catchment system are likely to create problems that require costly and sometimes environmentally damaging solutions.

In this context, it is encouraging to note that a major Flooding Research Consortium (sponsored by the UK Research Councils, EA/Defra and UKWIR) to begin on January

1, 2004 includes an element concerned with Modelling Sediment Connectivity in the River System.

4.6 Briefs for Geomorphological Studies

4.6.1 Introduction

Briefs to provide the basis for project managers and flood defence staff to procure the geomorphological services necessary to support a variety of studies were developed in Environment Agency R&D and reported by National Centre for Risk Assessment and Options Appraisal (Environment Agency 1998b). However, this document has not been widely promoted or disseminated. The briefs may be used as the starting point for preparation of tender documents. Each brief may be customised to suit the specific project or operation for which geomorphological input is required – and this may not be a trivial task. In cases of uncertainty regarding the precise requirements, advice should be sought from the Regional or national geomorphologist.

Experience of Contractor

Geomorphology may be studied in undergraduate and postgraduate courses at University and training is available within the Agency. However, no formal accreditation exists for geomorphologists, unlike the chartered status available to Engineers and Landscape Architects. While framework contractors may possess geomorphological capability, this type of specialised work is often sub-contracted to third parties. In practice, therefore, those responsible for contracting geomorphological services may need to invoke informal standards in assessing the suitability of prospective contractors. General information on the expected capability for different levels of training and experience in applied fluvial geomorphology is listed in Table 1.1.

It is important to recognise the different levels of expertise required to perform the various types of geomorphological study and match the qualifications and experience of the staff member or contractor to the demands of the task. To aid in relating the capabilities of the geomorphologist to the task in hand, Table 4.8 lists levels of specialisation, experience and capability. In this respect, the role of training within the Agency is important and this topic is dealt with at length later in this report.

Table 4.8 Capability to perform geomorphological studies in relation to specialisation and experience

Individual	Interpretation	Capabilities
Specialist - Practitioner	Theoretical understanding plus experience in applying geomorphic principles to solving river management problems.	Able to provide theoretically-based but practical solutions clearly and in terms understandable by non-specialists
Specialist - Academic	Strong on theory, but lacks experience in the applications to practical solution of real world problems.	Sound on geomorphic principles, but will have steep learning curve on practical issues and communicating with non-specialists.

Non-specialist - Trained	Environment Agency river manager, engineer, ecologist, landscape architect etc., trained in geomorphology.	Can identify potential problems, solve straightforward cases and make reliable decisions. Recognises when specialised advice is required.
Non-specialist - Untrained	Environment Agency staff member with no qualifications or training in geomorphology.	Able to recognise basic geomorphic features, with limited ability to interpret their significance and judge the need for specialist advice.

Within the Environment Agency itself, more specific guidance on the qualifications expected of geomorphologists may be found in National Contract 305 documentation (Environment Agency 2000).

In The Environment Agency, Fluvial Geomorphologist's CVs will be rated on a scale of 1 - 10, depending on qualifications and experience. The *minimum requirements* for consideration are:

Academic Qualifications: Fluvial geomorphology is a specialist discipline and as such requires good training to give a firm grounding in the principles of the field. As such a graduate qualification (and/or preferably a post-graduate qualification either taught or by research), giving a solid understanding of fluvial systems and sediment transport processes is desirable. If the qualification is taught then it should contain a dissertation (or equivalent) focusing upon fluvial geomorphology.

Experience: A minimum of 4 years experience working as a fluvial geomorphological consultant should be demonstrated. CVs that score highest will demonstrate a depth of fluvial geomorphological experience across a wide range of areas, such as:

- River engineering construction and capital works,
- River engineering maintenance and revenue works, (including sediment accretion and erosion issues),
- Water resources (including impacts of abstractions and all forms of impoundments),
- Water quality (including fine sediment and or suspended sediment transport),
- River restoration, rehabilitation and habitat improvement (may include fisheries schemes),
- Identification, conservation and protection of rare fluvial geomorphological features.

High scoring CVs may also include a demonstrated experience in the use of specialist methods (which will vary), but may include:

- Catchment baseline auditing / Fluvial auditing / Geomorphological auditing,
- Calculations of sediment transport / yield,
- Modelling of sediment transport / yield,
- Sediment sampling and analysis,
- Field measurements of sediment transport, yield or erosion.

The above profile corresponds to the 'engineer' ('scientist') grade as described in the Tender Documentation (Section 5, p.10). This is the minimum length of experience and qualifications that are required for an individual responsible for the quality of output of fluvial geomorphological work. Ideally CVs presented should fall into the 'senior engineer' ('senior scientist') category.

Cost of Geomorphological Studies

The cost associated with geomorphological investigations are largely a function of project complexity and the level of effort and expertise required on the part of the geomorphologist.

Daily rates for geomorphologists fall generally within the normal commercial range based on 1% of annual salary, incorporating overheads (for example, £200 to £600 per person, per day). Where the expert opinion of a geomorphologist is required for legal work, daily rates will be considerably higher.

For a typical catchment and river, the order of decreasing study costs and person-days of effort would be:

CBS > GDA > Fluvial Audit > GPPA

Actual study costs depend primarily on the scale of the catchment and extent of the problem or project reach. For example, geomorphological dynamics assessment of bank erosion, bar siltation and sediment fluxes at a single site might involve a year-long programme of measurement and monitoring, but would probably still cost less than Fluvial Audit of a catchment of 500 km^2. If the GDA involved installation of automatic sediment samplers and extended to multiple sites along a 5 km reach of channel, this situation might well reverse, however.

A further complicating factor concerns the cost of obtaining archive and historical data, mapping and remotely sensed imagery. Costs vary widely depending on the availability of project-related information in-house and the difficulties of accessing key data held by third parties. Further costs arise when geomorphologists are required to liase between specialist teams or communicate their findings to residents, landowners and other non-technical stakeholders.

R&D Technical report W89 (Environment Agency 1998) tabulated the costs of geomorphological studies (as a percentage of project cost) in relation to the areas of application and resulting benefits, based on 14 case studies (Table 4.9). In the schemes reviewed, inclusion of geomorphological considerations in to standard project costs added between 0.1 and 15% to the total project cost.

Table 4.9 Applications, Benefits and Costs of Geomorphological Studies

Areas of Application	Costs (% of Project Total)		Benefits
Environmental Enhancement	Strategic evaluation	0.4%	Efficient Targeting of Resources
Erosion Control	Option evaluation	0.2%	Improved Aesthetics
Habitat Improvement	Detailed design	0.2%	Increased Biodiversity
River Restoration	Implementation	0.1%	Reduced Maintenance
Siltation Control	Project maintenance	0.1%	Reduced Whole-life Costs
Stable Channel Design	Post-project appraisal	0.3%	Sustainable Solutions
			Value Engineering

4.6.2 Brief for a Broad Catchment Baseline Survey

Background

A Catchment Baseline Survey (CBS) provides a strategic overview of the geomorphological ‘state’ of the drainage network. A broad understanding of the network is useful in guiding planning priorities and it enables Agency staff to respond efficiently to requests for information concerning the stability status, geomorphological context and conservation value/susceptibility to disturbance of particular reaches that might be affected by development, capital works or maintenance operations.

A Broad CBS consists of an assessment of catchment geology, soils, topography, landuse and geomorphology performed through a desk-study using documented information supplemented by material obtained through consultation with relevant Agency staff and a 1 to 2-day site visit to key locations within the catchment. The resultant summary (1 to 2 pages) of catchment characteristics and issues can then be used to provide input to regional and strategic catchment planing studies.

Aims

To provide a brief (1 to 2 pages) overview of the study area through broad investigation and assessment of catchment and drainage network geomorphology. The report should summarise key catchment characteristics, channel attributes and management issues in the form of a high-level document that can be used as a guide to catchment planning and policy development.

Methodology

i. Desk study using appropriate maps and accessible historical information and records relating to geology, soils, topography, landuse, ecology, engineering (especially, water resource development and river works) and, where available, results of past geomorphological studies.

ii. Consultation with relevant Environment Agency personnel (identified by the Project Manager and likely to include staff from flood defence, land drainage, operations and maintenance, fisheries, conservation and recreation and, where applicable, geomorphology) to gather supplementary and detailed information and identify key issues such as channel instability, sediment-related problems (erosion, siltation), maintenance practices/frequencies and proposed channel enhancement schemes.

iii. Catchment visit (1–2 days) involving inspection of key sites to verify and update historical, archive and institutional information. An appropriate geomorphological survey sheet or enhanced RHS survey should be completed and a photographic record be made at each location inspected.

Outputs

A 1–2 page geomorphological overview of the catchment (or study area if this only constitutes part of a large catchment) with significant issues and problems identified clearly in the text and relevant maps, field survey sheets and photographs appended.

4.6.3 Brief for a Detailed Catchment Baseline Survey

Background

A Catchment Baseline Survey (CBS) provides a strategic overview of the geomorphological ‘state’ of the drainage network and its sediment transfer system. A broad understanding of the network is useful in guiding planning priorities and it enables Agency staff to respond efficiently to requests for information concerning the stability status, geomorphological context and conservation value/susceptibility to disturbance of particular reaches that might be affected by development, capital works or maintenance operations. A commitment to performance Catchment Baseline Surveys to provide underpinning information for all main rivers that would be available prior to and during project formulation would, thus, reduce the prevalence of reactive management.

A Detailed CBS consists of an assessment of catchment geology, soils, topography, landuse and geomorphology performed through a desk-study using documented information supplemented by material obtained through consultation with relevant Agency staff and an initial assessment of channels making up the drainage network, with the insights so obtained used to sub-divide the geomorphological components of the fluvial system. The detailed assessment methodology centres on a field survey used to supplement knowledge based on the desk study by collecting information on the morphology of channels, classifying their geomorphological conservation status and broadly identifying sediment dynamics the fluvial system. Geomorphic units are mapped on a catchment map, possibly using a geographical information System (GIS).

Aims

To provide a 5–10 page report characterising geomorphology, geomorphological conservation value (susceptibility to degradation) and sediment dynamics of a catchment, river system or watercourse on a reach-by-reach basis, identifying actual and potential problems and highlighting opportunities for improved river management.

Methodology

i. Desk study using appropriate maps and accessible historical information and records relating to geology, soils, topography, landuse, ecology, engineering (especially, water resource development and river works) and, where available, results of past geomorphological studies.

ii. Consultation with relevant Environment Agency personnel (identified by the Project Manager and likely to include staff from flood defence, land drainage, operations and maintenance, fisheries, conservation and recreation and, where applicable, geomorphology) to gather supplementary and detailed information and identify key issues such as channel instability, sediment-related problems (erosion, siltation), maintenance practices/frequencies and proposed channel enhancement schemes.

iii. Field survey of the catchment and river using appropriate Geomorphological Baseline Survey sheets and photographs to record information and classify reaches in the drainage network in a manner suitable to the purpose of the investigation. For example, reaches may be classified according to their geomorphological conservation value (e.g. high, medium, low, channelised, navigable, culverted) or their role in the sediment transfer system (e.g. sediment source, transfer, exchange or sink).

iv. Preparation of a geomorphological channel map(s), with channel reaches coded by colour or line type.

v. Identification of actual or potential issues, problems and opprtunities for improved river management in the catchment (or study area) as a whole and within individual sub-reaches, particularly (but not exclusively) with respect to the duties, functions and activities of the Environment Agency.

Outputs
A 5–10 page report detailing catchment characteristics and summarising issues, problems and opportunities relevant to the Environment Agency. A section presenting pragmatic suggestions for river management and enhancement, and recommendations for further study (Fluvial Audit, Geomorphological Dynamics Assessment) may be included. Appendices containing geomorphological susceptibility and, possibly, sediment dynamic maps, Baseline Survey sheets and photographs must be attached.

4.6.4 Brief for a Fluvial Audit

Background
Fluvial Audit is the recommended geomorphological data collection and presentation process developed and applied during R&D projects performed by and on behalf of the Environment Agency and its predecessors during the 1990s. For project reaches or reaches identified in the CBS as experiencing sediment-related problems, a Fluvial Audit is performed to provide the geomorphological basis for a sustainable solution. The Audit technique is intended to incorporate and build on the results of a prior CBS, but it can also stand alone when no CBS has been performed.

The Fluvial Audit relates sediment conditions in the study reach to those prevailing in the wider catchment, paying close attention to sediment transfer between source and sink areas. The method is intended to establish a semi-quantitative or first-approximation understanding of the reach-scale sediment budget, the geomorphological processes operating in the channel and the causes of instability or other sediment-related problems. Setting the context and identifying cause includes a historical dimension as the impacts of past as well as contemporary events and catchment changes may be important. In this respect, identification of historical and current Potentially destabilising Phenomena (PDPs) is an integral component of Fluvial Auditing.

Aims

To produce a substantial report building on the findings of a Catchment Baseline Survey by presenting qualitative and semi-quantitative information on sediment sources, transport and storage in selected problem or project reaches within the wider, context of the catchment sediment system, and determining the nature and causes of sediment-related problems or channel instability.

Methodology

i. Desk study to obtain overview of catchment geomorphology through review of the findings of a previous Catchment Baseline Survey, or by performing such a study if none exists.

ii. Select key (or project) reaches or sites for detailed geomorphological field survey, either on basis of existing reach-scale geomorphic classification map (product of CBS) or initial reconnaissance survey, using appropriate Geomorphological Assessment sheet.

iii. Conduct field survey to assess sediment sources, dynamics and storage that affect the study reach and identify the nature, intensity and extent of sediment-related problems or channel instability. A suitable Fluvial Audit record sheet should be used to record data and observations, which should include:
   - Cross-section data
   - Evidence of instability and its possible causes
   - Sedimentation patterns
   - Evidence of previous works and structures and degree of natural recovery
   - Effects of vegetation
   - Maintenance activities and requirements
   - Protection and enhancement value

iv. Consult relevant Environment Agency staff to gather information on history of catchment development, landuse changes, river management and engineering schemes, and existing or past erosion/sedimentation problems. Sample questions that could be used when interviewing staff could include:
   - What are your perceptions/experiences of erosion and sedimentation/maintenance issues within the catchment?
   - What projects have been undertaken?
   - To what extent was an integrated approach adopted for these projects?
   - Are there any projects which were partially successful or have experienced particular problems?
   - Which sites/reaches/projects have had sediment-related problems and why?
   - What do you perceive as the solutions to these problems?

v. Use all available information, including historical (extending to long timescales) and documentary evidence at the catchment scale, the results of reach-scale field surveys and consultation with Environment Agency staff, to identify Potentially Destabilising Phenomena (PDPs) at a catchment scale and on a reach-by-reach basis.

vi. Use field evidence and site specific documents/histories/observations to assess sediment-related issues and channel instability within the context of the catchment sediment system and identify causal links between reach-scale problems and particular local and/or catchment-scale PDPs listed in (v).

vii. Present the findings in a time chart of catchment changes that may have influenced river geomorphology, and catchment/channel maps showing features and links relevant to sediment dynamics, and the catchment distribution of PDPs.

Outputs
A report summarising the above information (including sections dealing with sediment sources, pathways and storage, morphological susceptibility, PDPs, sediment-related issues and channel stability assessments at both catchment scale and on a reach-by-reach basis) accompanied by pragmatic suggestions for improved management, efficient maintenance and environmental enhancement. A time chart of catchment changes and catchment/channel maps showing sediment dynamics, channel stability status and the spatial distribution of PDPs must be included. Paper maps should be at no more than 1:10,000 scale. Ideally, maps should also be in supplied electronic format, through application of either GIS or inter-active mapping technologies.

4.6.5 Brief for a Geomorphological Dynamics Assessment

Background
A Geomorphological Dynamics Assessment (GDA) forms the most intensive stage of a study into river geomorphology and sediment dynamics. The method requires detailed, quantitative investigation and analysis of the channel in an individual problem or project reach to assess its form, processes, process-form links and sensitivity to change. The field techniques employed are derived from research-level geomorphological studies and may include measurement and monitoring of channel hydrology, hydraulics, sedimentology, sediment movement and the geotechnical properties of the bank materials. A GDA will usually require a sustained programme of field measurement and monitoring over a time-span sufficiently long to detect seasonal changes in process-form relationships and observe the processes operating under of a range of geomorphologically-significant flows, up to and including bankfull discharge. Hence, the duration of a GDA will usually be at least one year.

Aims
To provide a comprehensive assessment and understanding of geomorpological processes, channel forms and process-form interactions at the site or reach-scale, within the context of the catchment fluvial and sediment systems. To provide a framework for using this understanding to support the selection of long-term solutions to serious sediment-related problems and channel instability issues that are based on matching the solution to the cause, severity and extent of the problem.

Methodology
The methods and techniques employed in GDA are drawn from research-level geomorphological practices and are tailored to the nature and parameters of the reach, processes and channel forms in question. Hence, it is not possible to write a definitive methodology for GDAs. However, the underpinning principles of the method can be illustrated, using the guiding principles for a GDA related to a serious sediment-related or channel instability problem. These are:

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. Assessment may be based on the results of earlier an CBS or Fluvial Audit, or may be undertaken specifically for the problem site through investigation of historical maps, archive information and

interviews with relevant Environment Agency staff, together with geomorphological stream reconnaissance using a suitable record sheet (see Thorne (1998), for example.

2. Perform an intensive and sustained programme of survey, measurement and monitoring to identify the cause of the problem in terms of reach-scale geomorphic processes, catchment change and sediment dynamics, evolution of fluvial system and morphological adjustments occurring in response to human impacts.
3. Use the results of (1) and (2) to predict the future morphological evolution of the reach under a 'do nothing' scenario. If it is determined that the problem is likely to persist and the risk this poses to people or infrastructure is unacceptable, identify possible solutions based on either active channel management or structural measures. (note: structural measures should only be invoked when there is no feasible solution through active channel management). Active management may involve:
    i. changing maintenance or usage of the reach if this is causing or contributing to the problem;
    ii. allowing adjustment of channel morphology if change is occurring naturally;
    iii. relocating assets (for example: footpaths or flood embankments) to reduce the risk posed by sediment-related processes or channel instability.
4. For active management or structural measures, use the results of (1)–(3) to predict morphological response to management or engineering works and ensure that morphological response to the solution does 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 (1) – (4) to match the scope, strength and length of channel covered by the solution to the cause(s), severity and extent of the problem (this may involve works off-site where a site-scale problem is associated with reach or system-scale instability);
6. Overall, be aware that it is necessary to balance conflicting goals in river management to achieve a sustainable solution that is optimum in terms of efficacy, economy, engineering and environment.

Outputs

Report detailing the assessment and recommendation process described above. This will include:

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 both archive studies and field surveys);
4. Justification for allowed morphological adjustment, active channel management or structural measures;
5. Proposed measures that match the solution to the problem and in which active management is preferred to structural approaches where feasible. In the case of solutions involving structural measures, soft engineering using natural materials should be used in preference to hard solutions using artificial materials wherever possible.

4.6.6 Guide to Geomorphological Post-project Appraisal

Background
The purposes of GPPA follow from those set out by Sadler (1988) for all environmental assessments. These are:

1. "in project regulation it should ensure that the activities are conforming to previously established conditions;
2. it should provide an opportunity to manage any unanticipated effects;
3. it should aid field development through an improvement of practices."

(Sadler, 1988, p131-132)

GPPA should also strive for an early dissemination of results so that future schemes in similar settings will avoid repeating past mistakes and so that valuable experience gained in one project can inform future projects.

Aims
The aims of GPPA are to:

- determine whether the scheme was constructed as planned;
- ascertain whether any unanticipated effects were occurring through comparing the performance of the scheme with stated objectives outlined in the design phase;
- aid identification of particularly successful techniques used in various schemes to develop a 'best practice' approach;
- provide an indication of whether the scheme has met short-term objectives and whether the scheme can be sustainable over a longer duration;
- provide the opportunity to identify any requirements for necessary maintenance work or adaptive management;

Methodology
The framework for a GPPA is set out in Figure 4.8. As guidance on GPPA has not previously been disseminated within the Environment Agency (unlike guidance on CBS, Fluvial Audit and GDA), each step is described in detail in this brief.

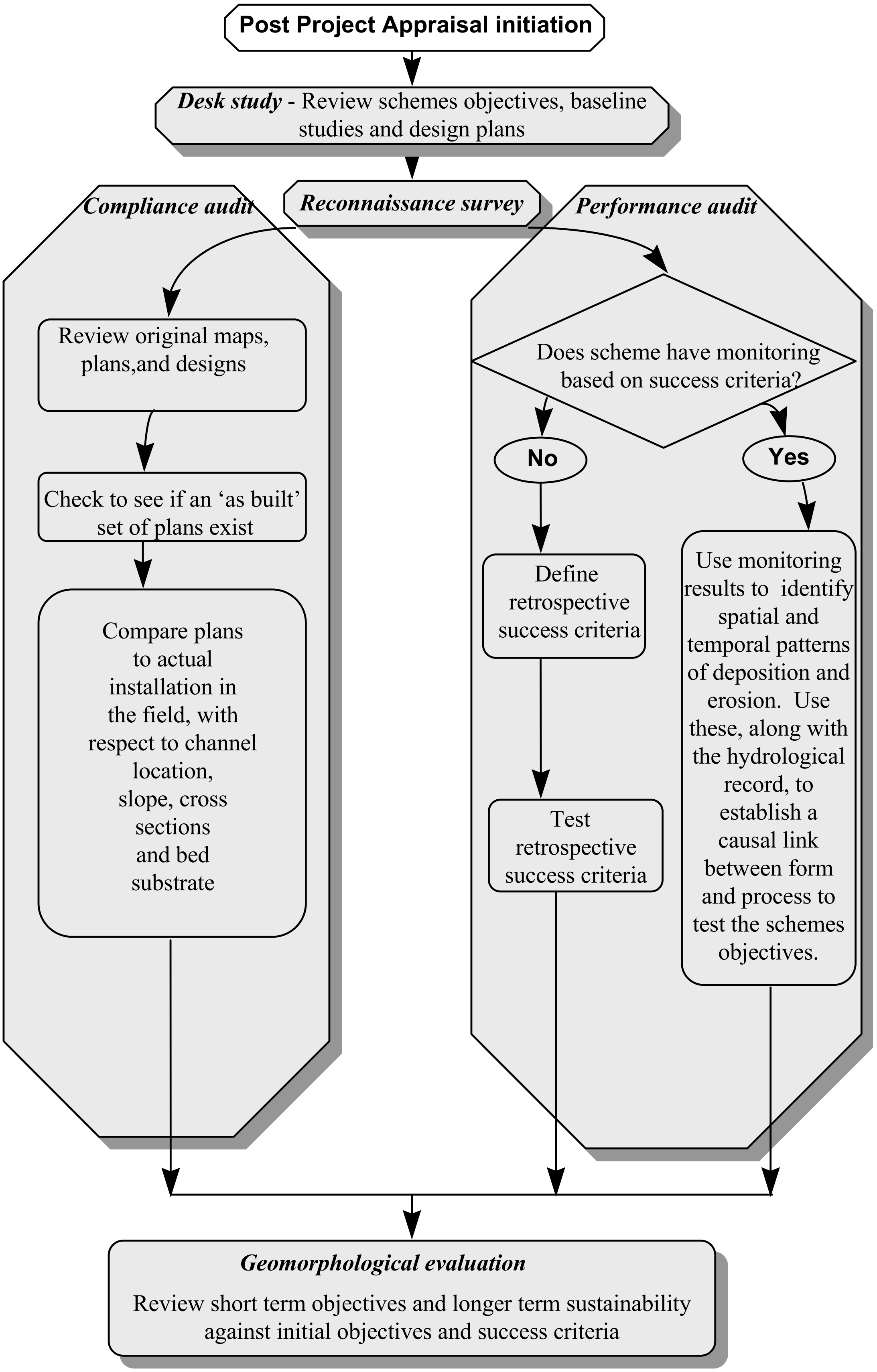


Figure 4.8 Framework for Geomorphological post-Project Appraisal (EA in review)

i. Desk Study to collect information relating to the pre-project state of the environment and background material on the scheme itself. The types of information to be obtained include any documents related to the scheme, such as an options evaluation report, a geomorphic assessment, any biological reports and design plans and maps. Along with this specific information on the scheme, other useful reports include documents relating to the area or reports on previous work that have been undertaken in the watershed. This information can be used, along with monitoring data and stated success criteria, to delimit the area to be covered by the PPA.
ii. Reconnaissance Study to establish morphological context for project and help distinguish the required baseline criteria. Uses field survey to collect site-specific geomorphological information (unless this already exists from prior CBA/FA/DGA studies) using suitable reconnaissance survey sheets (for example, Thorne, 1998). Survey area extends up and downstream to cover all reaches potentially affected by feedback to project.
iii. Compliance Audit to review whether the scheme was constructed according to design. This is an important starting point since details of a project as constructed often differ significantly from the original design due to miscommunication, contractor error or unforeseen circumstances that are accommodated through on-site changes. Such differences may be responsible for unexpected performance attributes or failure of the project, irrespective of the validity of the original design. Key parameters to be checked against designs include: channel slope, cross-section and bed material, key dimensions and materials used in construction. Other variables may also be important and these too should be appraised, on a case by case basis.
iv. Performance audit to establish the geomorphological impacts of the project and compare them to those intended when the scheme was designed (with due allowance made if the project was not constructed as designed). The first step is to determine what pre-project and post-project monitoring data already exist and use these to investigate the temporal and spatial performance of the scheme. If pre-project data are unavailable it might be necessary to synthesize data to represent conditions prior to construction of the project using a reference reach with matching characteristics. If this is required, qualitative and quantitative measurements performed in the reconnaissance survey can be used to help assess the response of the channel to the scheme. The third step is to design and implement post-project monitoring at a suitable frequency and over a sufficiently long period (perhaps up to twenty years for substantial schemes) that the results can used to identify significant changes that occur in response to installation and operation of the project. Significant geomorphological changes might include channel adjustments, zones of deposition and erosion, or heavy maintenance. A particular issue arises when GPPA is applied to river restoration or enhancment schemes that rely on ‘prompted recovery’ to achieve morphological improvements. The timescale required for recovery of natural forms and features is indeterminate since recovery relies on natural events that are weather–related. Consequently, the timing and duration of GPPA monitoring surveys and programmes cannot be specified and the commitment to monitoring must be, to some degree, open ended.
v. Geomorphic Evaluation is the final stage of the GPPA methodology. In this stage, post-project sediment dynamics and geomorphological adjustments in the project and adjacent affected reaches are compared to their pre-project counterparts. This

provides the basis to identify causal links between process-response mechanisms triggered by the project and channel adjustments in the river. The findings should then be considered within the context of the catchment and fluvial systems to provide an overall geomorphic appraisal.

Outputs

A substantive report (20-30 pages) detailing how the reconnaissance, compliance, performance and evaluation stages described above were undertaken and assessing the geomorphological performance of the project at two timescales.

The first timescale refers to the immediate geomorphological impacts of the project and its success in meeting its short-term objectives. This is important as many local interest, stakeholder and end-user groups expect to see immediate results following installation and are also likely to attribute any adverse developments in the river during the period following installation to the impacts of the projects. In both cases, a sound and authoritative GPPA can provide the basis for a more informed discussion of the situation.

The second timescale refers to the long-term impacts, management and sustainability of the project. When GPPA is undertaken soon after installation, comments with regard to long-term impacts and sustainability are predictive and represent a ‘forward look’. In later follow-up surveys, they record how the project-reach has adjusted and evolved as an integral part of the catchment and river systems. This part of the report should also comment on how resilient/sensitive the project (and its success) will be to extreme events.

The report should close with a section listing the lessons learned and giving pragmatic advice that could be used to guide modifications to the project designed to enhance its performance, changes to maintenance regimes and practices designed to reduce adverse impacts and measures to be considered in ‘adaptive management’ of the project and river designed to optimise performance against agreed success criteria.

5. GEOMORPHOLOGY AND RIVER ECOSYSTEMS: TOOLS AND STRATEGIES FOR RIVER AND FLOODPLAIN MANAGEMENT

5.1 Introduction

Simultaneously and in parallel with the R&D developments reported above, also funded largely by NRA and EA, fluvial geomorphologists have been contributing both strategic and operational advice to a much broader, interdisciplinary element of river management. Public policy has been and is being rapidly modified 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 (whilst permitting sustainable exploitation of resources by humankind).

Thus, 'R&D', 'RHS' (River Habitat Surveys) and 'Restoration' may be seen as marking the footprint of applied fluvial geomorphology in the UK during the 90s (Newson *et al.* 2001). 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 those concerned with habitat protection and flood protection have grown and so the early years of the new millennium will be qualified by the integration of the 'three Rs' above. This chapter describes the ways in which this integration can be achieved and the management tools already available, or in the process of refinement, to meet management needs (see also Newson 2002).

A major point for emphasis is that, although the main focus for the R&D reviewed here 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 – 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 were being designed; geomorphologists were invited to help with the survey specification and with analysis of the early data (e.g. Newson *et al.* 1998a and Section 5.4). Another development which encouraged the same deployment of geomorphological expertise was the River Restoration Project (RRP) (Kronvang *et al.* 1998 and Section 5.5).

5.2 'Fluvial hydrosystems'

It is a paradox that the traditional engineering works associated with river management are best designed as site-specific interventions to deal with particular problems: society respects such technically sound procedures. However, the nature of social responsibility in 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, to not merely leave holistic system-wide considerations as a precautionary check on 'business as usual' but to make 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.

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 (Figure 5.1 here) being dependent on longitudinal, lateral and vertical transfers of energy, material and biota.'

They distinguish five key features of the fluvial hydrosystem approach:

- It focuses attention on the river corridor, including floodplains;
- It stresses the lateral and vertical fluxes of energy and materials between the river and alluvial aquifer;
- Biota are clearly affected by the resulting environmental gradients, modified by biological processes;
- Environmental change and anthropogenic impacts become important at the catchment scale;
- Historical legacies help to explain the contemporary functioning of the system.

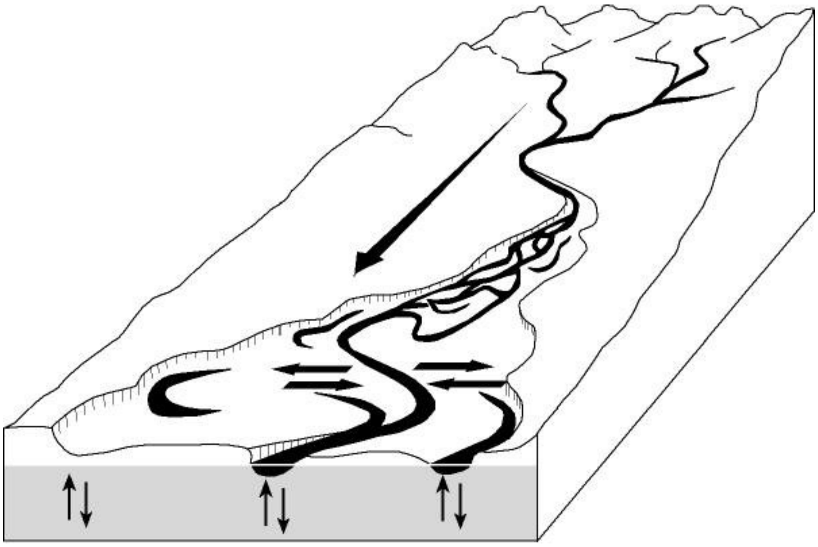


Figure 5.1 View of river as a three-dimensional system dependent on longitudinal, lateral and vertical transfers of energy, material and biota.

The most logical extension of the scope of river R&D in England and Wales is clearly to the floodplain. Figure 5.2 shows the extent to which floodplains are occupied by out-of-bank flows at a 100-year return period (the Environment Agency's definitive floodplain maps give the picture in much more local detail). By considering the 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).

Figure 5.2 Extent to which floodplains are occupied by out-of-bank flows with a 100-year return period.

5.3 Channel-floodplain interactions

Floodplains are not universal at the margins of British rivers. The idealised cross section in Figure 5.3 indicates 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) 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.

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 argument:

- empirical equations to predict channel form and dimensions mainly use the value of bankfull discharge as the independent variable;
- any artificial increase in channel conveyance (e.g. by the construction of flood embankments) for flood defence purposes will have profound impacts on processes.

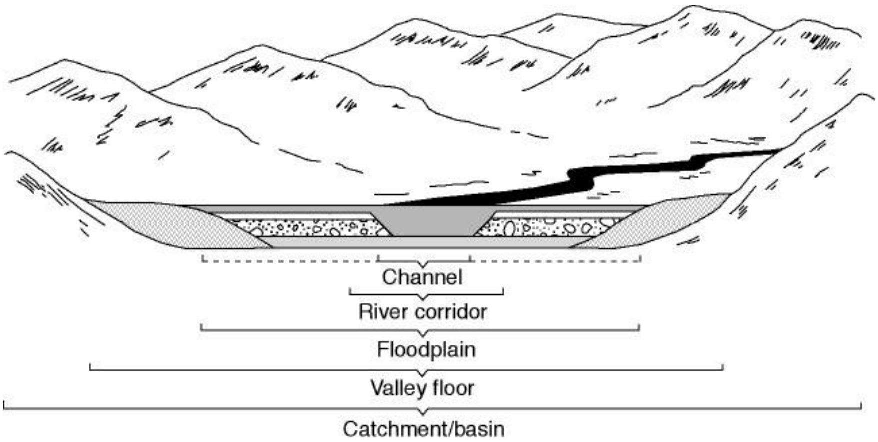


Figure 5.3 Idealised cross section indicating two additional components of relevance to both fluvial processes and the conservation of habitat for diverse flora and fauna: the river corridor (which may or may not function as a 'buffer zone' and the valley floor (after Newson 1992).

In practice, the bankfull discharge is difficult to identify precisely in field sites (Wharton 1992, 1995) and varies in return period according to flow regime, even within the fairly narrow climatic range of the UK (Harvey 1969, 1975). Channel characteristics, equally, will feed back to acting as a control on bank-full 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 had 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 and natural floodplain functions

As a result of the recent glaciation of much of Britain's land surface and of the profound changes of climate during and since deglaciation (ca. 12 000 years ago), many river channels flow as 'underfit' (Dury 1970) in their valleys. The valley's dimensions, particularly width, and veneer of drift materials may owe little to the current river or to fluvial processes. However, the combination of valley-floor alluvium from glaciofluvial processes and dynamic, supply limited rivers has resulted in considerable re-working of most valley floors in the last 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 important local aquifers, important in water resource planning, for example in connection with the influence of bank storage on reservoir releases.

Floodplains are known in some parts of Europe as the ‘winter channel’ of the river. Whilst society considers them as both attractive settlement sites 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.

It is an obvious physical principle that systems without storages are both sensitive and prone to rapid irreversible changes. Floodplains act to store water and sediment over a range of timescales. Within these physical functions they are also able to act as stores for biological material and as sites for the chemical exchange of pollutant material such as nutrients for less harmful materials.

5.3.2 Geomorphological processes on floodplains

The flow of rivers across floodplains has been neglected by all relevant disciplines until very recently: the complexity introduced by variable patterns of afflux and a floodplain relief of small-scale complexity (hitherto hard to measure), much complicated by land cover patterns has rendered the routing of floods out-of-bank very much a black-box procedure.

Recent advances in aerial survey (e.g. LIDAR) and the use of experimental flume facilities incorporating both channel and floodplain have, however, led to rapid progress. Geomorphologists have also paid much more attention to sedimentary processes on semi-natural floodplains and have stressed the subtle and variable relationship between accretion of sediments on the floodplain surface and the relative levels of that surface to the channel bed.

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 (and hence the flood hazard) varies through time as the result of relative elevations if nothing else.

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	2 198	2.37	0-97
Avon	1 870	0.50	0 – 3 000
Swale	550	0.53	0 – 130
Swale	550	13.00	1986 flood
Axe	31	0.54	0 – 312
Ripple Brook	19	0.05	0 – 2 500
Stour	620	10.20	1979 flood
Culm	276	0.05	1983-84

Table 5.2 Floodplain accretion, Low Prudhoe, R. 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	

Recent results from the UK Flood Channel Facility have emphasized 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.

It is very clear that floodplain flow and sedimentary systems will form the next fertile area in which academic geomorphological principles and concepts will need turning 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

For more than fifteen 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 river management. For example, in the production of the 'Rivers and Wildlife Handbook' (Lewis & 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 & Brookes 1994).

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), there remained no realistic assessment of the true extent of geomorphological features in UK river and hence no quantifiable idea of the amount of 'damage' caused by existing river management practice. The default situation in the minds of many conservationists was that 'damage' was almost universal from traditional land drainage and flood defence. The inception of the River Corridor Surveys (NRA 1992) had brought about precautionary mapping of remaining features of high habitat quality in the channels of Main Rivers and in a 10m river corridor zone - an important, partial, recognition of the 'fluvial-hydrosystem' concept.

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.

River Corridor Surveys became noted for a lack of central coordination, standardisation and for their unsuitability for statistical analysis. 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.

As part of the River Habitat Survey methodology a need was felt to incorporate fluvial geomorphology in two ways:

- 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;
- To utilise observations of hydraulic patterns (‘flow types’) to assess the diversity or otherwise of the 500m length of stream surveyed.

In fact there are many dimensions to the proper definition of instream habitat (Figure 5.4) but, over the review period for this Guide, fluvial geomorphology has made major strides in working with ecologists to define, parameterise and measure the physical element. Such is the interplay of flow and substrate variables that the EU's choice of 'hydromorphological' to describe the key elements is apt if not beautiful! It has placed further pressure on the academic community in geomorphology to design effective tools for survey, assessment and management.

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-digital camera and very general);
- Basic form, e.g. valley shape, and detailed form, e.g. bank profile types;
- Dimensions - bank-full 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.

5.4.1 Interaction of flow/substrate/morphology: 'hydromorphology'?

During the 1990s considerable R&D effort has gone into attempts to add detail to the hydraulic description of habitat available since the 80's via one-dimensional hydraulic models of flow such as PHABSIM. These models are known generically as IFIM (instream flow incremental methodology) because they seek to assess the available habitat to known species, particularly fish, in regulated rivers below dams. In the UK, contributions to the assessment of physical habitat have the context of smaller river systems requiring more detail and with channel form/substrate more often heavily modified than flow regime.

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 2002). 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). Geomorphologists moved closer to the growing body of research in 'habitat hydraulics' or 'eco-hydraulics' in a 'bottom, up' approach via the classification of habitat units in the channel, labelled 'physical biotopes'. The contrast is shown in Figure 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).

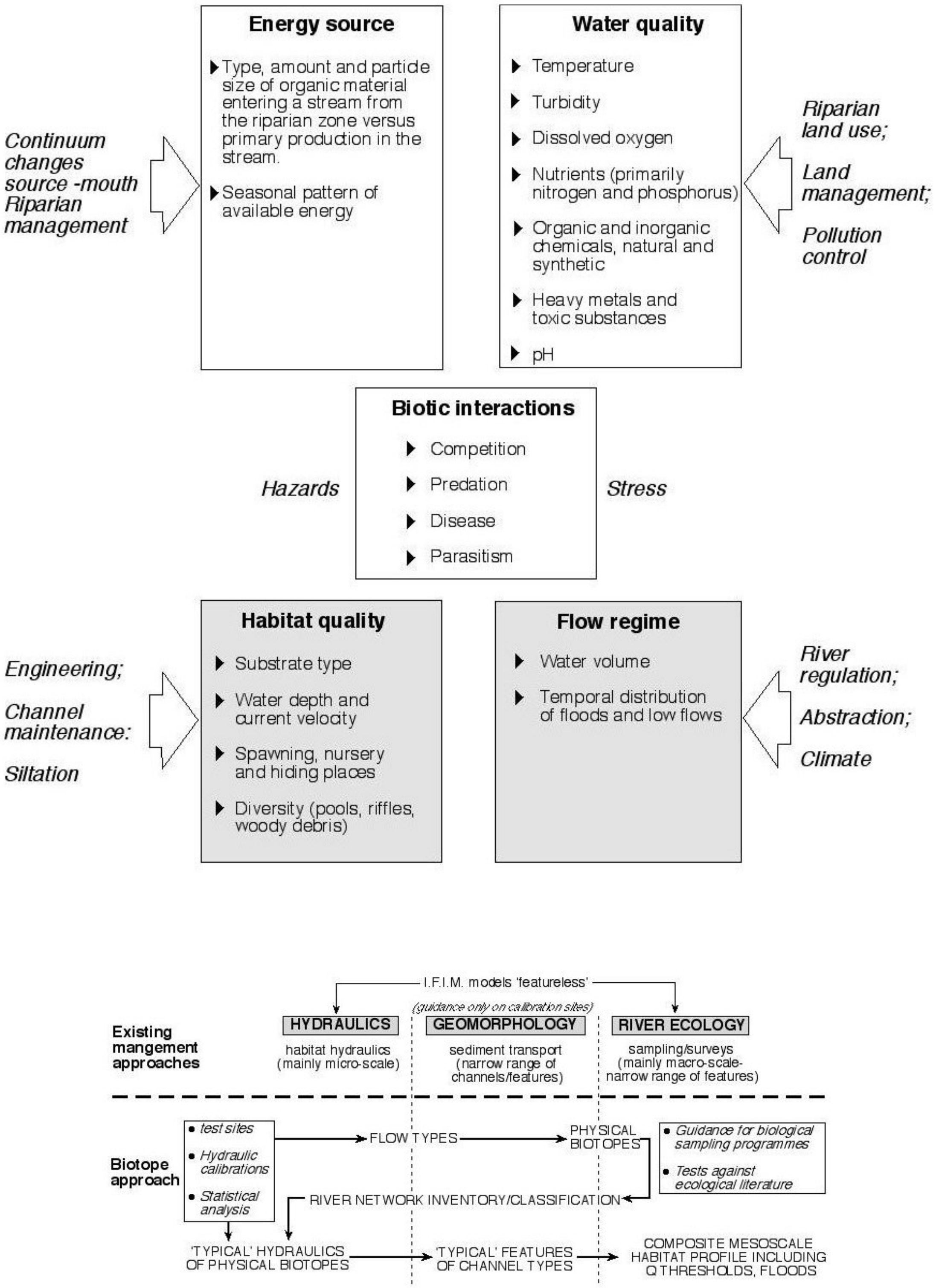


Figure 5.4 Alternative dimensions and approaches to the proper definition of instream habitats (after Newson & Newson 2000).

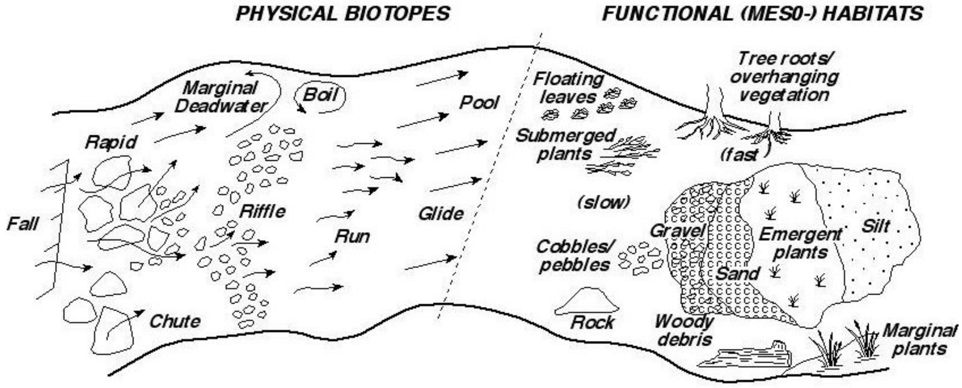


Figure 5.5 Comparison of two approaches to mapping spatial patterns inherent in physical habitats (Newson and Newson 2002). Freshwater ecologists may use 'functional habitats' or 'meso-habitats'. Geomorphologists may favour 'physical biotopes'. See text for full discussion of origins of these approaches.

At an early stage of this research a basic typology of hydraulic flow patterns, observable and mapable from river banks became incorporated as part of River Habitat Surveys as part of the input from the geomorphological community. 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.

5.4.2 RHS – geomorphological significance of results to date

Among the many relevant extensive-scale findings forthcoming from the first three years of RHS data collection in the UK (Raven *et al.* 1998) are:

- Coarse woody debris occurs in less than five percent 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 500km. Possibly, landuse 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 desire to define 'natural' with which geomorphology is still coping.

A further revelation from RHS relates to the riffle-pool sequence. The most common feature between riffles, where they exist, is generally a ‘run’ or a ‘glide’ with marginal deadwaters, rather than a full-width pool; there is clearly both a sedimentological and ecological significance in this outcome since the hydraulic calibration of these features (Padmore *et al.* 1998) reveals them to have a much shallower section and faster flow than is characteristic of the geomorphologist' established image and definition of 'pool'.

5.4.3 Issues of river classification emerging from RHS

In contrast to the highly variable, qualitative nature of the data collected during the zenith of River Corridor Surveys, the RHS database is deliberately open to quantitative analysis (albeit with caveats concerning the variety of scales on which habitat variables are measured).

Many practical schemes of river management designed to work 'with nature' would benefit from a system of river channel classification. 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' (Rosgen 1996, Miller and Ritter 1996). Geomorphologists are generally concerned that typologies or classifications based upon morphology alone (however discerning the choice of variables) do not reflect the vital management concern with 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 (whilst 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:

- 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);
- An approach through an entirely different spatial perspective, but also using map variables, that of principle components analysis (Jeffers 1998).

The latter is now the preferred route in RHS, simply because of the need to determine similar sites in England and Wales for the assessment of habitat quality in order to comply with the EU Water Framework Directive. One aspect of compliance with the Directive 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.

It can be argued that, for policy outlets such as Catchment Flood Management Plans (CFMS) or for Catchment Abstraction Management Schemes (CAMS) methodology, other classificatory approaches remain valid and should be implemented via statistical studies of the much greater volume of data from RHS now available (cf. Newson *et al.* 1998a). The initial use by CAMS of reach classification and flow sensitivity of channel types is naïve by comparison with the knowledge available - that knowledge is not being made available. For example, flow type mapping linked to the assessment of flow sensitivity in physical biotopes (Newson and Newson 2000) is capable of providing a firm picture of the needs for ecologically acceptable flows anywhere in England and Wales.

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 (Kern 1992, Brookes 1992). A clear role was created for geomorphological predictions (e.g. dimensions of meander bends, riffle spacing) for 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 were already available and many had been tested in the USA for decades. The River Restoration Project, a UK 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 & Nielsen 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 2km long, in the catchments of the Skerne ($250km^2$) and the Cole ($129km^2$) (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), 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 indeed of post-project appraisal); these formalised procedures resulted from a research and development programme sponsored by the National Rivers Authority and subsequently the Environment Agency in England and Wales. Both the Skerne and the Cole were given Catchment Baseline Surveys and Fluvial Audits (described in Table 5.1) before works began (Kronvang *et al.* 1998) but channel dynamics and structures on both streams remained within the engineering field. 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. At a recent European conference on river restoration the procedures developed in 'River Geomorphology: a Practical Guide' (EA 1998) were presented as best practice (Newson and Sear 2000).

Following the completion of the River Restoration Project (under the EU 'Life' scheme - hence the cooperative venture with the Danes) the protagonists have established the River Restoration Centre (RRC) which acts as an information and guidance 'hub' to the many sites now being restored or rehabilitated in the UK and Europe. The RRC is interdisciplinary in its core expertise but fluvial geomorphology forms a major focus for its annual conferences, including practical workshop sessions on the basic applications of geomorphology. A continuing theme has also been, however, a form of geomorphological 'fundamentalism' which calls for the complete, not partial, adoption of the principles of the subject, warning of lack of sustainability if this does not happen (e.g. Sear 1994, Newson *et al*. 2002).

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. As a case study of such a scheme of rehabilitation the following example is taken from Newson *et al*. (2002):

Geomorphological inputs to a lowland rehabilitation scheme: the River Waveney, East Anglia.

The River Waveney drains a catchment of 889km^2, 670km^2 of which is non-tidal. The catchment is of low relief and everywhere is below 100mAOD. 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. Amongst the terms of reference for the Waveney geomorphological surveys (Catchment Baseline, Fluvial Audit, Dynamic Assessment) were to describe and map:

1. the features considered as typical of this type of river in this part of Britain;
2. the location of the segments/reaches suitable for works;
3. the potential threats posed by current sediment dynamics and channel/catchment management;
4. the design specification of the features selected;
5. the stability of the features once emplaced;
6. 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 chub (*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 – 1 200 m), river bed slope (0.00093 – 0.0215), bankfull width (5.2 – 76.6 m). This dataset illustrates 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:

$$\lambda_r = 7.36.w^{0.896}S^{-0.03} \qquad r^2 = 0.67,\ p > 0.001 \qquad (5.1)$$

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, whilst 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 re-profiled 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 Wm^{-2} (Brookes 1990, Brookes and Sear 1996). Above this threshold, sites may be expected to experience erosional adjustment (depending on boundary materials), below 10 Wm^{-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 1-D 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:

$$U = R^{2/3}S^{1/2}n^{-1} \qquad (5.2)$$

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 Mannings '**n**'. The model is known to over-predict 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

1. desilting at some of the rehabilitation sites to permit a firm footing for the gravels;
2. desilting a length of channel upstream of the features to delay the onset of infilling and cementation;
3. ‘ploughing’ (or equivalent) of cemented gravels if this becomes a problem.

5.5.2 From implementation to strategy – what is ‘natural’?!

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.

Whilst the RRP conducted extensive feasibility studies at a large number of sites before selecting the Cole and Skerne, their final selection was heavily influenced by the willing participation of local authorities and communities. To make rehabilitation and restoration a widespread and cost-effective aspect of river management requires much greater attention to site and network properties, requiring information at a very large scale such is only available via the River Habitat Surveys.

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;

- 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 landuse, water management and in the context of climate change. Both spatial and historical analyses are essential (Sear, 1994, Kondolf & 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 is 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 & 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.

Both Fluvial Audit and Geomorphological Audit assessment techniques have been used to set up basin- or sub-basin- restoration strategies. 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.

5.6 Conclusions

The subject matter of this chapter has been, in some ways, divergent from the book's theme 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. It nevertheless reflects a parallel set of R&D initiatives that have occurred, paradoxically, partly as a result of a lack of geomorphological guidance in traditional channel management activities. The duty of river managers to promote conservation has directly led 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 to those concerned with river ecosystems. Newson (2002) risks an attempt at defining some of the new policy jargon from the viewpoint of geomorphology (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 the current situation of this Guidebook in which the conservation guidance has been separated from the engineering guidance! Yet another European Union Directive, that on Habitats, may encourage a technical dialogue between geomorphologists, ecologists and engineers on those rivers designated as Special Areas of Conservation (SACs). 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. Unfortunately there is very little predictive information on linkages between individual elements of ‘hydromorphological quality’ and the response of key species in the Habitats Directive, such as salmon, lamprey and *Ranunculus* (Water Crowfoot).

Table 5.3 Suggestions for geomorphological interpretation of some components of 'hydromorphological status' in the Water Framework Directive, relevant to UK rivers (Newson 2002).

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 landuse.
'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.

6. CASE STUDIES OF THE APPLICATION OF GEOMORPHOLOGICAL ASSESSMENT PROCEDURES

6.1 Introduction - geomorphological assessment, information and guidance.

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 due to headwater erosion and of repeated severe sedimentation at the supply intakes. The University of Newcastle upon Tyne 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, page 11); the two authors had become convinced that sediment transport is a much broader problem than anticipated in engineering science, involving both supply and magnitude/frequency complications. The Dunsop study is not directly reviewed here because of its exploratory nature (it is used by Newson *et al.* 1996) but it served to highlight the importance of two vital geomorphological factors that hitherto had not been considered as providing any potential guidance:

- Flood history;
- Landuse and land management.

Sources of sediment opened during the rare flood event were still contributing to the excessive deposition but newer sources had been created by e.g. bracken spraying, ATVs (All Terrain Vehicles) and rabbit infestation.

At this stage it was still unusual for river managers to commission geomorphological surveys; problems of erosion and sedimentation were normally addressed with engineering solutions such as revetment or traps. Whilst sediment-related problems were widely recognised, Hydraulics Research (1987) had 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) example of neglecting the sediment system was the Brecon flood protection scheme which, unintentionally, widened a channel to aid conveyance - the Usk - making 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.

Whilst a minority of academic fluvial geomorphologists had become involved in consultancy during the 1980s and 1990s, their contribution remained locked up in their confidential project 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 U.S. Army Corps of Engineers, the momentum that was building in the UK for geomorphological studies, e.g. in Thames Region of the National Rivers Authority, it was given little shape or structure via this route.

During the 1990's, however, a significant number of R&D contracts were let by the 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 1998).

Simultaneously, NRA/EA was 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 here and papers by Newson *et al.* (2001) and Newson (2002).

At the time of writing in 2002 there are further policy drivers for the incorporation of fluvial geomorphology – including those relating to floodplains: the recent resurgence of flooding as a hazard to life and property in England and Wales (e.g. Easter 1998 floods, Autumn/Winter 2000 floods) has provided the impetus to bring together all relevant engineering and environmental sciences to focus on the problems of conveyance, stability and sustainability (including ecosystem protection and enhancement). Appropriate R&D to develop the necessary tools is ongoing but this Chapter audits the application of the practices and procedures introduced by the early wave of R&D outputs, notably from Guidance Note 18 (EA 1998); it therefore relates mainly to the principles and practice of geomorphological assessment for river channels.

6.2 Dimensions of the review

Between 1992 and 1994 what may be termed the 'first generation' of Fluvial Audits were undertaken under an R&D contract to the University of Newcastle. Having completed an analysis of the general problems of erosion and sedimentation in England and Wales (Sear *et al.* 1995), specific problems became the focus of a second phase of the contract. It is essential to note the direct problem orientation of the assessments during this phase; subsequently Fluvial Audit and an extension to the River Habitat Methodology ('geoRHS') became much more strategically orientated before returning once more in 2002 to addressing specific river management problems. We may simplistically label these phases as the first, second and third generation of geomorphological assessments (Table 6.1).

During the first generation of assessments pressure was applied by the contractors for an opportunity to provide a geomorphological assessment of a river management dilemma 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. (see Appendix 1). In view of the slightly 'forced' nature of the contribution 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. 'Nothing has happened'! The lesson is clear - there must be a willingness to incorporate geomorphological advice at the project planning stage. 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.

As further background to the review one needs to recognise that R&D becomes incorporated only slowly in practice. 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 (Appendix 2). The course was designed at the University of Newcastle and has been delivered to 18 EA groups in 6 regions, by staff from Newcastle and from the University of Southampton, with the aim of creating ‘an intelligent client’ for geomorphological procedures in the Agency (there is now a National Geomorphologist in North West Region but only two regions employ a geomorphologist). 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.

It is now timely to ask whether the case studies indicate successful use of the procedures, whether modifications have been necessary, whether management actions have followed geomorphological assessments and to describe the range of river channel problems targeted for geomorphological guidance.

In detail, the review seeks 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 it has been applied.

6.3 Sources

The sources for this review essentially fall into six groups of geomorphological projects (Table 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). NRA (1994) brought together the first examples of the more formal procedures that are described in 'River Geomorphology: a Practical Guide' (EA 1998a); he used Catchment Baseline Survey and Fluvial Audit on reaches and catchments of ten rivers with a wide geographical distribution in England and Wales.

Geomorphological assessment also formed part of several of the other R&D ventures completed within the 1990's (Table 6.1).

The two remaining categories of comprehensive application of geomorphological assessment are those carried out for EA and by EA under the remit of 'River Geomorphology: a Practical Guide' and the River Habitat Surveys respectively.

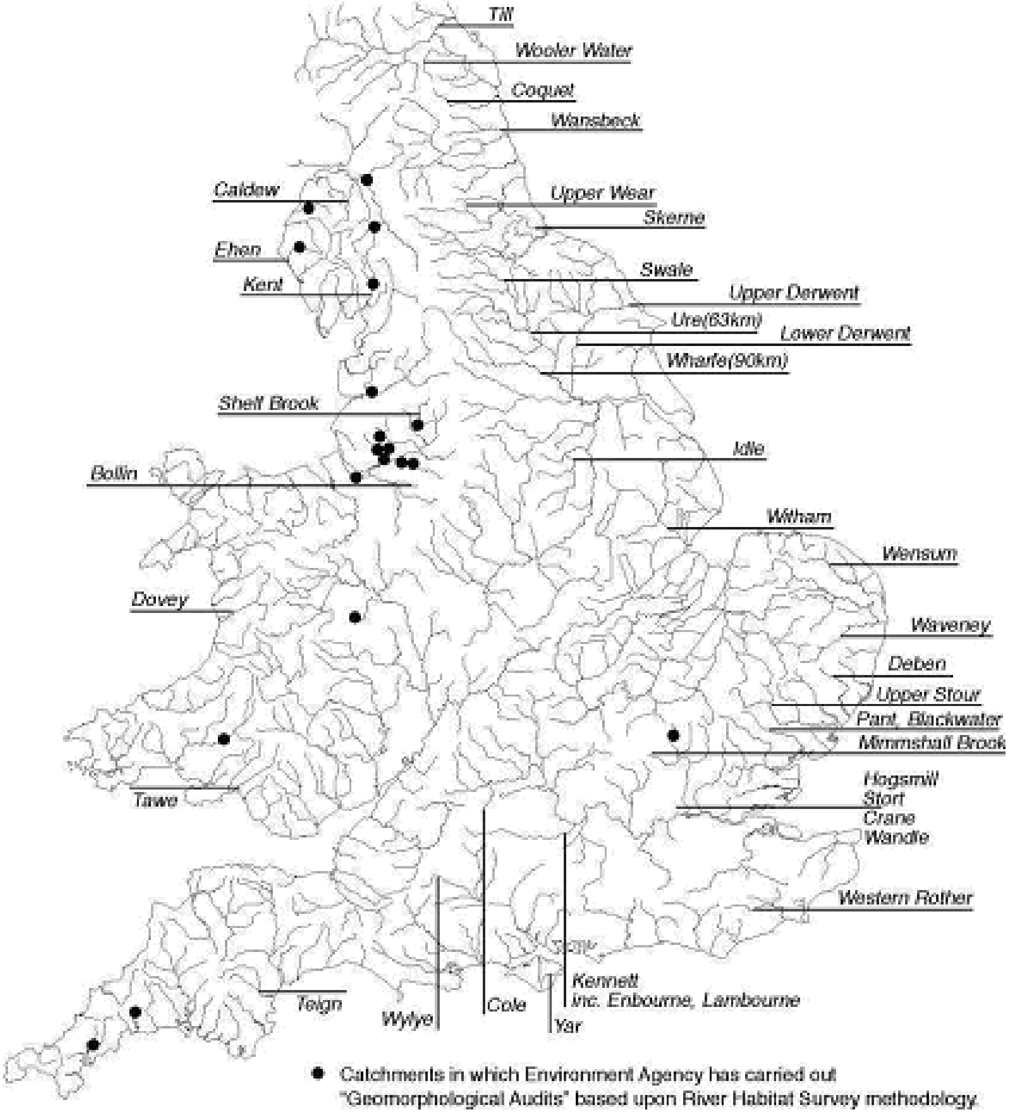


Figure 6.1 Distribution of Fluvial Audits and RhS Geomorphological Bolt-on assessments in England & Wales up to 2002 (after Newson *et al*. 2002)

Table 6.1 Sources for case studies of geomorphological assessment*

<u>Reported by Newson *et al*. (1997) but dating from 1986-1991.</u>

- Neath
- Blackwater
- Mimshall Brook
- Upper Severn
- Brennand/Whitendale
- Wolf/Thrushel
- Wensum

Rivers for which assessments were made as part of other R&D

Hey and Heritage 1993

- Ecclesborne
- Kent

'First generation' of formal assessments

Sear and Newson 1994 (see also Appendix 6.1)

- Derwent
- Ehen
- Idle
- Mimshall Brook
- Sense
- Shelf Brook
- Tawe
- Ure
- Wansbeck

Catchment Baseline Surveys and Fluvial Audits constituting the 'second and third generations' of formal assessments (1998-2002)

Universities of Newcastle, Lancaster, Southampton and consultants

- Skerne}
- Cole } *River Restoration Project*
- Upper Wharfe (including Dynamic Assessment)
- Derwent
- Waveney (including Dynamic Assessment)
- Kent
- Upper Stour
- Pant
- Deben (including Dynamic Assessment)
- Blackwater
- Swale
- Ure
- Wharfe
- Caldew
- Upper Derwent (*Arup and Partners*)
- Boscatle streams (*Halcrows*)

Geomorphological Audit (EA extension of RHS system 1999+)

- Eden
- Glaze Brook

(sites below are unpublished – see Walker 2000 for some sites)

- Ribble
- Mersey
- Rock
- Pendle Water
- Keekle
- Calder
- Irwell
- Trannon
- Weaver

- Camel
- Sankey Brook
- Tywi
- Mimram
- Bollin
- Sugar Brook
- Byne Brook
- Padgate Brook

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* Maps and lists are available as Figure 6.1 here, but also in Newson *et al.* (1997), EA (1998a) (River Geomorphology: a Practical Guide), and EA (1998b) (Sediment and Gravel Transportation in Rivers). An update of the most recent fluvial survey sites may be obtained by contacting the Environment Agency's Lead Region for geomorphology (North-West at Warrington) or the authors.

6.4 Analysis

It is not the purpose of this Guidebook to simply provide an academic review of our experiences in adding a component of fluvial geomorphology to the assessment of river management problems. Instead we need to identify, from the questionnaire survey returns analysed above (see Preface), the needs of the user community for information – or rather for confidence in identifying appropriate uses for geomorphological assessment.

Case studies from the third section of Table 6.1 (i.e. the 'first generation' have been given a homogeneous review (Appendix 6.1). 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 is 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). In all of these case studies the main procedure was what we now label as 'Fluvial Audit'; none required the more detailed procedures and the Catchment Baseline Survey formed a seamless preface to the Audit in most cases.

Table 6.2 Geomorphological themes addressed by the case studies - see also Appendix 1 for a detailed listing of techniques etc.

Theme	Sub-theme	Detail
EROSION	Catchment sources	Agriculture/forestry Urban waste/roads
	Bank erosion	STWs Engineering
	Bed scour	Transferred/ regulated flows
	Structures	

DEPOSITION	In-bank	Tributaries Zonal
	Out-of-bank	Structures
	Interstitial in Gravel bed	
CHANNEL ADJUSTMENT	Planform change	Progressive Event-related
	Channel capacity	
	Channel gradient	
	Channel realignment	
CHANNEL STATE	Reference conditions	
	Habitat description	
	Stable channel or feature	
	Recovery from capital works	
	Reduce maintenance	

There is obviously a considerable policy and legal obstruction to the direct incorporation of geomorphological assessment into practical river management; one might paraphrase as 'too many factors, too many agencies'. Thus, fluvial geomorphology bears a responsibility for fundamentally altering the normal approach to river management problems - it is not merely a technical 'add-on'. Virtually no actions resulted from the 'first generation' of geomorphological advice. We know, however, that the advice provided was regarded as being very useful context to the problem, one which often justified no action, or indirect action through, for example, Catchment Management Plans and LEAPs.

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, whilst 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. Boxe 6.3 shows an abbreviated summary of the Catchment Baseline Survey of the Waveney

Box 6.3 Summary and conclusions of Waveney Catchment Baseline study

GEOMORPHOLOGICAL CONSIDERATIONS

- 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

- 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

- 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

- 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

- 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 Waveney Fluvial Audit followed 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 Dynamic 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;
- the impact of features on channel roughness and therefore conveyance can be predicted, either geomorphologically or using industry-standard hydraulic models.

Here, therefore, we see evidence of a transitional 'vehicle' for geomorphological advice in that it is in formats that correspond with engineering science.

By the time Newson and Sear (2002) carried out a Dynamic Assessment on the River Deben (again following Fluvial Audit) it was merely necessary 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 has become 'comfortable' with the changes to river dynamics effected by restoration schemes if geomorphologists were involved in assessment.

For the remainder of the second generation of Fluvial Audits it appears that geomorphological advice is seen by both customer and contractor as a strategic procedure for sensitive river systems. Quotations from the published Fluvial Audits illustrate this conclusion:

- **Kennet/Lambourn** (p2) 'the geomorphological issue/issues were never clearly specified, although wider and often multifunctional 'problems' were perceived'
- **Ure** (p1) '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** (p.v) the Audit brief included 'catchment wide issues involving poaching, perceived aspects of landuse change and the potential impact of climate change'
- **Swale** (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** (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'.

6.5 Recent trends in geomorphological assessment projects

There are clear signs, however, that in a more recent clutch of applications (again, almost totally restricted to Fluvial Audit procedures) the Environment Agency 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).

For example, the recently published Fluvial Audit for the River Wylye (www.english-nature.org.uk/lifeinrivers) 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.' (p4)

This orientation is in the same vein as that for the earlier Audits on the Skerne, Cole, Upper Wharfe, Waveney and Deben but none of these Audits utilised the power of GIS as a platform for geostatistical analysis or for decision support. It is perhaps the move from traditional reporting techniques (albeit map-based) to a more rigid methodology and a standard technology - partly inspired by the Environment Agency's own use of River Habitat Surveys - that allows us to enter an entirely new phase of applications.

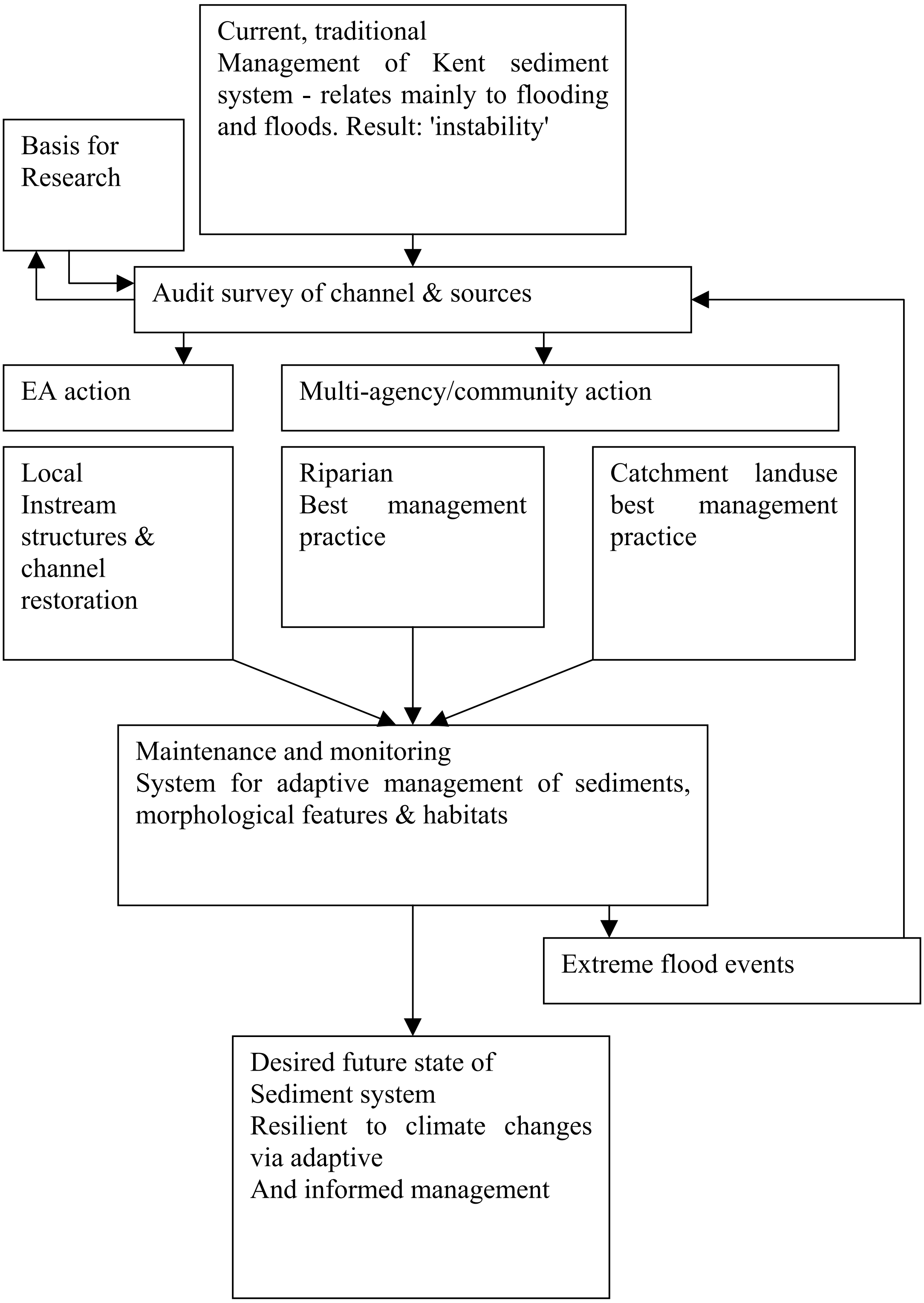
For example, a recent project brief for the River Till in north-east England gave the following requirement for geomorphological advice:
'The driver for the project is to ensure that decisions taken by the statutory agencies which have the potential to affect the hydrogeomorphological status of the system 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 schemes'

As an example of a remit for Fluvial Audit that yielded a proto-decision-support device, the River Kent Fluvial Audit (Orr *et al*. 2000), commissioned by North West EA region may be used as a case study (Box 6.3 and Figure 6.1).

Figure 6.1 Management advice flow diagram arising from the River Kent Fluvial Audit (Orr *et al.* 2000)



Box 6.3 River Kent - suggestions for managing the sediment system based upon the findings of the geomorphological assessment.

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 channelization as major contributors to 'instability'). A problem here is the lack of certainty with which we can model, for example, tributary contributions and rare events - nevertheless, those reaches and subreaches which are clearly ill-adjusted would benefit from re-design 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 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 landuse 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. Whilst 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.

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 de-stabilised by their volume and timing. Fluvial Audit was accompanied by the field survey techniques of the EAs 'Waterway Bank Protection' manual (EA 1999) and 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.

Box 6.4 - Fluvial Audit leading to geomorphological advice concerning channel stability in a river impacted by transferred flows (Newson and Block 2002)

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 back-water conditions, so it is unlikely that the erosion total is an underestimate. The erosion recorded by 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 landuse 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 landuse follows that of the late 1960’s 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. Whilst 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. Whilst the left-bank landuse 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.

6.6 Recent geomorphological extension of River Habitat Surveys

Whilst not a direct outcome of the R&D on geomorphological assessment reviewed here, Geomorphological Audit (Walker 2000) has now had a wide deployment in support of Environment Agency 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 of scale and the density of the survey reaches. When performed in 500m '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 (Environment Agency 2002).

An added component of the spatial power of Geomorphological Audit lies in its association with RHS. The RHS database allows both the assessment of directly similar sites throughout the UK (using principal components analysis - Jeffers 1998) and, by comparison with reference conditions at key sites classified by expert review, allows an assessment of habitat quality. Insofar as habitat considerations and comparative quality are now major drivers for river management policy Geomorphological Audit has key advantages. However, its outputs constitute inventory and classification, and therefore its management contributions are destined to be less flexible than those powered, for example, by a complete Fluvial Audit incorporated into a GIS permitting geostatistical analysis of a wide range of spatial phenomena and direct inspection of the properties of any particular reach or cross-section.

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 the outputs 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 below.

Table 6.3 Geomorphological management inputs from Geomorphological Audit

6.3a Erosion statistics for Eden sub-catchments

Catchment	Erosion m^2m^{-1}	'natural' (%)	Accelerated (%)	Fine (%)	Coarse (%)
Belah	.46	91.5	8.5	63.4	36.6
Lowther/Eamont	.30	88.2	11.8	48.6	51.4
Hilton Beck	.21	87.3	12.7	76.4	23.6
Eden	.16	82.8	17.2	97.2	2.8
Scandal Beck	.15	87.9	12.1	74.3	25.7
TOTAL	.27	88.9	11.1	65.9	34.1

6.3b Summary of site and system management options (a selection from Parsons *et al.* 2002)

Management option	Current risks	Benefits of option	Target areas	Comments
• Maintenance of existing habitat & geo-morphological quality	• Current high quality may degrade without appropriate monitoring & management	• Protection of high quality environment; • Safeguarding existing habitats for SAC species	• Across study area	-
• Stock-proof fencing of river banks	• Poor bank protection vegetation structure; • Accelerated erosion from poaching; • Reduced river habitat quality	• Improved bank vegetation structure; • Reduction of accelerated erosion; • Improvements to river habitat quality	• Scandal Beck; • Hilton Beck; • Upper Lowther; • Areas of Belah; • Eden main river	• Hedges or other 'live barriers' might be useful durable alternatives where floodplain frequently inundated.
• Enhancement of artificial bank materials (e.g. planting/seeding reinforced banks, replacement of 'builder's waste' with local stone rip-rap).	• Adverse habitat and landscape impacts; • Bank protection not optimised	• Improved habitat and landscape value; • Potential to increase resilience of some forms of bank protection.	• Lowther; • Hilton Beck; • Scandal Beck; • Eden main river	• Use soft engineering methods in combination with existing or replacement hard engineering may make bank protection more resilient.
• Detailed assessment of fine sediment infiltration into gravels	• Gravel-bed habitat may be sub-optimal for salmonids	• Inform as to whether there is a need to improve gravels for salmonids	• Target to known spawning areas (information from local fisheries interests).	• Freeze-core analysis may be used.

6.7 Geomorphological assessment - conclusions

To conclude this review it pays, firstly, to return to basics - i.e. to recognise that we are witnessing the transformation of a body of academic information into prescriptions for action. There are no national networks to gather geomorphological information, either morphological or sedimentological (cf. 3 500 river gauging stations in the USA routinely measuring sediment loads). We do not overlook the emerging contribution and development of the River Habitat Surveys but an orderly comparison of their virtues and failings is beyond the scope of this Chapter.

Thus, simultaneously with their incorporation in inter-disciplinary river management efforts, 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 characterize 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 'useable 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 dimensions of a successful geomorphological approach to a river management problem, exemplified by the River Blackwater (Thames region), are stated as:

- Develop an overview of the primary processes and characteristic channel forms throughout the river system;

- Flag particular aspects of the system that are crucial to the understanding of its current status and likely reaction to human intervention;
- Identify key reaches which are particularly important due to their morphology, sensitivity or instability; and
- Select appropriate procedures for more focused investigations at key locations and reaches.

This review has highlighted rather more the issues that lie at the interface between fluvial geomorphology and river management:

- Geomorphological advice is impossible in most instances in the UK without a data gathering exercise; the procedures promoted by R&D and established by applications do not, however, guarantee the incorporation of the advice;

- 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 and in major consultancy firms, whilst most academic practitioners are driven to a research orientation. Whilst River Habitat Survey data forms an important filler in this gap, apparently universal and transparent, it cannot compensate for a profound lack of expertise (as defined above);

- The current dominance by non-engineering river management functions, such as conservation, in the use of geomorphological procedures has tended to emphasise the strategic and indirect incorporation of the advice provided by, for example, Fluvial Audit. However, both a more focused specification by users and a more rigid and technological output from contractors is encouraging more direct incorporation;

- Whilst the first generation of Fluvial Audits attempted to apply a wide range of process-related observations and techniques, such as sediment source finger-printing and dating techniques, process approaches have tended to become subsumed within 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;

- 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.

APPENDIX 6.1: Review of case studies used in the development of Fluvial Audit procedures by Sear and Newson (1994)

RIVER	Derwent (Yorkshire)
LOCATION	U/s of Rye confluence
TYPE	Lowland, agricultural
PROBLEM	Persistent siltation since 1970s, following channel straightening
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	(engineered) straight
W/d ratio	6
Sediment size	D50 = 1mm
HISTORICAL CONTEXT	
'Large, rare' floods	1877,1928,1938,1954,1960,1967/68,1979,1982/3,1990
Landuse change	Afforestation of headwaters, intensification of arable uses
Capital works	1800-1810, 1830, 1950-60
Maintenance	Regular de-silting
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA (problem reaches only)
Extra data collected	Sediment fingerprinting, water quality records
ADVICE GIVEN	
Sediment sources	Field and floodplain soils
Sediment transport/yield	Stream power shows engineered channel transports more sediment to problem length
Channel instability	-
Channel design/restoration	Hydraulic study of tributary backwater effects recommended
Bank erosion protection	-
Sediment trapping	Buffer strips, 5-10m wide for floodplain drainage
Planning/monitoring	Better riparian management as part of catchment planning

RIVER	Ehen (Cumbria)
LOCATION	D/s of Ennerdale to the coast
TYPE	Mountain headwaters, lake storage, moderately steep, gravel-bed river
PROBLEM	'instability' leading to reduced fishery
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Sinuous, truly meandering in parts
W/d ratio	6-12
Sediment size	Coarse gravel (heavily armoured) d50 = 32-45mm
HISTORICAL CONTEXT	
'Large, rare' floods	1890s, 1928-30, 1954, 1966, 1977
Landuse change	None of relevance to the problem
Capital works	Braystones flood protection and fishery rehab.
Maintenance	Stone pitching and traditional spiling/pitching
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	CBA/FA (lower catchment)
Extra data collected	Climate trends (rainfall), bed material grain size
ADVICE GIVEN	
Sediment sources	-
Sediment transport/yield	-
Channel instability	Apparent reactivation of traditionally 'unstable' reaches
Channel design/restoration	Advice against some forms of fishery rehab. Involving ad hoc structures
Bank erosion protection	Braystones reach needs re-thinking in terms of erosion below revetments
Sediment trapping	-
Planning/monitoring	-

RIVER	Idle (Nottinghamshire)
LOCATION	D/s of Retford (Mattersey length)
TYPE	Sand-bed lowland channel with washlands. Low gradient
PROBLEM	Siltation
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	
W/d ratio	
Sediment size	D50 = 0.3mm
HISTORICAL CONTEXT	
‘Large, rare’ floods	1795. 1932, 1947, 1978 (but declining flood magnitude through 1980s)
Landuse change	Coal mining, sand and gravel extraction, urbanisation, intensification of arable agriculture
Capital works	River Idle improvement scheme (1980s)
Maintenance	Regular de-silting
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA (reach)
Extra data collected	Sediment transport data, sediment storage volumes (from x-sections)
ADVICE GIVEN	
Sediment sources	Local - identified from fingerprinting, sand-size routing, vulnerable soils
Sediment transport/yield	Repeat x-sections suggested
Channel instability	Naturally stable (old maps consulted)
Channel design/restoration	-
Bank erosion protection	N/a
Sediment trapping	-
Planning/monitoring	Landuse advice via catchment management

RIVER	Mimshall Brook (Bucks)
LOCATION	Warrengate Road area (TL231032)
TYPE	Urban, lowland, alluvial - gravels and silt/clay
PROBLEM	Sedimentation leading to flooding and habitat damage (SSSI)
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	(engineered - mainly straight)
W/d ratio	5
Sediment size	D50 = 13-22mm
HISTORICAL CONTEXT	
‘Large, rare’ floods	1877, 1883, 1903, 1912, 1913, 1915, 1916, 1951, 1961, 1979, 1989
Landuse change	Urban development and motorway construction
Capital works	Channelisation (loss of wetland) and land drainage
Maintenance	Dredging (both official and informal)
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA (problem lengths)
Extra data collected	Long profile, x-sections
ADVICE GIVEN	
Sediment sources	Dredging leads to bank erosion; use buffer zones for catchment sediments
Sediment transport/yield	Stream power calculations indicate both u/s erosion and d/s deposition
Channel instability	Prediction of active meandering u/s (recommended as a rehab. Option)
Channel design/restoration	Restore meanders, riffle-pool sequence and floodway. Assisted natural recovery will ensue
Bank erosion protection	Grade controls
Sediment trapping	(use natural storage)
Planning/monitoring	Long-term wetland restoration

RIVER	Skell/Laver (Yorkshire)
LOCATION	Ripon (SE316709 - Alma Weir)
TYPE	Lowland, urban
PROBLEM	Siltation - flood conveyance, gauging station
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Sinuous
W/d ratio	10
Sediment size	D50 = 54mm
HISTORICAL CONTEXT	
‘Large, rare’ floods	N/a
Landuse change	Urban - intensification
Capital works	New weir - backwater effects
Maintenance	Annual desilt
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA of context length
Extra data collected	-
ADVICE GIVEN	
Sediment sources	Urban - streets, drains, disturbance
Sediment transport/yield	Bar forms in logical position, complicated by vegetation growth
Channel instability	None
Channel design/restoration	Accommodate capacity, raise walls or use vane deflectors to alter flow pattern
Bank erosion protection	-
Sediment trapping	-
Planning/monitoring	-

RIVER	Sence (Leicestershire)
LOCATION	Kilty Bridge - Crow Mill (589978)
TYPE	Lowland, agricultural, silt-clay, sand
PROBLEM	Siltation, bank erosion (not threatening to assets)
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Meandering
W/d ratio	4
Sediment size	D50 = 2mm
HISTORICAL CONTEXT	
'Large, rare' floods	1975, 1980-83
Landuse change	Urbanisation and intensification of arable agriculture
Capital works	River Sence improvement scheme, 1967-85 (channel capacity raised by 46%)
Maintenance	Comprehensive regrade, toe-protection with stone + willow stake/weave
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA of affected reach
Extra data collected	x-sections for 6 dates; empirical bank stability analysis
ADVICE GIVEN	
Sediment sources	Not catchment soils. Bank slumping, livestock pressure, weathering of exposed sediments
Sediment transport/yield	HR survey indicates bank sources
Channel instability	None apparent from old maps - comes from bank oversteepening at regrade
Channel design/restoration	Compound channel to stop bank failure - achievable during maintenance
Bank erosion protection	Complete the empirical stability analysis. Fencing stock. Spiling for basal sands
Sediment trapping	-
Planning/monitoring	-

RIVER	Tawe
LOCATION	U/s of Ystalyfera (SN771085)
TYPE	Upland gravel/cobble
PROBLEM	Siltation
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Wandering
W/d ratio	Highly variable
Sediment size	D50 = 55mm
HISTORICAL CONTEXT	
'Large, rare' floods	Incr. Frequency 1840-80, 1960-64, (inferred from Shrewsbury record: 1849,69; 1946,47)
Landuse change	Afforestation
Capital works	Straightened u/s of Haffes tributary - leading to incr. Slope and erosion potential
Maintenance	Regular, breakdown
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA
Extra data collected	Old maps, lichonometry
ADVICE GIVEN	
Sediment sources	Spoil heaps from coal mines, incision u/s, afforestation?
Sediment transport/yield	-
Channel instability	Problem exaccerbated by careless dredging. Planform instability in fact decreasing
Channel design/restoration	Bed-check weirs in riffle locations (habitat spin-off)
Bank erosion protection	-
Sediment trapping	Advice against
Planning/monitoring	Monitoring instability zones. Survey of Twrch tributary for sediment sources

RIVER	Ure
LOCATION	Jervaulx Park Estate (SE172863)
TYPE	Upland, gravel-bed
PROBLEM	Scour hole, bank erosion
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Meandering
W/d ratio	8.2-11
Sediment size	D50 = 30mm but wash load of sand complicates
HISTORICAL CONTEXT	
'Large, rare' floods	1967, 1982, 1991 (set up the problem)
Landuse change	Local conversion from pasture to arable - promotes concern
Capital works	None
Maintenance	None
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA of 2.1km
Extra data collected	Old maps
ADVICE GIVEN	
Sediment sources	Weak materials in floodplain - randomly accessed by current position of channel
Sediment transport/yield	Competence of river to move up to 460mm - do not use local 30mm gravel to protect!
Channel instability	Stable for last 100 years due to traditional management; before that very dynamic
Channel design/restoration	Stream power increased by flood banks - ease back? Windrow revetment
Bank erosion protection	Regrade scour hole and add willows/stone pitching. Fence against stock
Sediment trapping	-
Planning/monitoring	-

RIVER	Shelf Brook (Derbyshire)
LOCATION	Glossop
TYPE	Steep moorland boulder - sand bed material range
PROBLEM	Sedimentation of flood defence channel through town
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Irregular
W/d ratio	9-15
Sediment size	D50 = 100mm (wide sd)
HISTORICAL CONTEXT	
'Large, rare' floods	1930, 1944 + seven major sedimentation events 1834-1973. Bog-burst records for moorland
Landuse change	-
Capital works	Flood defence channel d/s
Maintenance	Breakdown desilting after floods
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA of catchment
Extra data collected	Detailed historical flood impacts
ADVICE GIVEN	
Sediment sources	1930 and 1944 floods set up active sources; river cliffs remain active suppliers
Sediment transport/yield	34 - 742m3yr-1
Channel instability	Uncontrollable in headwaters - liability to cloudbursts/bog bursts
Channel design/restoration	Encourage u/s deposition zone
Bank erosion protection	-
Sediment trapping	Design of gravel traps - to promote d/s armouring
Planning/monitoring	Photographic monitoring suggested for very active system

RIVER	Wansbeck (Northumberland)
LOCATION	Morpeth town centre
TYPE	Moorland headwaters - agricultural u/s - urban channel (gravel-bed)
PROBLEM	Siltation in town centre - flood conveyance problem
Topic	*Commentary*
GEOMORPHOLOGICAL CONTEXT	
Planform	Controlled
W/d ratio	3.8
Sediment size	D50 = 9-45mm u/s but in problem section 1.6-16mm
HISTORICAL CONTEXT	
'Large, rare' floods	1992. Silt said to build > 100-150 m3s-1
Landuse change	-
Capital works	Flood defence scheme 1968-71 (but problem pre-dates this)
Maintenance	Regular desilting
PROCEDURES FOLLOWED	
CBA/FA/DA/ECD	FA (sampling approach)
Extra data collected	Observations during flood of 1.4.92. Old maps. Sediment sourcing via heavy metal analysis
ADVICE GIVEN	
Sediment sources	Urban sources include road cleansing, clearing of trash racks. Weirs complicate sources
Sediment transport/yield	Bars self-limiting in height - only becme a hazard via vegetation growth
Channel instability	Increasingly stable since 1925
Channel design/restoration	-
Bank erosion protection	-
Sediment trapping	High Stanners bars u/s allowed to become natural traps
Planning/monitoring	Reduce water abstraction u/s (which promotes low flow urban deposition)

APPENDIX 6.2: TRAINING COURSE AND TRAINING MATERIALS

(As supplied to Environment Agency regions by the Universities of Newcastle upon Tyne and Southampton)

1. Introduction and Organisational Material

1.1 Organisation of the existing course

Following the completion of Environment Agency R&D Project 661, an extension of funding to Newcastle University facilitated a refinement of their existing Continuing Education course in Applied Fluvial Geomorphology. The course was moulded to fit the format and terminology of 'Fluvial Geomorphology: a Practical Guide' (EA, 1999) and has to date been delivered on nine occasions in five EA regions - Thames, South West, North West, Anglia and Midland.

The course is aimed at people who need to know what geomorphology is about and how it may be applied. It provides introductory knowledge and guidance. The course does not seek to qualify trainees as such (unlike RHS accreditation), but is more concerned with supplying the insights necessary to recognise the value and limitations of geomorphology as an aide to river analysis and the design of improvement works. Training in geomorphology is intended to be an on-going element in professional development.

The course should be run by an experienced, practising geomorphologist; whilst it is hard to define the level of experience, he or she should be post-graduate and must have completed a number of projects related to geomorphology in the service of river management under UK conditions. The course does not include estuarine or coastal geomorphology, because the dynamics of sediment movement in those environments are so different to the fluvial case. Experience shows that grasping the principles of sediment dynamics and morphological adjustments in rivers with unidirectional flows provides a sufficient challenge for students new to geomorphology.

Supporting materials are included with this Guidebook on a CD-ROM inside the back cover.

1.2 Aims and objectives of training in fluvial geomorphology

Aims:

- To **describe** the subject matter and methodology of fluvial geomorphology to a new audience;
- To **relate** geomorphology to practical problems of river *and catchment* management;
- To **illustrate**, by means of examples and case studies, the applications of fluvial geomorphology and show its value in broadening options for project appraisal;
- To **summarise** the use by the Environment Agency of geomorphology and geomorphologists at plan and project levels.

Objectives:

- To provide, at an appropriate management level, a work-related **appreciation of the potential** of fluvial geomorphology in river management;
- To provide a **compressed experience** of the attitudes, approaches and precautions exercised by fluvial geomorphologists in their research and applications;
- To impart **confidence in the use of terminology**, simple techniques and provisional inferences as a preface to commissioning more detailed studies;
- To relate fluvial geomorphology to the **context of strategies and operations in the Environment Agency** and to other specialist contributions and procedures;
- To show the uses of fluvial geomorphology in regulating external developers, e.g. through EIA procedures.

1.3 Importance of training in the field and interactive discussions

Experience and remarks made in course evaluation questionnaires have both emphasised the value of a field visit as part of the course. However, the need to make fieldwork successful and efficient is paramount and the visit(s) must be carefully thought out and well organised. The tutor may need assistance from an experienced confederate to help deal with the group as a whole completing different tasks in the field. Those attending feel more comfortable to expose their ignorance of, for example, terminology if they feel a common bond; first-hand observations are more lasting than even the best classroom illustration and field techniques are almost impossible to demonstrate in the classroom. A field visit also provides an opportunity for more relaxed discussions and the exchange of experiences, particularly concerning best practice.

Successful field visits are based on efficient travel and good access, preferably to sites where there is a documented record of study or problems. A visit by the course trainer during the few days prior to the course is also helpful togerth with collection of e.g. flow or climate records for the site or nearby.

The field visit is deliberately timed after Session 3 so that trainees have acquired some knowledge on the sediment system, geomorphological methods and channel forms/features *before* venturing in the field. The suggested sequence of sites (or different parts of one site) is:

- simple, natural channel with a range of features to map and opportunity to size sediments;
- ‘disturbed’ channel with a management problem involving erosion or deposition;
- channel with previous management intervention, perhaps unsuccessful.

Equipment needed may include:

- catchment maps (e.g. 1:50 000);
- maps or air-photos of the sites (at least 1:10 000);
- clipboards for notes;
- details from the RHS database for any sites in the vicinity…or the system;
- checklist of features to identify (e.g. from RHS Manual);
- survey forms developed in 'River Geomorphology: a Practical Guide';
- sediment sizing equipment;
- forms for recording sediment size;
- forms for recording bank erosion.

1.4 Use of literature resources on the course

This guidebook now provides a good introduction to recent R&D results and approaches. All delegates should also receive, before attending, the R&D Publication: 'River Geomorphology, a Practical Guide' (EA 1998). This report gives access to the range of geomorphological R&D sponsored by EA, as well as presenting a concise review of selected applications of fluvial geomorphology. It also contains important material on geomorphological procedures, as does the guidebook.

Trainees often, however, request 'a simple text-book' on the subject. A range of texts is available but none is wholly accessible to the newcomer to the field. It may be best to enter the literature some way below the research level with a book aimed at undergraduates, one in which jargon is minimised and introduced slowly. Perhaps the best simple text of this type remains:

Knighton D A, 1998 (2nd Edition) *Fluvial forms and processes*. London: Edward Arnold.

However, a number of the most experienced fluvial geomorphologists in the UK collaborated to produce a highly practical text whose chapters are an ideal adjunct to topics covered on the course and in the Guidebook:

Thorne C R, Hey R D & Newson M D, 1997 *Applied Fluvial Geomorphology for River Engineering and Management*. Chichester: John Wiley.

1.5 A note on the British Geomorphological Research Group and its prime scientific journal

Whilst Fluvial Geomorphology has yet to achieve professional status in the UK, the subject is fortunate in having a learned society of long standing and leading status in the world. The British Geomorphological Research Group (BGRG) is more than thirty years old and has been responsible for promoting and publishing the practical uses of all geomorphology during that period. It is a study group of the Royal Geographical Society and the senior practitioners are Fellows of that Society and perhaps also of a water industry society such as the Chartered Institution of Water and Environmental Management. The BGRG jointly publishes with John Wiley the journal 'Earth Surface Processes and Landforms' – a repository for many of the best new papers in fluvial geomorphology. Articles from the Journal can be downloaded from the Wiley web site at www.interscience.wiley.co.uk.

1.6 Format of the two-day course (for those encouraged by the Guidebook and these materials to organise a course through EA Training)

DAY ONE (suggested start time 0900 or 0930)

Session 1 (45minutes)

THE NATURE AND USES OF FLUVIAL GEOMORPHOLOGY

- Brief history of the subject: importance of time and space scales
- Developing the practical potential of fluvial geomorphology through R&D
- Sediment-related problems and opportunities in EA duties
- Relationship with river engineering

Session 2 (1 hour)

THE SEDIMENT SYSTEM IN CATCHMENTS

- The 'jerky conveyor belt' from hillside to sea: needs for field study
- Natural, semi-natural and degraded channels - towards channel classification
- Channel features: spotter's guide and significance to sediment system
- Basic fluvial dynamics and notions of 'stability'

Coffee break, followed by short discussion, question-and-answer

Session 3 (1 hour)

CHANGING CHANNELS - FORM AND FUNCTION

- Sinuosity and lateral change; river planforms and secondary flows
- Vertical change: aggradation and incision: where, when, how?
- Field indicators of the rate and direction of change in channels
- Use of historical documentation in fluvial geomorphology

Lunch (or packed lunch, eaten on field visit)

FIELD VISIT(S) - ALLOW 5 HOURS

DAY TWO (suggested start time 0900)

Session 4 (1.5 hours)

EROSION AND DEPOSITION - THE BASIC PROCESSES

- Sediment transport - problems of prediction; the stream power approach
- Erosion of banks and beds - supply limitation of transport and important controls

- Deposition - forms, locations and rates
- Role of floods - challenges to breakdown maintenance
- Role of landuse and climate
- Sediment measurements, loads and yields

Coffee break , followed by discussion, question-and-answer

Session 5a (1 hour)

INTRODUCTION TO GEOMORPHOLOGICAL PROCEDURES

- Precautionary principles - geomorphology and habitat protection
- Designing, maintaining and restoring rivers: current problems and available guidance
- Strategic procedures - the Catchment Baseline
- Geomorphology in CMP/LEAPs and in Environmental Assessment

Lunch

Session 5b (1 hour)

GETTING THE JOB DONE - OPERATIONAL PROCEDURES AND PERSONNEL

- Operational procedures: fluvial audit, dynamic assessment, channel design
- Post-project appraisal with geomorphology
- Discussion of case studies in 'Practical Guide'
- Identifying, commissioning and costing the geomorphological input
- Sample costs and benefits

Tea break, followed by general discussion or (recommended) case studies and problems brought in by delegates. Filling in of course evaluation questionnaire, depart.

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